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Mitteilungen des naturwissenschaftlichen Vereines für Steiermark | Bd. 139 | S. 5–36 | Graz 2009

Geology of Styria: An overview

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With 17 figures and 1 table

Angenommen am 30. Oktober 2009

Zusammenfassung: Geologie der Steiermark: Ein Überblick. – Im Frühling 2009 organisierte die steirische Doktoratsschule Erdwissenschaften eine geologische Exkursion zum Thema „Geologie der Steiermark". Die Exkursion wurde von Doktoranden der drei steirischen Universitäten KF Graz, TU Graz und MU Leoben geführt. Resultierend aus dieser Exkursion präsentieren wir hier eine vereinfachte Beschreibung der Geologie der Steiermark, basierend auf modernen Konzepten zur tektonischen Entwicklung des Bundeslandes. Im ersten Teil werden die tektonischen Einheiten, welche die Steiermark aufbauen, präsentiert. Im zweiten Teil wird die zeitliche geodynamische Entwicklung dieser Einheiten beschrieben. Ein dritter Teil behandelt die wirtschaftliche Bedeutung von geologischen Rohstoffen in der Steiermark. Die Abbildungen dieses Artikels sind auch auf den Seiten des naturwissenschaftlichen Vereins und auf http://wegener.uni-graz.at zu finden.

Summary: In 2009 the Styrian Doctoral School of Earth Sciences organised a field workshop on the geology of Styria. The field trip was led by PhD students of the three participating universities: KFU Graz, TU Graz and MU Leoben. As an outcome of this field trip, we present here the geology of the entire province in a simplified way, taking into account modern concepts of the tectonic evolution. In a first part, the tectonic units building up Styria are presented; in a second part the geodynamic evolution of these units through time is described. A third part deals with the economic significance of mineral resources in Styria. The figures of this contribution are available online on the pages of the naturwissenschaftlicher Verein and at http://wegener.uni-graz.at.

1. Introduction

Styria, the second largest province of Austria, has a very rich and diverse geological history. Located at the transition from the European Alps in the west to the Pannonian Basin in the east, it contains rocks that tell a fascinating story of mountain building and basin formation that covers at least the last 500 million years of Earth's history. Indeed, the capital of Styria, Graz, can probably boast with the fact of having a more variable geology within 50 km radius than just about any other state capital in the world: from volcanism to high-grade metamorphic rocks, from young limestones to ancient marbles, from active mountain building to sedimentary basin formation, all can be found within an hours drive in Styria.

Earth Sciences in general and the processes that shaped the geological history of Styria in particular can be studied at three universities in Styria: the Karl Franzens University Graz (KFU), the Technical University Graz (TUG) and the Montan University Leoben (MUL). As part of the newly founded joint Doctoral School of Earth Sciences of the three universities, a geological field trip for PhD students took place in May 2009 (Fig. 1). The

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Fig. 1: Group photo of participants of the first field excursion with the topic "Geology of Styria" of the joint doctoral school "Earth Sciences" of the three universities KF Graz, TU Graz and MU Leoben. The rock boulder consists of a Permian gabbro eclogitized during the Cretaceous orogeny, Koralpe, Styria. Participants: 1 Thomas Wiedel (KF), 2 Dr. Prof. Roland Bakker (MU) 3 Latif Yalcinoglu (MU), 4 Lorenz Scheucher (MU), 5 Bernhard Hubinger (KF), 6 Patrick Grunert (KF), 7 Andrea Kern (KF), 8 Stefan Hausegger (TU), 9 Emilie Bruand (KF), 10 Florian Mittermeyer (TU), 11 Oliver Krische (MU), 12 Jürgen Gusterhuber (MU), 13 Muhammad Imran (MU) 14 Omar Mohammed (KF), 15 Nantasin Prayath (KF), 16 Ivana Cuperova (MU), 17 Barbara Puhr (KF), 18 Nina Gegenhuber (MU), 19 Dr. Prof. Kurt Stüwe (KF), 20 Rhamat Ali Gakkhar (MU), 21 Nicolas Legrain (KF), 22 Thomas Wagner (KF), 23 Deta Gasser (KF), 24 Tamer Abu-Alam (KF), 25 Esam Abu El-Siba (MU).

aim was to introduce the (partly international) students to the geology of Styria and to provide an overview of the complex geological history of this area. The excursion was led by PhD students who work on geological projects in different parts of Styria and was coordinated by K. Stüwe. During the field trip, the idea was born to present the geology of Styria to a wider audience. This contribution is the outcome of a combined effort of the involved PhD students to present a simplified, modern overview of the geological history of Styria to professional earth scientists and non-professionals alike. Our contribution presents an overview over the different tectonic units building up the province, the different rock types occurring in these units, the evolution of these units through time as well as the economic significance of ore deposits in the state.

Around 200 years of geological research in Styria led to the formulation of many different models and concepts explaining its geological history. A milestone in the understanding of the geological history of Styria was the contribution by Flügel & Neubauer 1984. However, since then, many debates were led about the exact tectonic relationship between different units, or about which rocks actually belong to which units and which do not. Some of these debates are still ongoing (fortunately for the active geologists!). There are debates of only local importance; others deal with the large-scale origin of huge

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areas in Styria. We are aware of these controversies, but a short overview contribution like ours can never cope with all of them. We therefore decided to closely follow the two recent contributions of Schmid & al. 2004 and Froitzheim & al. 2008, except for the Northern Calcareous Alps where we follow Frisch & Gawlick 2003. In addition we would like to point to the contribution by Neubauer & al. 2000 where a different nomenclature and tectonic interpretation is used. In addition, we selected a small number of the most recent/relevant contributions on each geological unit. Clearly, this selection is our personal choice and meant to give the reader only a starting-point.

2. Geographical division of Styria

On a topographic map derived from a digital elevation model (Fig. 2), a first-order geographic division of Styria is immediately obvious: whereas the northern, western and south-western parts of Styria are built up of rugged mountains, the south-eastern part is made up of relatively flat lowlands with only minor topographic relief. This transition is spectacular: it marks the passage from the Alps, which extend hundreds of kilometres westward all the way to Nice, to the Pannonian Basin, which extends hundreds of kilometres eastward all the way to the Carpathian arc. Three main rivers drain the Alpine part of Styria to either side of the principal Alpine divide (located at the Schoberpass, Präbichl and Semmering): the Enns towards the north-west and the Mur and Mürz towards the south-east (Fig. 2). The valleys formed by

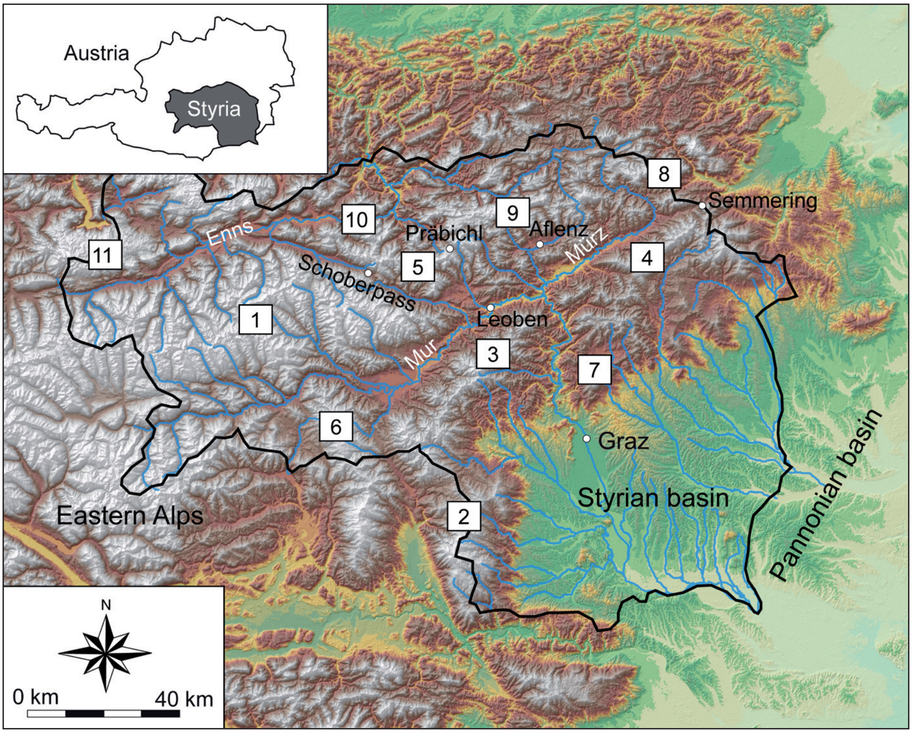

Fig. 2: Topographic map derived from a digital elevation model of Styria with the transition from the Eastern Alps into the Styrian/Pannonian Basin nicely visible. The Alpine part of Styria is divided into several regions, whereof the most important ones are: (1) Niedere Tauern, (2) Koralpe, (3) Gleinalpe, (4) Fischbacher Alpen, (5) Eisenerzer Alpen, (6) Seetaler Alpen, (7) Grazer Bergland, (8) Rax, (9) Hochschwab, (10) Gesäuse, (11) Dachstein. More detailed topographic maps of Styria are online at: www.austrianmap.at.

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these three river systems divide the Alpine part of Styria into several smaller massifs, of which the most important ones are the Niederen Tauern, Koralpe, Gleinalpe, Fischbacher Alpen, Eisenerzer Alpen, Seetaler Alpen, Grazer Bergland, Rax, Hochschwab, Gesäuse and Dachstein (Fig. 2). The part of the Pannonian Basin exposed in Styria is called the Styrian Basin. Typical photographs of different Styrian landscapes are shown on Fig. 3. Each of these landscapes has its own geological history, which will be discussed in the following chapters.

Fig. 3: Air photographs of typical Styrian landscapes as controlled by their geology. (a) The crystalline rocks of the Austroalpine Units form sharp ridges with regular slopes. Rottenmanner Tauern in the fore-ground, Seckauer Tauern in the background. (b) The low-grade Paleozoic sedimentary rocks of the uppermost Austroalpine Units form wooded hills and sharp limestone cliffs: the Grazer Bergland with Röthelstein/Rote Wand in the foreground and Hochlantsch in the background. (c) The Paleozoic rocks of the Greywacke Zone build up sharp, steep mountains. Erzberg mine in Upper Devonian limestones with the village of Eisenerz in the foreground. The mine is the largest siderite mine in the world and the largest open-pit mine in Central Europe. (d) The Northern Calcareous Alps are dominated by Triassic and Upper Jurassic carbonate platforms building up major cliffs intercalated with more soft sediments forming the flatter slopes below the cliffs. The Hoher Dachstein in the foreground, with 2995 m the highest peak in Styria, consists of Upper Triassic limestone. (e) The Neogene sediments of the Styrian Basin form relatively flat low-lands with good agricultural land. In the background small hills of Tertiary volcanic rocks. (f) The Riegersburg in south-eastern Steiermark is built upon very young, Plio-Pleistocene basaltic lava. All photos by R. Homberger, Arosa.

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3. Geological division of Styria

The first-order geographic division of Styria into Eastern Alps and Styrian Basin is also a geological division (Fig. 4 and 5). The Alpine part consists of poly-phase deformed and partly metamorphosed sedimentary and crystalline rocks of the Austroalpine Units, whereas the Styrian Basin consists of less deformed and unmetamorphosed sediments that overlie the Austroalpine Units.

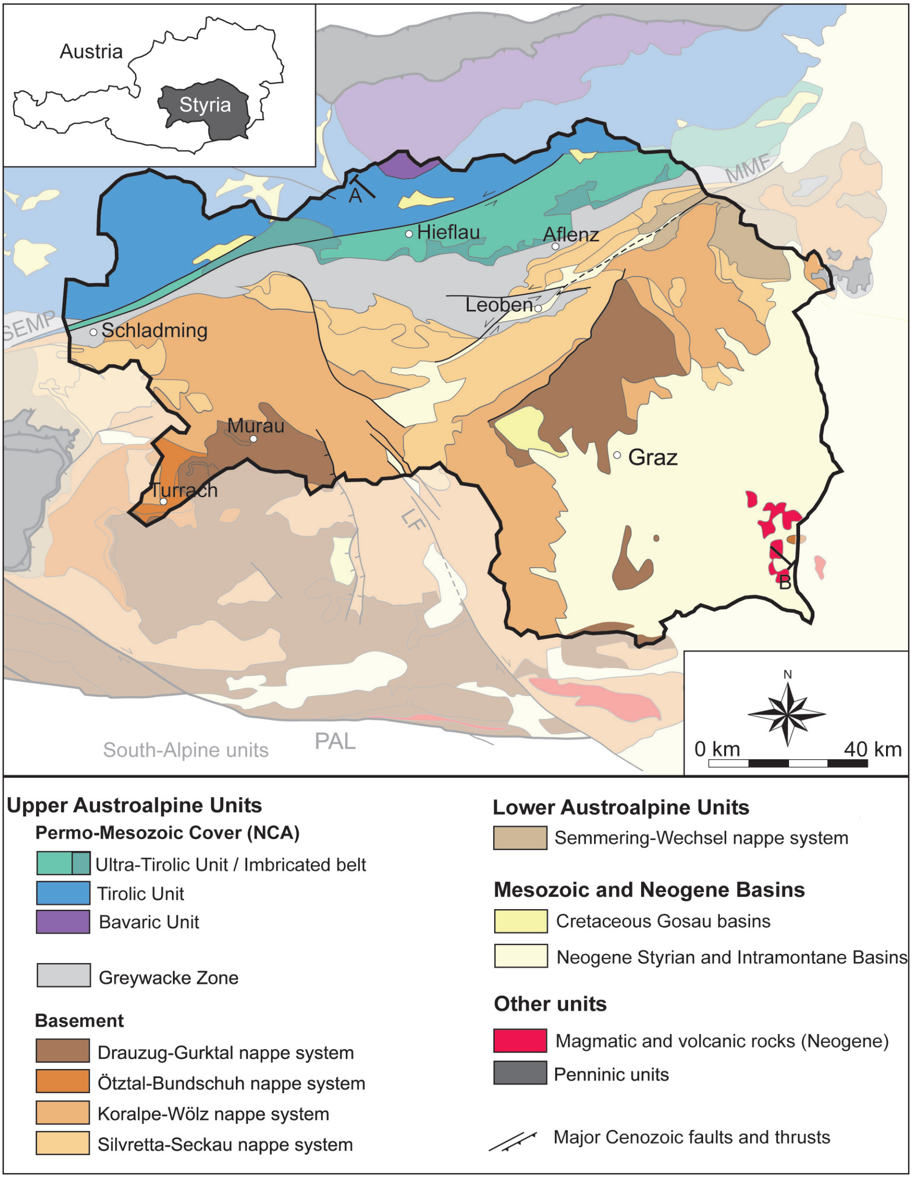

Fig. 4: Tectonic overview map of Styria, after Schmid & al. (2004) and Frisch & Gawlick (2003) (NCA). A-B = Profile trace of Fig. 5. Abbreviations: NCA = Northern Calcareous Alps, SEMP = Salzach-Ennstal fault system, MMF = Mur-Mürz fault system, LF = Lavantal fault system, PAL = Periadriatic Lineament. Geological maps of Styria are for download at www.geologie.ac.at.

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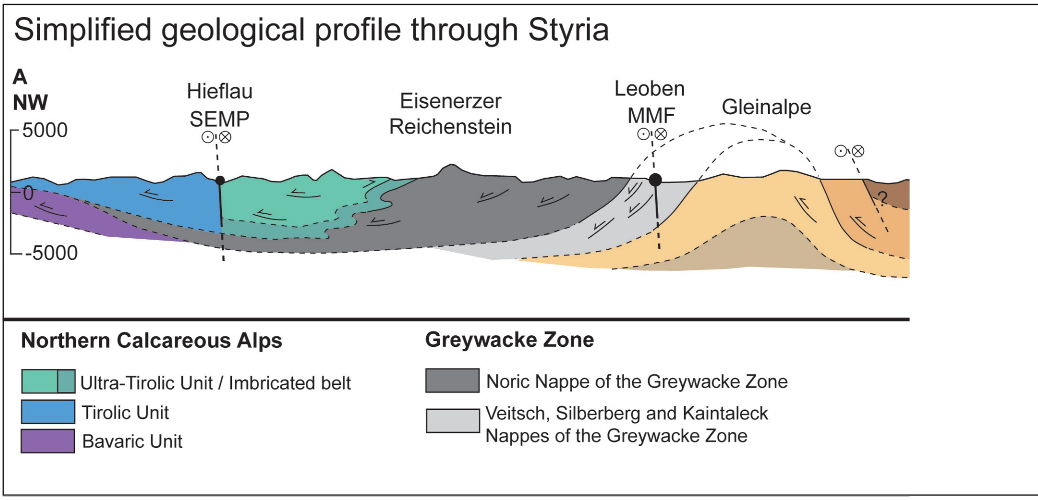

Fig. 5: Simplified geological profile through Styria. Abbreviations: SEMP = Salzach-Ennstal fault system, MMF = Mur-Mürz fault system. Profile trace is indicated on Fig. 4.

3.1 The Austroalpine units

All geological units exposed in the Alpine part of Styria belong to the so-called Austroalpine nappe complex. They consist of several nappe systems stacked on top of each other and separated by either flat-lying shear zones or by major steep strike-slip faults from each other. North of a line Enns valley – Schoberpass – Leoben – Aflenz – Rax (Fig. 2 and Fig. 4) Paleozoic to Mesozoic sediments and low-grade metamorphic metasediments of the Greywacke Zone and the Northern Calcareous Alps (NCA) are exposed. South of this line, a series of low- to high-grade Paleozoic and Mesozoic metamorphic rocks with complex poly-phase tectonic and metamorphic histories is exposed. A schematic tectonostratigraphy according to Frisch & Gawlick 2003 (for the NCA), Schmid & al. 2004 and Froitzheim & al. 2008 is displayed in Fig. 6 and the different units are discussed in more detail below.

3.1.1 Crystalline basement units

The Crystalline basement units to the south of a line Enns valley – Schoberpass – Leoben – Aflenz – Rax (Fig. 2, Fig. 4) can be separated into several nappe systems. They are from bottom to top the Semmering-Wechsel, Silvretta-Seckau, Koralpe-Wölz, Ötztal-Bundschuh and Drauzug-Gurktal nappe systems (after Schmid & al. 2004 and Froitzheim & al. 2008). A simplified geological map with the different rock types occurring in this nappe systems is displayed in Figure 7 (except for the uppermost Drauzug-Gurktal nappe system, which is displayed in Fig. 9). A metamorphic map indicating the peak metamorphic grade reached during the last two important metamorphic events (Permian and Eo-Alpine, see Chapter 4) is displayed on Figure 8. The different nappe systems are described in more detail below.

Fig. 6: Schematic tectonostratigraphic relationships as they are observed today between the different tectonic units in Styria. This tectonostratigraphy is the result of mainly three different orogenies: Upper Jurassic thrusting in the NCA, Cretaceous nappe stacking in all Austroalpine Units, and Miocene strike-slip tectonics. After Frisch & Gawlick (2003; NCA), Schmid & al. (2004) and Froitzheim & al. (2008). Abbreviations: UAA = Upper Austroalpine Units, LAA = Lower Austroalpine Units.

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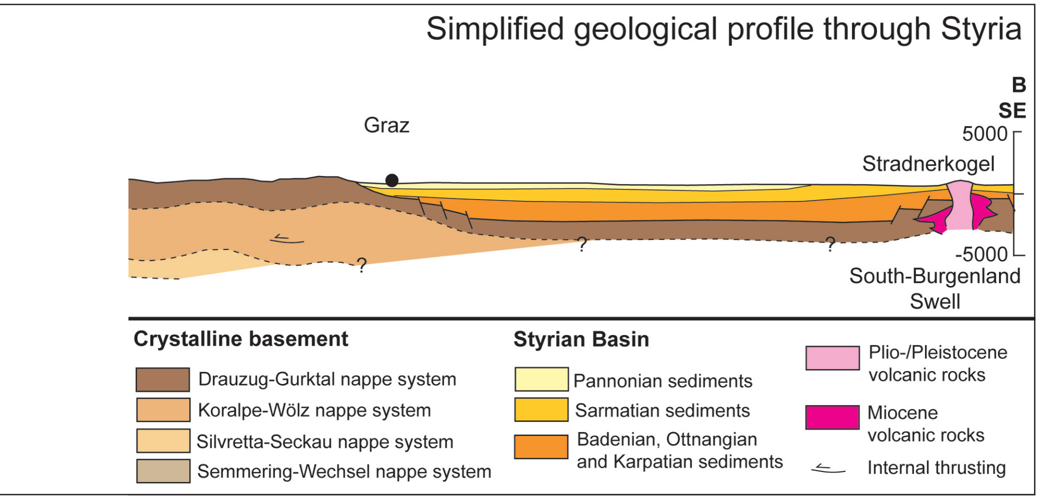
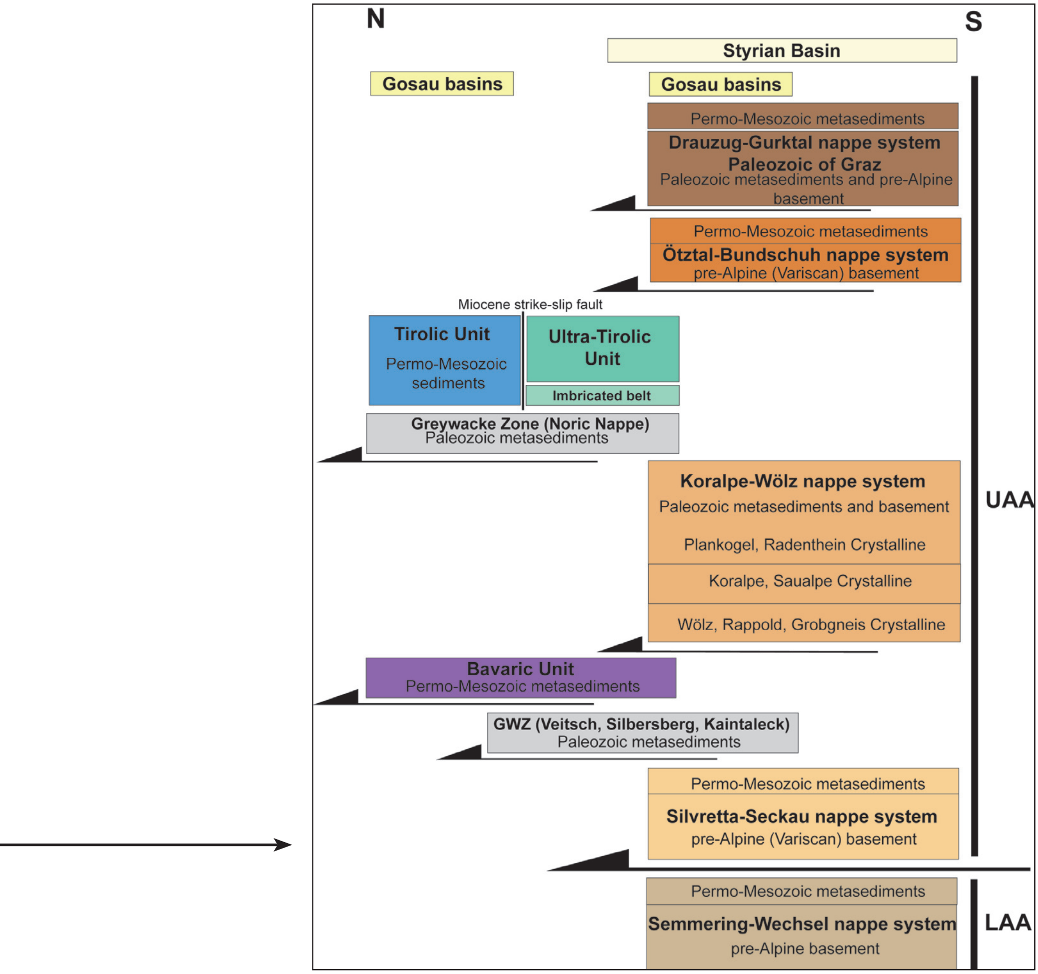


Simplified geological profile through Styria



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Semmering-Wechsel nappe system (Lower Austroalpine Units LAA)

The Semmering-Wechsel nappe system is only exposed in a small area in northwestern Styria close to the Semmering pass and in the Wechsel mountains (Fig. 2, Fig. 4). It consists mainly of paragneisses and phyllitic micaschists, but orthogneisses, greenschists, amphibolites and quartzites are also present (Fig. 7). Permo-Mesozoic carbonaceous, siliciclastic and volcanoclastic metasediments partly overlie and are folded into the crystalline basement. As in all crystalline units of the Austroalpine nappe stack the metamorphic history in the Semmering-Wechsel nappe system is complex. Relics of a Variscan (Carboniferous) and a Permo-Triassic metamorphic event are overprinted by a greenschist facies Eo-Alpine event (Fig. 8; Schuster & al. 2001, 2004).

Silvretta-Seckau nappe system (Upper Austroalpine Units UAA)

The Silvretta-Seckau nappe system builds up a small region south of Schladming, the Rottenmanner and Seckauer Tauern which are part of the Niedere Tauern, the Gleinalpe region in central Styria and an elongated region north of the Mürz valley between Kap-

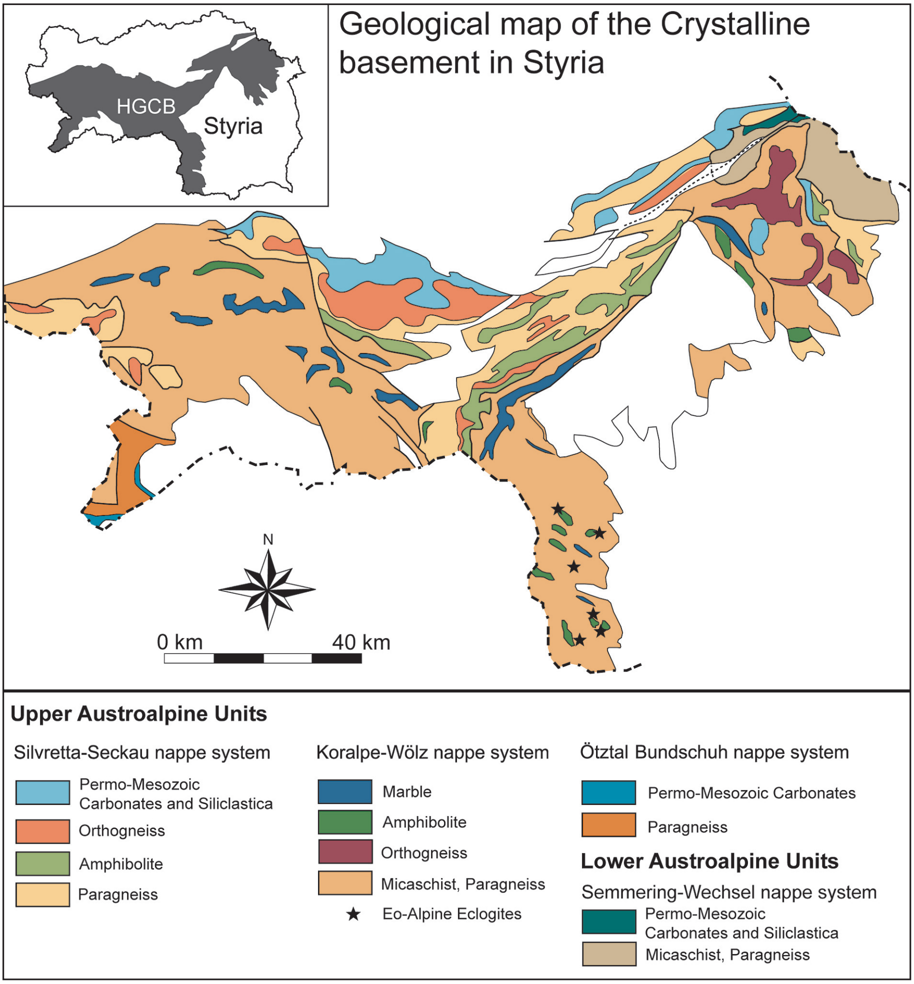

Fig. 7: Geological map of the medium- to high-grade metamorphosed units of Styria. Simplified after Flügel & Neubauer (1984) and Egger & al. (1999) with the tectonic division of Schmid & al. (2004).

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fenberg and Rax (Troiseck-Floning Zug) (Fig. 2; Fig. 4). It consists of biotite-plagioclase gneisses and mica schists, hornblende gneisses, amphibolites and orthogneisses (Fig. 7). Migmatites and ultramafic complexes locally occur. Remnants of Permo-Mesozoic cover sequences, such as siliciclastic, volcanoclastic and carbonaceous sediments are locally present. Variscan tectonics and metamorphism is widely distributed in this nappe system, but no Permo-Triassic metamorphism is recorded (Fig. 8a). The whole nappe system is overprinted by a greenschist to epidote-amphibolite facies Eo-Alpine metamorphism

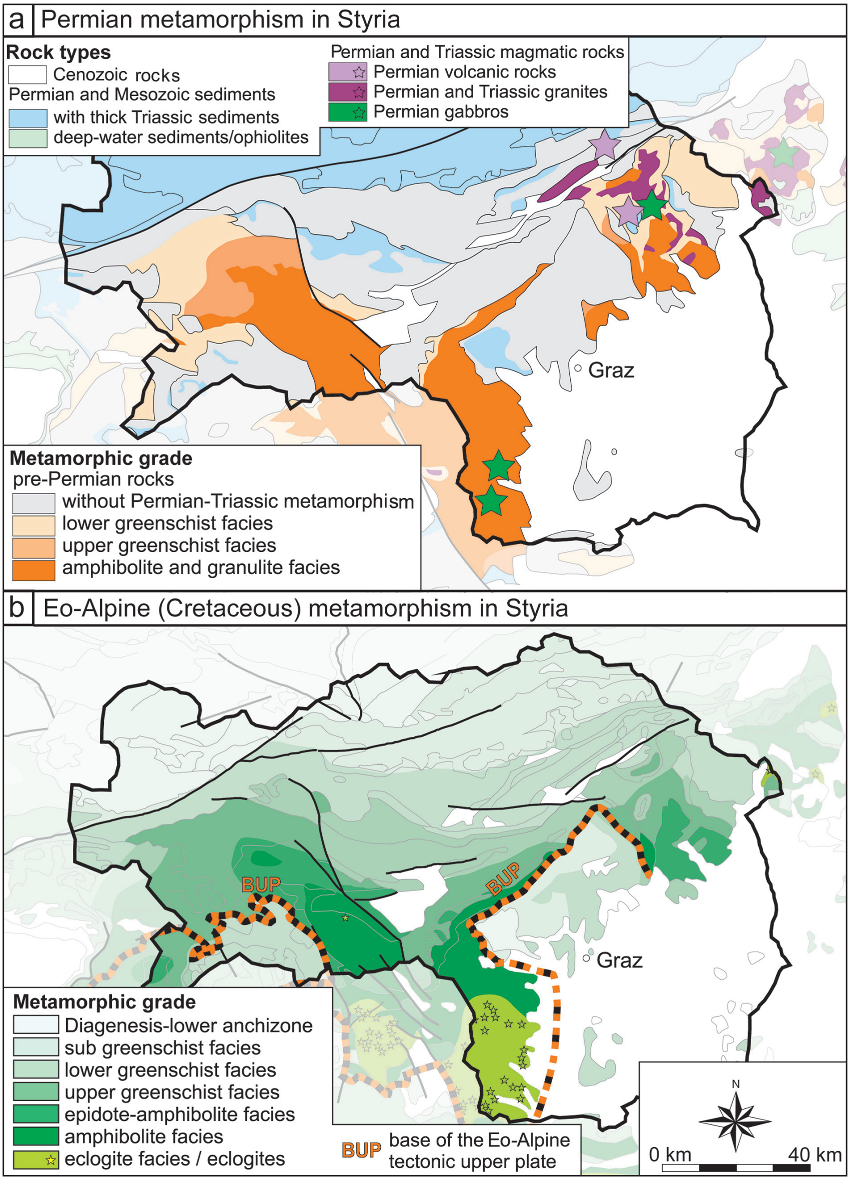

Fig. 8: Metamorphic map of Styria: (a) peak metamorphic grade reached during the Permian metamorphic event, (b) peak metamorphic grade reached during the Eo-Alpine event. Note that the colour code is only valid inside Styria. After Schuster (unpublished).

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(Fig. 8b; Scharbert 1981; Schermaier & al. 1997; Neubauer & al. 1995; Faryad & al. 2002; Faryad & Hoinkes 2003).

Koralpe-Wölz nappe system (UAA)

The Koralpe-Wölz nappe system is exposed in much of the western Niederen Tauern, the Seetaler Alpen, the Koralpe and the Fischbacher Alpen and therefore builds up large parts of Styria (Fig. 2, Fig. 4). In contrast to the other crystalline units, it lacks Permo-Mesozoic metasediments (Fig. 6, 7). It consists mainly of micaschists and paragneisses, pegmatites and orthogneisses. Locally marbles, amphibolites and eclogites occur (Fig. 7). A wide-spread Permo-Triassic metamorphic imprint up to amphibolite facies and local anatexis is recorded, accompanied by Permian gabbros, granites and volcanic rocks

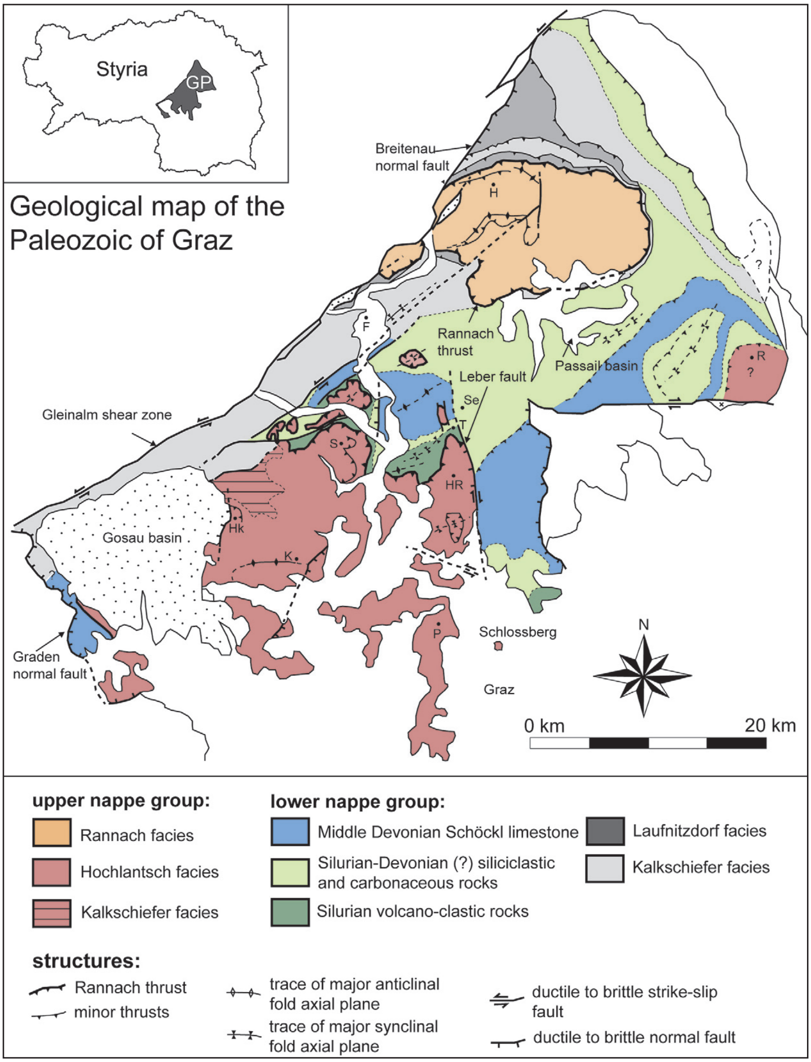

Fig. 9: Structural map of the Paleozoic of Graz. Geographic locations: P = Plabutsch, K = Kehr, Hk = Höllererkogel, S = Schartnerkogel, HR = Hohe Rannach, F = Frohnleiten, H = Hochlantsch, R = Raasberg, T = Taschen, Se = Semriach. Modified from Gasser & al. (2009).

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(Fig. 8a). The Eo-Alpine imprint rises from north to south from greenschist/epidote-amphibolite facies (Wölz complex, Fig. 6) to eclogite facies (Koralpe comlpex) (Stüwe & Powell 1995; Bruand & al. in press). Across the so-called BUP (base of the Eo-Alpine upper plate, see Chapter 4) on top of the Koralpe-Wölz nappe system a decrease in metamorphic grade down to lower greenschist facies is recorded (Fig. 8b; Tenzcer & Stüwe 2003; Schmid & al. 2004; Schuster & al. 2004).

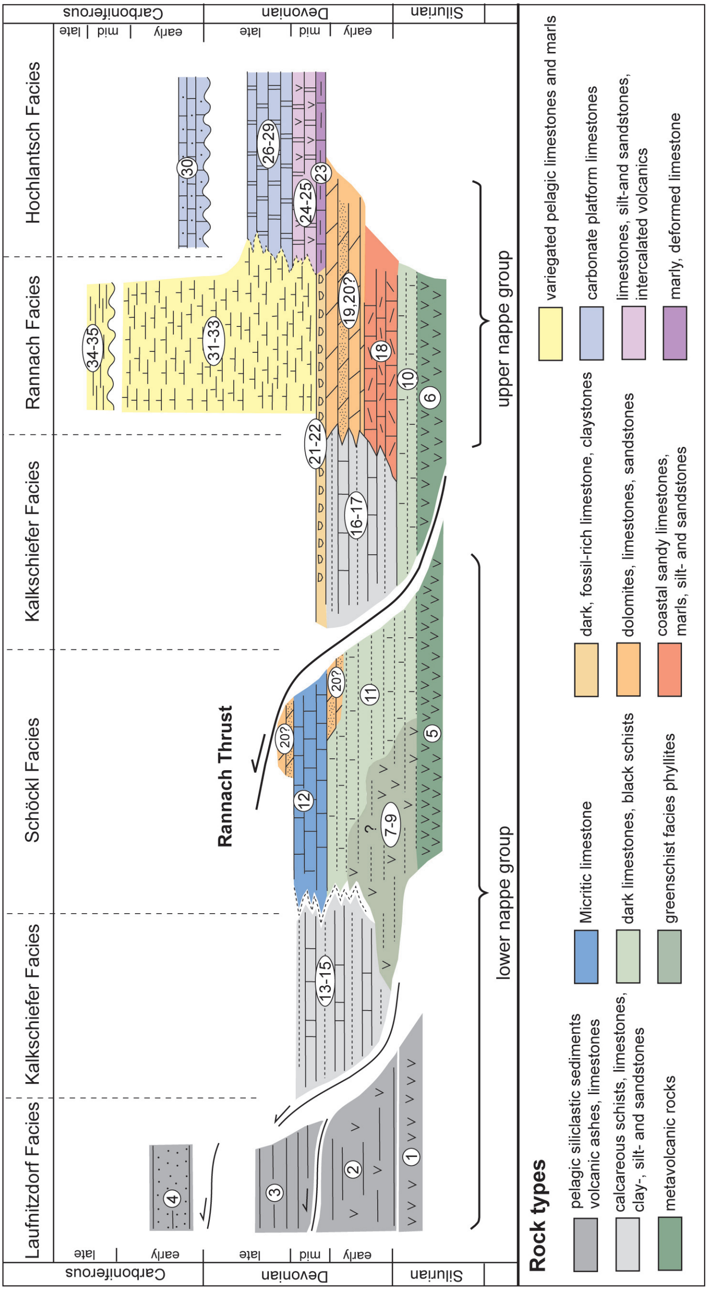

Fig. 10: Stratigraphic relationships as they are observed today in the major tectonic units of the Paleozoic of Graz. Formation numbers: 1 = Hackensteiner Fm, 2 = St. Jakob Fm, 3 = Harrberger Fm, 4 = Dornerkogel Fm, 5 = Taschen Fm, 6 = Kehr Fm, 7 = Semriach Phyllite Fm, 8 = Heilbrunn Phyllite Fm, 9 = Hirschkogel Phyllite Fm, 10 = Kötschberg Fm, 11 = Schönberg Fm, 12 = Schöckl Fm, 13 = Kogler Fm, 14 = Hochschlag Fm, 15 = Hubenhalt Fm, 16 = Bameder Fm, 17 = Heigger Fm, 18 = Parmasegg Fm, 19 = Flösserkogel Fm, 20 = Raasberg Fm, 21 = Plabutsch Fm, 22 = Draxler Fm, 23 = Osser Fm, 24 = Tyrnaueralm Fm, 25 = Rotmüller Fm, 26 = Zachenspitz Fm, 27 = Hochlantsch Fm, 28 = Schweinegg Fm, 29 = Fahrneck Fm, 30 = Bärenschütz Fm, 31 = Kollerkogel Fm, 32 = Steinberg Fm, 33 = Sanzenkogel Fm, 34 = Höchkogel Fm, 35 = Hahngraben Fm. Modified from Gasser & al. (2009).

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Ötztal-Bundschuh nappe system (UAA)

The Bundschuh Nappe of the Ötztal-Bundschuh nappe system is only exposed in a small area in westernmost Styria around Turrach (Fig. 4). It contains mainly biotite-plagioclase gneisses, mica schists, amphibolites and orthogneisses. Remnants of Permo-Mesozoic cover sequences are present (Fig. 7). Up to amphibolite facies metamorphism occurred during the Variscan event, overprinted by an Eo-Alpine greenschist to amphibolite facies metamorphism (Fig. 8b; Miller & Thöni 1995; Koroknai & al. 1999; Schuster & al. 2004).

Drauzug-Gurktal nappe system (incl. Paleozoic of Graz) (UAA)

The Drauzug-Gurktal nappe system represents the uppermost unit of the Austroalpine nappe stack in Styria. Remnants of it are exposed in two isolated areas: The Paleozoic of Graz in central Styria north of Graz (Grazer Bergland, Fig. 3b, Fig. 9) and the Gurktal nappes in western Styria (in the region of Murau; Fig. 2, Fig. 4). Both occurrences show similar sedimentary and tectonic features. In general, they consist of low-grade metamorphic Paleozoic sedimentary rocks with a few relics of Permo-Mesozoic cover occurring in the Gurktal nappes.

The Gurktal nappes consist from bottom to top of the Murau Nappe, the Stolzalpe Nappe and the very small Ackerl Nappe (Flügel & Neubauer 1984). The Murau Nappe is dominated by low-grade black schists and calcareous phyllites of probably Silurian age overlain by carbonates of Lower Devonian age. The Stolzalpe Nappe consists of (a) basal Upper Ordovician to Silurian volcanics, overlain by (b) carbonaceous, sandy and pelitic sediments of Silurian and Lower Devonian age that are in turn overlain by (c) Upper Devonian to Lower Carboniferous pelagic carbonates (Neubauer & Pistotnik 1984; Koroknai & al. 1999).

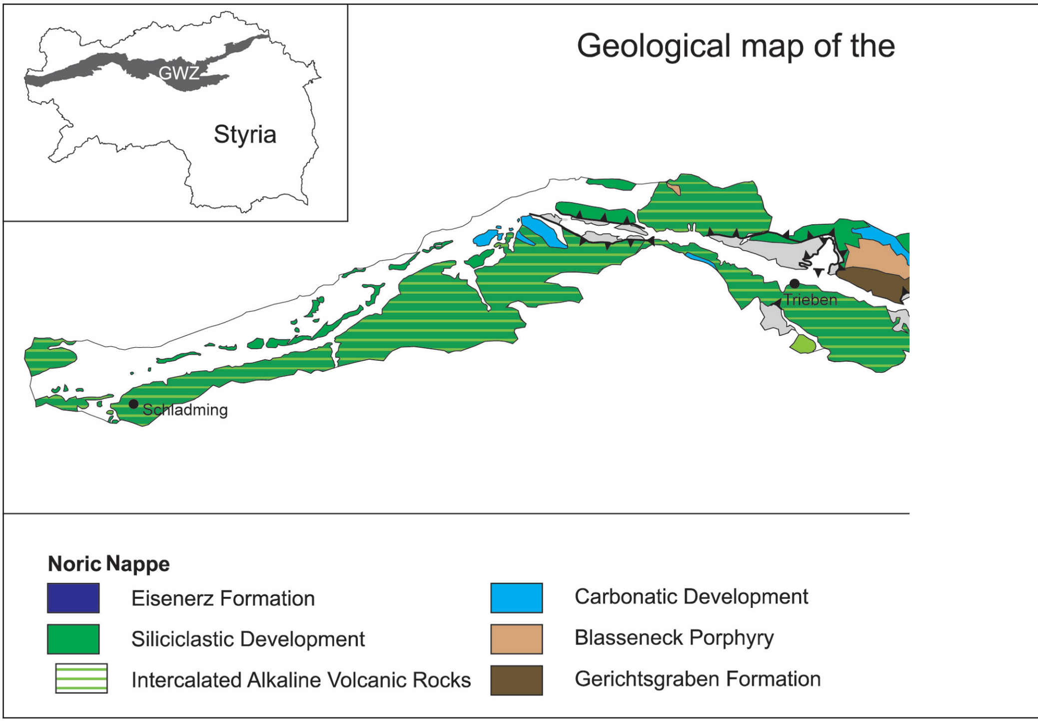

Fig. 11: Geological map of the Greywacke Zone in Styria, after Flügel & Neubauer (1984) and Neubauer & al. (1994). Abbreviation: ND = Niederung mountain.

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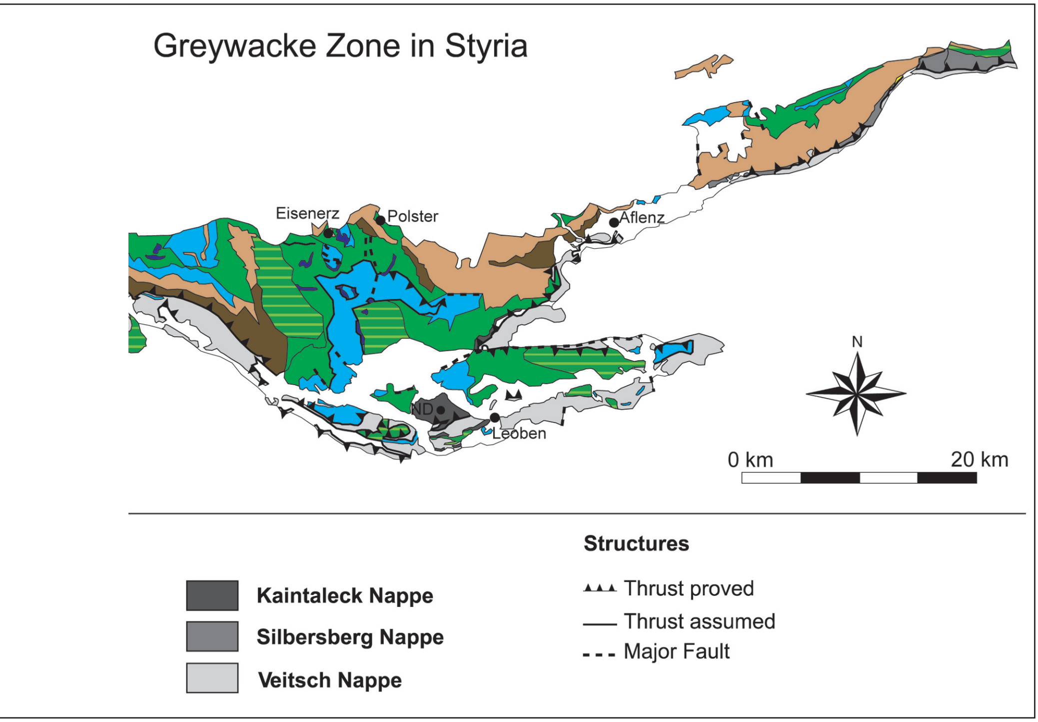
The Paleozoic of Graz also consists of a lower and an upper nappe group (Fig. 9; Gasser & al. 2009). Both nappe groups are built up of several different sedimentary facies zones (Fig. 10). The northern part of the lower nappe group around Breitenau (Fig. 9) in the Grazer Bergland is dominated by Devonian to probably Carboniferous calcareous schists and pelitic sediments of the Kalkschiefer and Laufnitzdorf facies. The central and southern part of the lower nappe group south and east of the Passail Basin is dominated by basal Silurian volcanic rocks, overlain by Silurian to Devonian siliciclastic and carbonaceous rocks and Middle Devonian limestones (Fig. 10). The upper nappe group is also characterized by basal Silurian volcanic rocks, exposed around Kehr. They are overlain by Devonian to Carboniferous carbonaceous schists, sandstones and limestones of the Kalkschiefer facies and Rannach facies exposed west of the Mur valley and in the Hohe Rannach, and of the Hochlantsch facies exposed in the Hochlantsch massif. Upper and lower nappe groups are separated by a major out-of-sequence thrust, the Rannach thrust (Fig. 9 and 10; Gasser & al. 2009; Flügel 2000).

3.1.2 Greywacke Zone (UAA)

The Greywacke Zone represents an up to 23 km wide zone of Paleozoic rocks between the sedimentary rocks of the Northern Calcareous Alps in the north and the higher-grade crystalline basement units to the south (Fig. 3c, Fig. 11). This zone extends from Innsbruck in the west to Lower Austria in the east, where it plunges beneath Tertiary cover of the Vienna Basin (Fig. 4). The Styrian and Lower Austrian parts are named the Eastern Greywacke Zone (Schönlaub 1980). Akin to the crystalline basement units, the Greywacke Zone has a complex internal structure and consists of several tectonic nappes



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stacked on top of each other. They are from bottom to top the Veitsch, Silbersberg, Kaintaleck and Noric nappes (Neubauer & al. 1994; Figs. 11, 12).

Veitsch Nappe

The Veitsch Nappe is exposed in a long but narrow strip at the southern border of the Greywacke Zone extending from Bruck a.d. Mur towards Leoben and St. Michael, and further along the northern margin of the Palten-Liesing valley. It consists of Carboniferous metasediments with metamorphosed coal intercalations and magnesite (Neubauer & al. 1994).

Locally, Permian clastic sediments are present (Neubauer & Vozarova 1990). In the region of Hohentauern south of Trieben (Fig. 11), Ratschbacher 1987 subdivided the sequence of the Veitsch Nappe into three formations (from bottom to top): (1) the Steilbachgraben Formation, composed mainly of clastics and minor carbonates, (2) the Triebenstein Formation with carbonates and some greenschists, and (3) the Sunk Formation with quartz conglomerates and anthracite/graphite deposits (exploited in

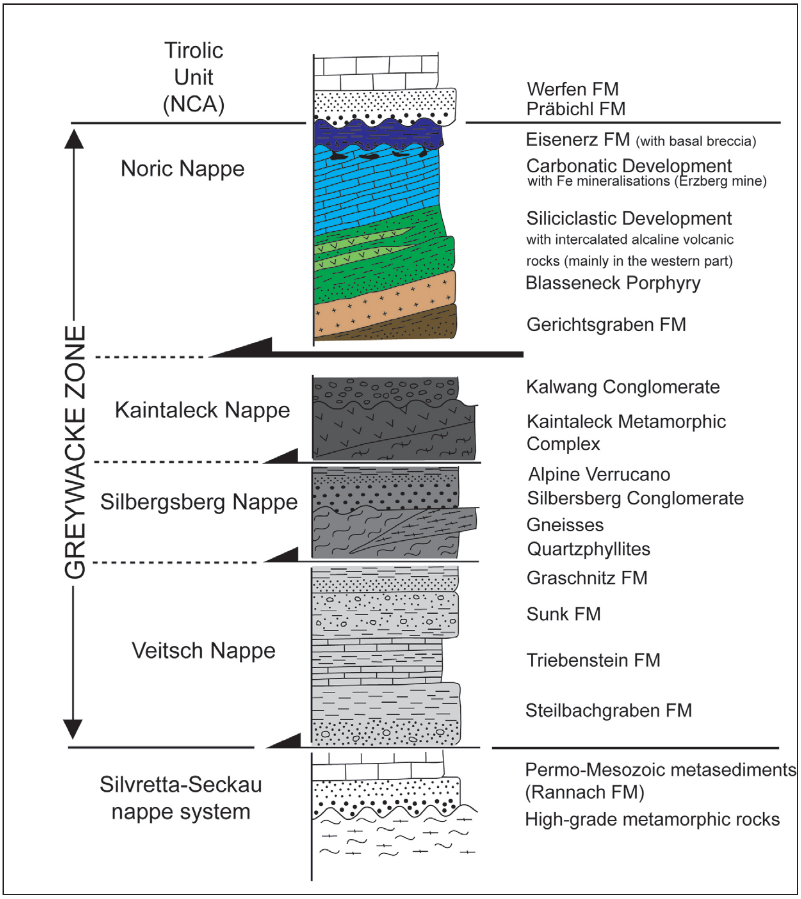

Fig. 12: Schematic tectonostratigraphy of the Greywacke Zone. Thickness of units is not for scale. Colours correspond to colours on Fig. 11. Modified after Neubauer & al. (1994). Note that according to Froitzheim & al. (2008) the Veitsch, Silbersberg and Kaintaleck Nappes originate from the Silvretta-Seckau nappe system, whereas the Noric Nappe originates from the Koralpe-Wölz nappe system.

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the Sunk mine). Locally, in the Mürz valley close to St. Marein, the hanging wall of the Sunk Formation is built up by the Graschnitz Formation (Neubauer & Vozarova 1990), which contains brownish to reddish sandstones and phyllites (Fig. 12).

Silbersberg Nappe

The Silbersberg Nappe is only exposed in a narrow strip in the easternmost part of the Greywacke Zone in Styria (Fig. 11). As well as the other nappes, the Silbersberg Nappe consists of a number of formations that are clearly tectonically separated from all other footwall and hanging wall formations. At the base, these formations include early Paleozoic carbonate-chlorite schists, quartz phyllites and gneisses. The main constituents of the Silbersberg Nappe are the Silbersberg conglomerate and the Alpine Verrucano Formation (light-coloured greenish quartzitic phyllites) on the top. The Silbersberg conglomerate is characterized by interspersions of reddish coloured quartz pebbles (Hermann 1992). After Neubauer & al. 1994 the succession of the Silbersberg Nappe is probably of Permian age.

Kaintaleck Nappe

The Kaintaleck Nappe is exposed north-west of Leoben on the mountain Niederung (Fig. 11). Different structural and geochronological investigations suggest that the Kaintaleck Nappe consist of various allochthonous flakes from over- and underlying stratigraphic members. The subdivision was introduced after studies of Neubauer & Frisch 1993: the succession starts with mica schists, amphibolites and paragneisses and passes into the transgressive overlying Kalwang Conglomerate (Fig. 12). The crystalline rocks in the lower part of the nappe show an early Variscan amphibolite facies imprint at around 360 Ma (Neubauer & al. 1994).

Noric Nappe

The Noric Nappe constitutes the main part of the Greywacke Zone in Styria. It forms a sedimentary-volcanogenic nappe stack (Hermann 1992). At the base, The Gerichtsgraben Formation is composed of greyish sandy, phyllitic and mica bearing schists, sandstones quartzites and banded limestones (Fig. 12). Conodonts investigations within these limestones indicate a Middle Ordovician age. The overlying lower Upper Ordovician Blasseneck porphyry is of ignimbritic origin (rhyolitic rock), mainly composed of quartz, sericite and chlorite (as conversion products of feldspars and biotite). It reaches thicknesses of up to 1000 m. During the Upper Ordovician, Silurian and Devonian both a carbonaceous and a siliciclastic development was deposited. Within the siliciclastic sequence, Silurian alkaline volcanic rocks, predominantly in the western part of the Greywacke Zone in Styria, are intercalated. The Devonian limestones are occasionally mineralized with siderite (mined at the Erzberg, Fig. 3c, see Chapter 5). After an erosional event during the Lower Carboniferous with thin karst filling breccias, the Eisenerz Formation was deposited. It represents the uppermost stratigraphic member of the Variscan succession, before Variscan orogeny started at the Lower/upper Carboniferous border (Schönlaub 1982). The Noric Nappe is transgressively overlain by the Tirolic Unit of the Northern Calcareous Alps (Fig. 12). The Präbichl area near Eisenerz is a classic region where all units of the Noric Nappe are in close proximity and can be studied on walks up the Polster mountain (Fig. 11).

3.1.3 Northern Calcareous Alps (NCA, UAA)

The NCA are an elongated thrust belt of more than 500 km length from the Rhein valley in the west to Vienna in the east. They are located north of the Greywacke Zone and south of the Penninic flysch zone. They build up the northern part of Styria (Upper Styrian region). Some cities and villages inside the NCA are Mariazell, Eisenerz, Gams,

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Admont, Liezen and Bad Aussee (Fig. 4 and Fig. 13). In the eastern part of Styria, the NCA are exposed in a forest-rich low mountain range with moderate altitudes around 800–1800 m. In the Hochschwab and Gesäuse the NCA reaches more than 2000 m and shows a real high mountainous character with karstified plateaus and steep, exposed ridges. The Salzkammergut area in northwestern Styria is a hilly area with isolated high plateaus of 1800–2700 m altitude (Totes Gebirge, Dachsteinplateau). The highest peak of Styria, the Hoher Dachstein with 2995 m, is built up of rocks belonging to the Northern Calcareous Alps (Fig. 3d).

Geologically, the Northern Calcareous Alps consist of Permo-Mesozoic sediments affected by several tectonic and metamorphic events, which led to a complex internal structure. In Styria, the following tectonic units can be distinguished according to Frisch & Gawlick 2003: The Upper Bavaric Unit, the Tirolic Unit with the Hallstatt Mélange, the Ultra Tirolic Unit and an imbricated belt (Fig. 6, Fig. 13).

Upper Bavaric Unit

According to Krystyn & al. 2008 the Upper Bavaric Unit is only exposed in a small tectonic isolated area around the Gamsstein in northern Styria (Fig. 13). It consists of a sedimentary sequence from lower Middle Triassic carbonate ramp sediments (Gutenstein and Steinalm Formations), overlain by the Middle Triassic Reifling Formation (hemipelagic carbonates) and the Partnach Formation (marls, claystones, platy limestones), to the lower Upper Triassic Wetterstein Platform (allodapic limestones of the Raming Formation), forereef, reef and lagunal facies of the Wetterstein Formation). The siliciclastic sediments in the hanging wall show the drowning of the Wetterstein platform during the

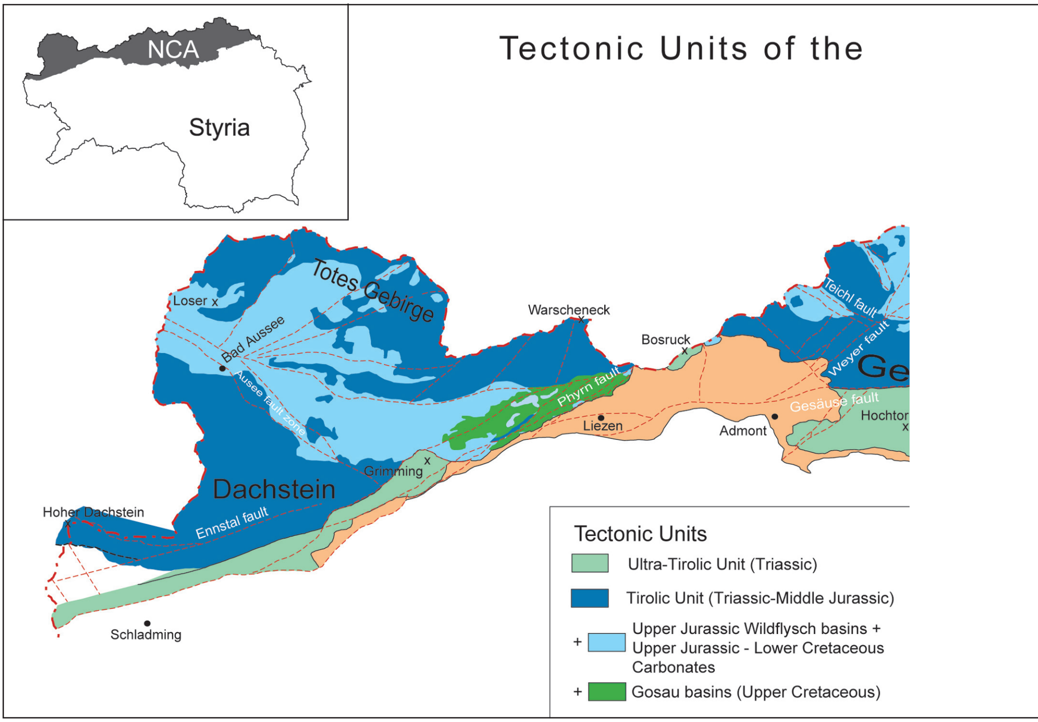

Fig. 13: Geological map of the Northern Calcareous Alps in Styria. Modified after Flügel & Neubauer (1984), Gawlick & al. (1994), Gawlick & al. (1999), Mandl (2001) and Byrda (2009).

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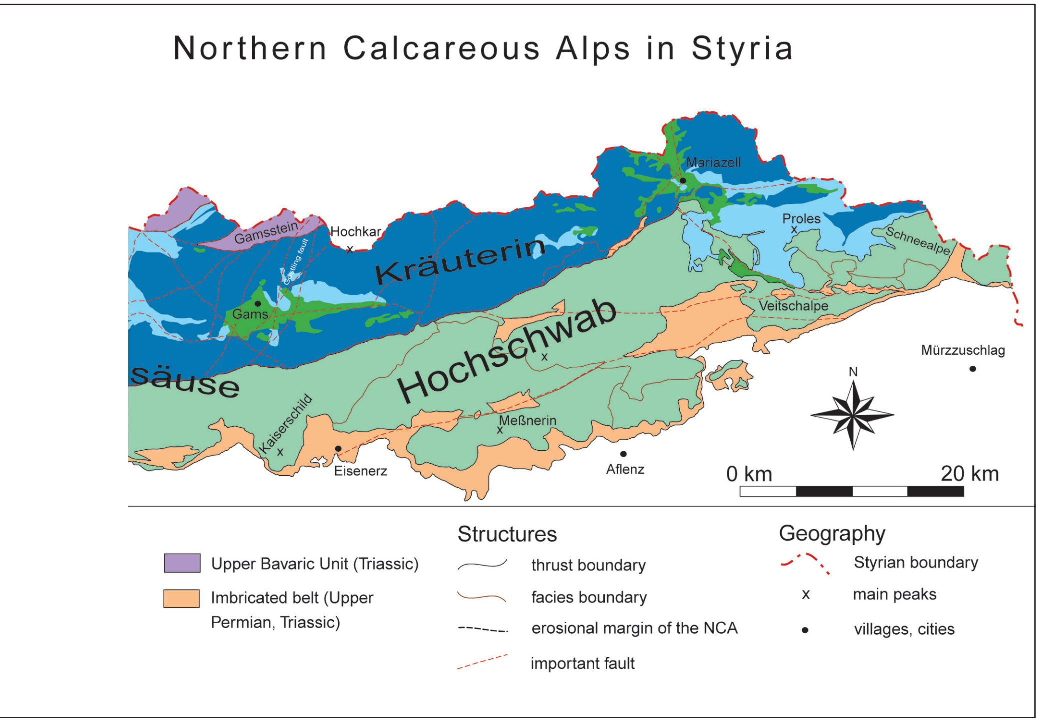
so-called Lunz Event. The Gamsstein was brought into its actual position during younger, tectonic movements because its sedimentary features and the facies conditions do not fit with the surrounding Tirolic blocks (Krystyn & al. 2008).

Tirolic Unit

The Tirolic Unit builds up the northern half of the NCA in Styria (Fig. 4, 13). It consists of two Upper Jurassic nappes: the upper and the lower Tirolic Unit (Frisch & Gawlick 2003), but the database in central and eastern Styria is too scarce to differentiate them on the map scale (Fig. 13). In general the sedimentary succession of the Tirolic Units can be separated into a Permo-Triassic to Middle Jurassic part deposited on a passive continental margin, and an Middle Jurassic to Eocene part dominated by convergent tectonics (Fig. 13, see also Chapter 4).

The Permo-Triassic to Middle Jurassic succession starts with Permian siliciclastics and Upper Permian evaporites (anhydrite, salt, gypsum; generally known under the term "Alpines Haselgebirge"). These Permian evaporites formed preferential shear horizons during younger tectonic movements and are therefore today mostly found tectonically separated from their surroundings. The Upper Permian evaporites, mined today in the Salzkammergut (see Chapter 5) were transferred into Upper Jurassic basins during the Upper Jurassic deformation (see Chapter 4) and occur now in a matrix of Upper Jurassic radiolarites (Wildflysch basins, Fig. 13). In the Lower Triassic, red, green and violet siliciclastic rocks with an increasing amount of shallow-marine carbonates towards the hanging wall were deposited (Werfen Formation). The Werfen Formation is overlain by shallow marine carbonate ramp sediments of the Gutenstein and Steinalm



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Formations (dolomites and limestones), which are in turn overlain by pelagic carbonates intercalated with volcano-clastic rocks (Reifling Formation). In Middle and Upper Triassic times sediments of a classically structured carbonate-dominated continental margin build up the succession. A shallow-marine carbonate platform (Wetterstein Formation) and hemipelagic carbonates from the deeper shelf (Hallstatt Formation) occur. Upper Triassic siliciclastic and mixed siliciclastic-carbonatic rocks (Raibl and Leckkogel Formation) drowned the platform and lie between the Wetterstein Platform and the Upper Triassic Hauptdolomit and Dachstein Platform. The Tirolic succession can be observed in the steep cliffs of the Gesäuse and the Dachstein mountains. In the hemipelagic shelf to the SE of the platform the Pötschen (dolomites, limestones) and Hallstatt Formations (limestones) were sedimented. The Hauptdolomit-Dachstein Platform is again overlain by fine-grained siliciclastic rocks of the Kössen Formation, and in the basin the sediments changed to the Zlambach Formation (marls, marly limestone). The Triassic/Jurassic boundary is marked by the transition from the Triassic shallow-marine carbonate platform to Lower Jurassic hemipelagic grey and red limestones and marls (e.g. Adnet and Allgäu Formation, Dürnberg Formation, to name only a few). Lower Jurassic breccias related to contemporaneous normal faults occur (e.g. Adneter Scheck). The Middle Jurassic rocks are characterized by hardgrounds (gaps) or condensed limestones (e.g. Klaus Formation).

In the upper Middle Jurassic the sedimentation changed rapidly from a calcareous to a radiolaritic one. Typical sediments are red, black and grey radiolarites and cherty limestones. In front of the Upper Jurassic nappe stack (see Chapter 4) different radiolaritic Wildflysch basins such as the Sandlingalm (GAWLICK & al. 2007), Lammer (GAWLICK 1996) and the Tauglboden Basin (GAWLICK & al. 1999a) were deposited. Simultaneously with thrusting and syn-deformational basin formation, isolated carbonate platforms of Upper Jurassic to Lower Cretaceous age occur (Plassen Carbonate Platform, GAWLICK & SCHLAGINTWEIT 2006) with adjacent sediments (mass flows: Barmstein Formation, pelagic micrites: Oberalm Formation) deposited in the former radiolaritic basins. They are in turn overlain by Lower Cretaceous siliciclastic molasse-type rocks that coarsen upwards (Schrambach Formation, Rossfeld Formation). Above a Middle Cretaceous unconformity Upper Cretaceous to Eocene, terrestrial to deep marine sediments of the Gosau group were deposited (WAGREICH & al. 2009). These Gosau sediments are today only preserved along younger tectonic faults and in front of overthrusts, for example along the Miocene Salzach-Ennstal fault north of Liezen or in the area of Gams in the central NCA of Styria (Fig. 13).

Ultra-Tirolic Unit

The Ultra-Tirolic Unit builds up the southern half of the NCA in Styria (Fig. 4, 13). It consists of strongly deformed nappes with olistholitic megablocks in a melange like matrix affected by greenschist facies metamorphism in Upper Jurassic times (GAWLICK & al. 1994; FRISCH & GAWLICK 2003) or in late Early Cretaceous times (e.g. FRANK & SCHLAGER 2006). It lies on top of an imbricated belt (described below) and is separated from the Tirolic Unit by Miocene strike slip faults or Eocene southvergent thrusts. In the western part between Schladming and Grimming, the Ultra-Tirolic Unit is termed the Mandling Unit, whereas in the eastern part (southern part of the Gesäuse, Hochschwab, Veitsch and Schneealpe) the name Mürzalpen Nappe is in use (Fig. 13).

The Ultra-Tirolic Unit consists of Middle Triassic Gutenstein dolomite, Reifling dolomite, Upper Triassic Wetterstein dolomite, Leckkogel beds and Waxeneck dolomite up to Dachstein limestone and Aflenz Formation. It shows a thermal overprint investigated by Conodont Alteration Indices (CAI) values from 5.5 to 6.0. Some parts in the Mürzalpen Nappe reach CAI values of 6.5–7.0 (300 °C).

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Imbricated Belt

This tectonic unit is part of the Hallstatt Mélange (Frisch & Gawlick 2003) crops out in a small narrow zone at the southern rim of the NCA and in some windows in between the Ultra Tirolic unit, building up the flat slopes and the hilly area at the foot of the overlying platform carbonates. These rocks are beautifully visible along this southern margin of the Hochschwab (Tragöss, St. Ilgen) and at the base of the Dachstein in the Ramsau. The boundaries to the GWZ in the footwall and to the Ultra Tirolic Unit in the hanging wall are of tectonic nature. The belt consists of diverse sedimentary successions with different metamorphic grades occurring in a mélange like architecture. Quartzites, sand-, silt-, claystones and carbonates of the Werfen Formation are brought together with un- and metamorphosed clays, salt and gypsum of Upper Permian age. In some parts un metamorphosed Hallstatt limestones and Zlambach marls can be found.

3.2 Neogene basins

Several basins filled with Neogene sediments occur in Styria (Fig. 14). They range from Ottnangian to Badenian and rarely to Upper Pannonian in age with partial Plio-/Pleistocene cover sediments (Fig. 15). There are marine, brackish and limnic-fluviatile developments. The Styrian Basin is the largest of the Neogene basins in Styria. It repre-

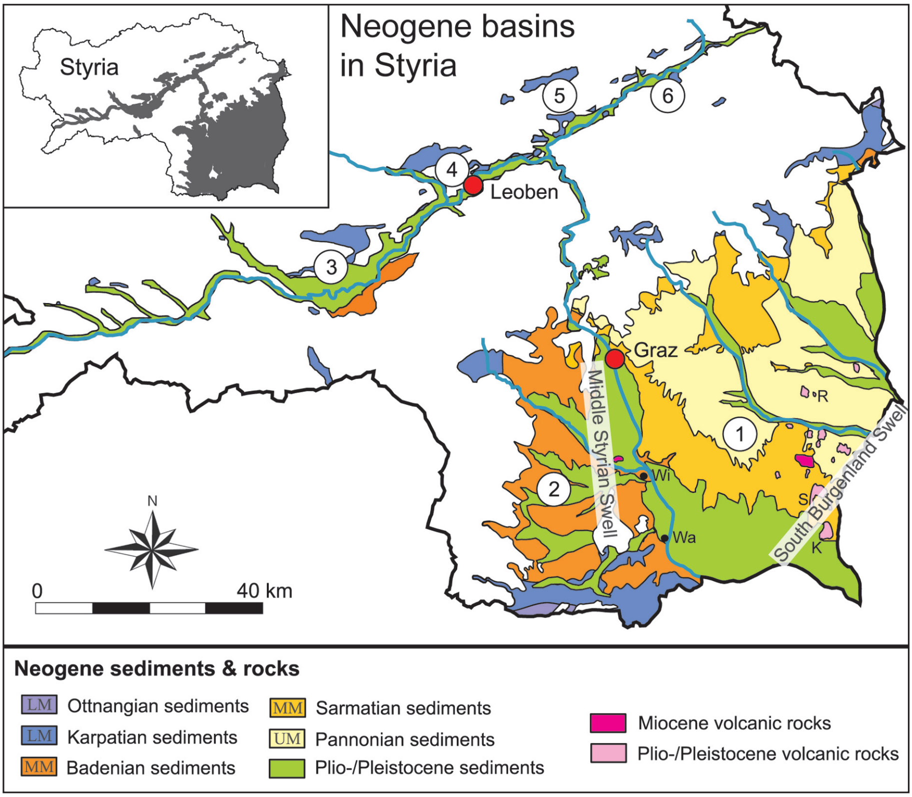

Fig. 14: Geological map of Neogene sediments and volcanic rocks in Styria. Modified after Gross & al. (2007). Abbreviations: MMS = Middle Styrian Swell, SBS = South Burgenland Swell, LM = Lower Miocene, MM = Middle Miocene, UM = Upper Miocene, Wa = Wagna, Wi = Wildon, R = Riegersburg, S = Straden, K = Klöch. (1) Eastern Styrian Basin, (2) Western Styrian Basin, (3) Fohnsdorf Basin, (4) Trofaiach Basin, (5) Kapfenberg Basin, (6) Krieglach Basin.

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sents the western-most lobe of the Pannonian Basin at the south-eastern margin of the Eastern Alps and forms the orogen – basin transition zone. It is separated from the Pannonian Basin by the northeast-southwest striking South Burgenland Swell. It is an east-west elongated basin, where the easternmost part is situated in the province of Burgenland. Whereas in the Styrian Basin thick Miocene and minor Pliocene sediments occur, the adjacent Western Pannonian Basin shows the contrary: thin Miocene and thick (up to 2 km) Pliocene sediments are deposited. The Styrian Basin itself can be subdivided into a deep (~4 km) Eastern and a rather shallow (~1km) Western Styrian Basin, separated by the Middle Styrian Swell. The Eastern Styrian Basin shows three distinctive depocentres. A hilly landscape characterizes the topography of the basin, showing a general south-east trending drainage system. Some volcanic cones of Plio- and Pleistocene age in south-eastern Styria (Fig. 3f) add to the basins special geomorphological appearance which attracted researchers at all times (e.g.: Winkler-Hermaden 1957; Ebner & Sachsenhofer 1995; Sachsenhofer & al. 2000; Gross & al. 2007).

There are a number of other smaller intramontane Neogene basins in Styria, for example the Fohnsdorf and Seckau Basin, the Trofaiach Basin, the Kapfenberg Basin and the Krieglach Basin. All of these basins are exposed along the Mur-Mürz fault system (Fig. 14; Sachsenhofer & al. 2000). In contrast to the Styrian Basin, the Intramontane Basins only contain the syn-extensional sediments of Karpatian – Badenian age (Fig. 14, 15). Many of

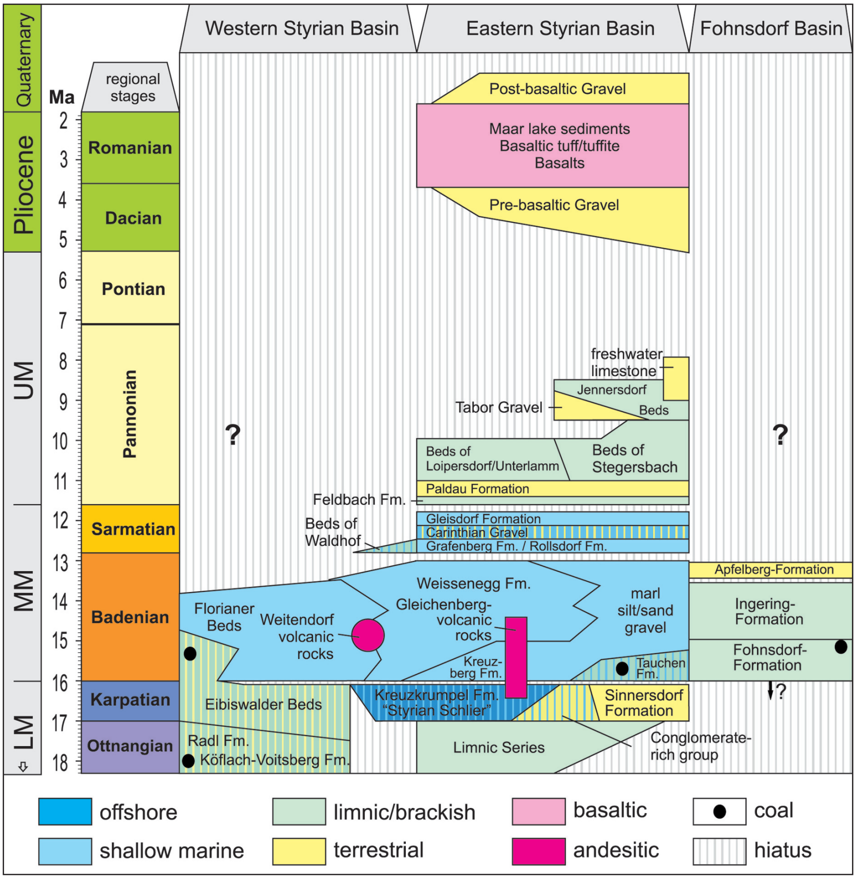

Fig. 15: Stratigraphic chart of the Neogene basins in Styria. Modified after Piller & al. (2004).

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them contain coal deposits (see chapter 5). Other related pull-apart basins outside of Styria are the Tamsweg and the Vienna Basin and the Ennstal and Lavanttal depressions. All show a rather similar evolution related to Miocene brittle tectonics (see Chapter 4). Today's drainage pattern is mostly governed by these prominent and still active strike-slip fault systems highlighting their importance for shaping the present landscape.

4. Geodynamic evolution of Styria

All the geological units described in the previous chapter allow reconstructing the evolution of Styria over at least the last 500 million years from the beginning of the Paleozoic to today. The processes of plate tectonics changed the distribution of continents and oceans: continents broke apart and oceans formed; continents collided and mountain chains grew. Several distinct time periods influenced the evolution of Styria in particular – a simplified summary of what happened where and when is given in Fig. 16 and is discussed in detail below. The amount of knowledge clearly increases towards the present: whereas not much is known about the oldest events at the beginning of the Paleozoic, detailed reconstructions of landscape evolution are possible for the last few millions of years.

Ordovician to Devonian sedimentation

Plate tectonic reconstructions show that during Late Ordovician and Silurian time, the world was dominated by the presence of a large landmass, Gondwana, located around the present south pole, and several smaller landmasses, such as Laurentia, Siberia and Baltica that were located at and north of the equator (plate tectonic maps of the different time periods can be downloaded at www.scotese.com). Between these landmasses, the so-called Rheic ocean existed. Paleomagnetic and stratigraphic studies show that the low-grade Paleozoic sediments present in the Greywacke Zone as well as in the Drauzug-Gurktal nappe system were deposited on the shelf of this Rheic ocean, at the northern margin of Gondwana. They were probably part of smaller terranes that broke off from the northern margin of Gondwana in Upper Ordovician to Silurian times at a southern latitude of up to 60° and drifted northward towards the landmasses of Laurentia during Devonian times. During this time period, terrestric sequences were deposited, intercalated with volcanic rocks; shallow-water carbonate platforms developed on shelf margins and pelagic sequences were deposited in deeper basins (e.g.: Schönlaub 1992; von Raumer & Stampfli 2008).

Variscan orogeny during the Carboniferous

During Late Devonian to Carboniferous time, the situation changed. The terranes originally broken-off from the southern Gondwana continent were located close to the equator and collided with the landmass of Laurentia. This collision led to a belt of complex deformation and metamorphism that can be followed through entire Central Europe: the Variscan orogen. The low-grade Paleozoic rocks of the Greywacke Zone and the Drauzug-Gurktal nappe systems escaped serious metamorphic and magmatic overprint during this collision and sedimentation partly went on into the Lower Carboniferous. But erosional unconformities, a low-grade metamorphic overprint and deformation structures such as thrusts and folds related to the Variscan orogen are present. The higher-grade crystalline basement units below the Drauzug-Gurktal nappe system show a more intense overprint related to the collision: high pressure – low temperature metamorphism occurred around 350 Ma, followed by a thermal peak at around 340 Ma and cooling until 310 Ma. Intrusions of Variscan age also occur. However, the metamorphic and tectonic overprint related to two later events (Permo-Triassic and Eo-Alpine, see below) make an unequivocal interpretation of the Variscan history of the crystalline basement units difficult (e.g.: Tait & al. 1997; Neubauer & Handler 2000; Schuster & al. 2004).

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Permo-Triassic metamorphism and Permo-Mesozoic sedimentation

At the beginning of the Permian, terrestrial to shallow-marine sediments (e.g.: siliciclastics, carbonates and evaporites), today exposed at the base of the NCA and as remnants on the crystalline basement units, were deposited in graben structures on top of the eroded Variscan nappe stack (Neubauer & al. 2007). They indicate that Variscan

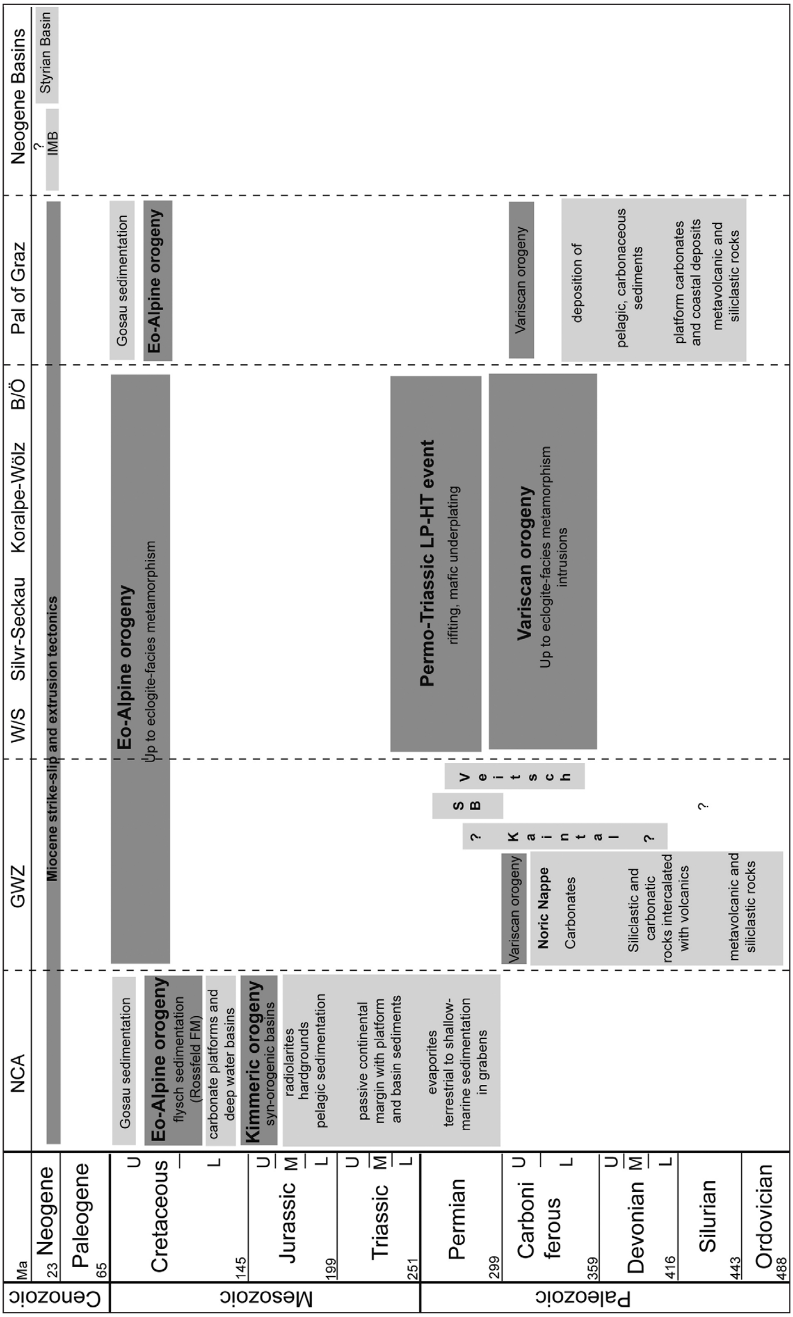

Fig. 16: Geodynamic evolution of Styria through time with the most important sediment accumulation events (light grey) and metamorphic and deformational events (dark grey) indicated. Abbreviation: IMB = Intramontane Basins.

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deformation ceased and topography decreased to sea level. Today, these units are exposed as the monometamorphic units found along the northern margin of the Seckauer Tauern and in the Schladminger Tauern. Simultaneously, low pressure – high temperature metamorphism affected the basement, especially the future Koralpe-Wölz nappe system (Fig. 8a). This metamorphism was accompanied by mafic intrusions and abundant pegmatites, indicating that the basement was thinned and stretched in north-south direction. At the beginning of the Triassic, this thinning and stretching finally led to the opening of a new oceanic basin, the Meliata ocean, and the subsidence of the adjacent margins (eg.: Schuster & al. 2001; Schuster & al. 2004; Schuster & Stüwe 2008).

On the northwestern passive margin of this new Meliata ocean, the Triassic to Middle Jurassic sedimentary succession of the NCA developed. Remnants of this succession are also locally present on the crystalline basement units. During the Triassic, siliciclastic and volcanic sediments were shed onto this margin from a continental landmass to the northwest, carbonate platforms developed on the shelf and were drowned again, marls and pelagic limestones were deposited in deeper parts of the margin towards the southeast. A global mass extinction at the Triassic/Jurassic boundary marked the transition into more pelagic sedimentation with less continental input during the Jurassic. Normal faulting and breccia formation, followed by deep-water pelagic sediments on northwestern parts of the margin (today represented by the Bavaric nappes) documented the opening of another oceanic basin to the north: the Penninic ocean. This ocean began to separate a northern European continent from the southern African continent, including the Adriatic micro-continent which separated from Africa during the Cretaceous (Schmid & al. 2008). On the central and southern parts of the shelf, pelagic carbonates are typical in Lower and Middle Jurassic times. In Middle Jurassic times also sedimentary ommissions, hardgrounds and condensed sediments are common (Frisch & Gawlick 2003).

Middle to Upper Jurassic deformation

In the upper Middle Jurassic, conditions on the shelf described above changed completely. Compressive to transpressive deformation affected the sediments deposited on this shelf progressively from SE towards NW. An accretionary prism formed with the deposition of elongated, syn-orogenic basins in front of the advancing nappe stack. These basins were filled with small to huge (up to km-sized) blocks of eroded Triassic to Middle Jurassic carbonatic and siliciclastic rocks of the former passive margin which was now broken into pieces and thrust on top of each other. Multiple sets of erosion, deposition, re-erosion and re-deposition of such basins can be documented (Fig. 13, Upper Jurassic Wildflysch basins; Gawlick 1996). Parts of the nappe stack were affected by an up to greenschist facies metamorphism according to Gawlick & al. 1994, 1999a (Ultra Tirolic Unit). The compressional structures (nappe piles, thrust fronts, basins) are sealed by uppermost Jurassic to Lower Cretaceous carbonate platforms and basinal sequences. Gawlick & al. 1999a and Frisch & Gawlick 2003 interpret this deformation as the result of subduction of the shelf sediments below oceanic crust or below an unknown part of contincental crust. In contrast, Frank & Schlager 2005 interpret this deformation as being the result of a transpressive regime along major-scale strike-slip zones.

Cretaceous (Eo-Alpine) orogeny

Compressional tectonics re-started on the previously deformed shelf in the Lower Cretaceous and now also seriously affected the underlying crystalline basement. An intracontinental subduction zone started inside the Adriatic micro-continent around 145 Ma between the later Koralpe-Wölz nappe system and the Ötztal Bundschuh nappe system. It successively consumed more and more parts of the Adriatic plate until ultimately the Penninic ocean in the north started to subduct in the Upper Cretaceous (e.g.: Froitzheim

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& al. 2008; Stüwe & Schuster in press). The main nappe stack of the Austroalpine Units as displayed in Fig. 6 formed. The Drauzug-Gurktal nappe system thrust on top of the Koralpe-Wölz nappe system. The Koralpe-Wölz nappe system was subducted and metamorphosed up to eclogite-facies grade (Fig. 8b). During this time one of the largest shear zones of the Alps formed as one of the major shear horizons during nappe stacking: the Plattengneiss shear zone inside the Koralpe-Wölz nappe system. The already formed nappe stack of the Tirolic and Ultratirolic Units together with the underlying Paleozoic rocks of the Noric nappe were sheared off from the Koralpe-Wölz nappe system. The Silvretta-Seckau nappe system was thrust on top of the Lower Austroalpine Semmering-Wechsel nappe system. The lower nappes of the Greywacke Zone (Veitsch, Silbersberg, Kaintaleck) as well as the Bavaric nappes were sheared off from the Silvretta-Seckau nappe system and transported northwestwards. Molasse-type sediments were deposited in front of the Tirolic nappe systems.

The whole nappe stacking process is reflected in the metamorphic gradient developed (Fig. 8b; Tenczer & Stüwe 2003). The peak of this activity is marked by the peak metamorphic conditions in the Koralpe-Wölz nappe system that were reached around 92 Ma in the central Koralpe. After about 90 Ma, cooling and exhumation of the high-grade rocks occurred between 90–60 Ma during the Upper Cretaceous. Final exhumation of the metamorphic rocks occurred around 40–50 Ma. Simultaneously to cooling and exhumation, the entire region was warped on a 10 km long wavelength (Putz & al. 2006) and normal and strike-slip faults formed. These faults are associated with sedimentary basins filled with terrestrial to marine sediments (Gosau group, e.g. Wagreich & al. 2009). These basins are located on top of the Tirolic Unit and the Drauzug-Gurktal nappe system north and east of the Dachstein region and west of Graz, respectively. In the Upper Cretaceous, the Penninic ocean located to the north of the Adriatic continent entered the subduction zone and nappe stacking and exhumation in the Austroalpine Units ceased. The Bavaric, Tirolic, Ultra Tirolic Units and the imbricated belt at their base were thrust out of sequence to the north and also simultaneously backthrust to the south. Only the Bavaric Unit was finally thrust over the northern Rhenodanubian flysch zone in Eocene times. This thrusting was followed by peneplanisation and deposition of the Oligocene to Lower Miocene fluvatile sediments of the Augenstein Formation (Frisch & Gawlick 2003).

Miocene tectonics and Neogene basin formation

In the Lower Miocene, north-south convergence between the Adriatic and the European continent in the Penninic domain was still ongoing. However, beside continuing nappe stacking (in the Molasse zone in the north and in the Klagenfurth Basin), the convergence was compensated by strike-slip faults along which individual blocks could escape eastwards towards the Pannonian realm where space was created by a retreating subduction zone in the Carpathians (Ratschbacher & al. 1991; Frisch & al. 1998). Thus, the Miocene is generally considered to be the period of lateral extrusion. Major conjugated fault systems developed such as the Mur-Mürz fault system (MMF), the Lavanttal fault system (LF), the Salzach-Enns fault system (SEMP) and the Periadric Lineament (PAL) (Fig. 4). The nappe stack of the NCA was fragmented into individual smaller fault-bounded blocks with rotations and displacements in the order of tens of kilometres during this phase (Decker & al. 1994; paleostress analysis by Peresson & Decker 1997). Along these fault systems, the formation of intramontane pull-apart basins led to local subsidence. These basins were filled with syn-rift sediments (Márton & al. 2000) and bear the coal deposits of Styria. Especially along the MMF, the so-called Noric Depression developed (Sachsenhofer & al. 2000). The most important of these small pull-apart basins are the Fohnsdorf Basin (at the junction between Lavanttal fault system and MMF), the Leoben Basin, the Krieglach Basin and several others along the Mur-Mürz lineament. The Styrian Basin evolved simultaneously to the Intramontane basins on top of one of

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the extruding blocks due to extensional normal faulting (Ebner & Sachsenhofer 1995). Extension favored the ascent of magmas, which generated andesitic shield volcanoes during Lower and up to Middle Miocene times. Volcanic rocks from this time are found today in Weitendorf near Wildon and Bad Gleichenberg (Fig. 14).

At the Karpatian/Badenian boundary (Fig. 14, Fig. 15), strike-slip and extensional faulting ceased and an unconformity due to a tectonic event and contemporaneous sea level low stand developed: the so-called "Styrian Phase" may be observed in quarries near Wagna in western Styria. In the Badenian, post-extensional regional subsidence due to cooling of the lithosphere was ongoing in the Styrian Basin and marine sediments were deposited. One of the last fully marine sediments that were deposited in the basin was the ~13 Ma old Leitha limestone that builds up the white limestone cliffs near Wildon and Leibnitz. During Sarmatian and Pannonian times, the basin experienced a transition from marine to brackish and eventually to terrestrial sedimentation. The reconstruction of the depositional history for this time interval is complicated by the fact that there are no Sarmatian and Pannonian sediments present in the Western Styrian Basin or the Noric depression (Fig. 15). It is not known if such sediments were deposited and if they were eroded subsequently or no deposition happened at this time. Indications for the erosion of at least some hundreds of meters of sediments suggest the former (Dunkl & Frisch 2002; Dunkl & al. 2005). In Pliocene to Pleistocene times a major change in the stress field led to basin inversion, and consequential young tectonic uplift of the whole Styrian Basin and erosion of a few hundred meters of sediments. A contemporaneous tilting of the basin by 1–2 degrees to the east leads to the map scale distribution of the sedimentary units with the oldest being exposed at the western margin of the basin and the youngest in the very east of the state (Fig. 14). During the Pliocene to Early Pleistocene a second (basaltic) volcanic phase erupted forming volcanoes for example at Riegersburg (Fig. 3f), Straden and Klöch (Fig. 14). An elevated heat flow since Sarmatian times is related to thinned lithosphere below the Styrian Basin and is currently being exploited in terms of thermal springs and spas in south-eastern Styria. In the last few million years karstification of the mountains dominated by limestones in Styria (Grazer Bergland, NCA) led to the formation of large caves (f.ex. Lurgrotte, north of Graz). The youngest sediments present in Styria are glaciation-related Pleistocene deposits mostly present along the major drainage pattern. The Pleistocene ice sheets itself never reached beyond Judenburg in the Mur Valley and Völkermarkt in the Drau Valley leaving much of Styria ice-free during the entire Pleistocene.

5. Mining in Styria

Styria has many natural resources of economic importance which are currently mined. Table 1 and Fig. 17 show an overview of all raw materials mined in Styria in 2007 and corresponding locations of the mines (data from Österreichisches Montanhandbuch 2008). Production data of 2006, including information on historical mining in Styria back to 1950, are given by Ebner 2008. There are several raw materials where Styria has a leading position in Austria. In the case of iron, all of the Austrian production is mined in Styria (The small specularite mine near Waldenstein (Carinthia), which produces a few thousand tons of platty hematite is not regarded as an iron mine because specularite is not used as a source for iron). In addition, more than 50 % of the total Austrian production of talc/leucophyllite, magnesite, quartz/quartzite, basaltic rocks and ultramafic rocks are mined in Styria. Styria also produces the majority of gypsum/anhydrite, limestone and diabase in Austria. Production data and percentages of the most important natural resources mined in Styria are shown in Table 1 and a short description of the deposits is given below. Further information on Austria´s natural resources (with corresponding geologic framework) can be found in Ebner 1997 and Weber & al. 1997.

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Tab. 1: List of all raw materials mined in Styria in 2007 (data from Österreichisches Montanhandbuch, 2008).

Raw material	2007 production (t)	Percentage of total Austrian production
Iron	2 150 000	100
Gypsum and anhydrite	490 649	46
Salt (brine)	1 158 490 m^3	47
Talc and leucophyllite	119 815	78
Magnesite	557 183	67
“Limestone” (≥ 95 % $CaCO_3$)	3 620 238	25
“Limestone”	2 175 921	31
Clay	605 708	26
Diabase	898 407	40
Dolomite	484 206	12
Quartz and quartzite	204 311	67
Basaltic rocks	1 607 969	85
Ultramafic rocks	1 142 770	62
Gneiss	72 388	8
Sand an gravel	1 573 347	7

Iron

The only Fe-mine in Austria is located at the “Steirischer Erzberg” in Eisenerz (Fig. 3c). The Erzberg is the largest siderite mine of the world and the largest open-pit mine on metallic ores in Central Europe (according to 2007 production; the siderite mine in Bakal (Russia) produced 1.7 Mio. t of siderite in 2007, compared to 2.15 Mio. t produced at the Erzberg). The main Fe-bearing minerals are siderite, ankerite and Fe-dolomite. Other minerals like pyrite, hematite and magnetite only occur in very small proportions (Schönlaub 1982). The host rocks of the iron ores are Devonian limestones of the Noric Nappe (Fig. 12). In 2007, the Voest Alpine Erzberg mined approx. 5.6 Mio. t of crude ore. After processing, about 2.15 Mio. t of iron ore, containing about 34 % Fe, were produced. A recent overview of the Fe-mineralisation and the genesis of the Erzberg deposit (and also other Fe-mineralisations within the Noric Nappe and the Northern Calcareous Alps) is given by Prochaska & Henjes-Kunst 2009.

Evaporites

Gypsum, anhydrite and salt deposits, which are economically important, occur in the “Alpines Haselgebirge” in the Northern Calcareous Alps (see Chapter 3, NCA). In Styria, salt (halite) is mined at the underground mine in Altausee. The halite is extracted from the host rock using water, which dissolves the salt. About 1.16 Mio. m^3 of brine were produced in 2007. In addition, 1172 t of solid salt were mined at Altaussee. Gypsum and anhydrite are mined in the areas of Grundlsee, Tragöß and Admont. Together, these mines produced 477201 t of gypsum and 13 448 t of anhydrite in 2007. Schauberger 1986 gives an overview of evaporitic deposits in the Eastern Alps.

Talc and leucophyllite

These ores occur in crystalline basement units. Talc and leucophyllite were formed in alpidic shear zones by hydrothermal fluids (leucophyllite is defined as mix-

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ture of quartz, muscovite and chlorite which was formed by hydrothermal influence, Prochaska, 1991). Talc is mined at the open-pit mine Rabenwald near Weiz, which is located in the Strallegg Complex of the Koralpe-Wölz nappe system (Fig. 6). A summary of talc (and also magnesite) deposits in Austria, including genetic models, is given by Prochaska (2000). The leucophyllite deposit Kleinfeistritz near Zeltweg is located in the Silvretta-Seckau nappe system. Detailed investigations of the Kleinfeistritz deposit have been carried out by Prochaska (1991). In total, these two mines produced 119 815 t of talc and leucophyllite in 2007, which corresponds to 78 % of the total Austrian production.

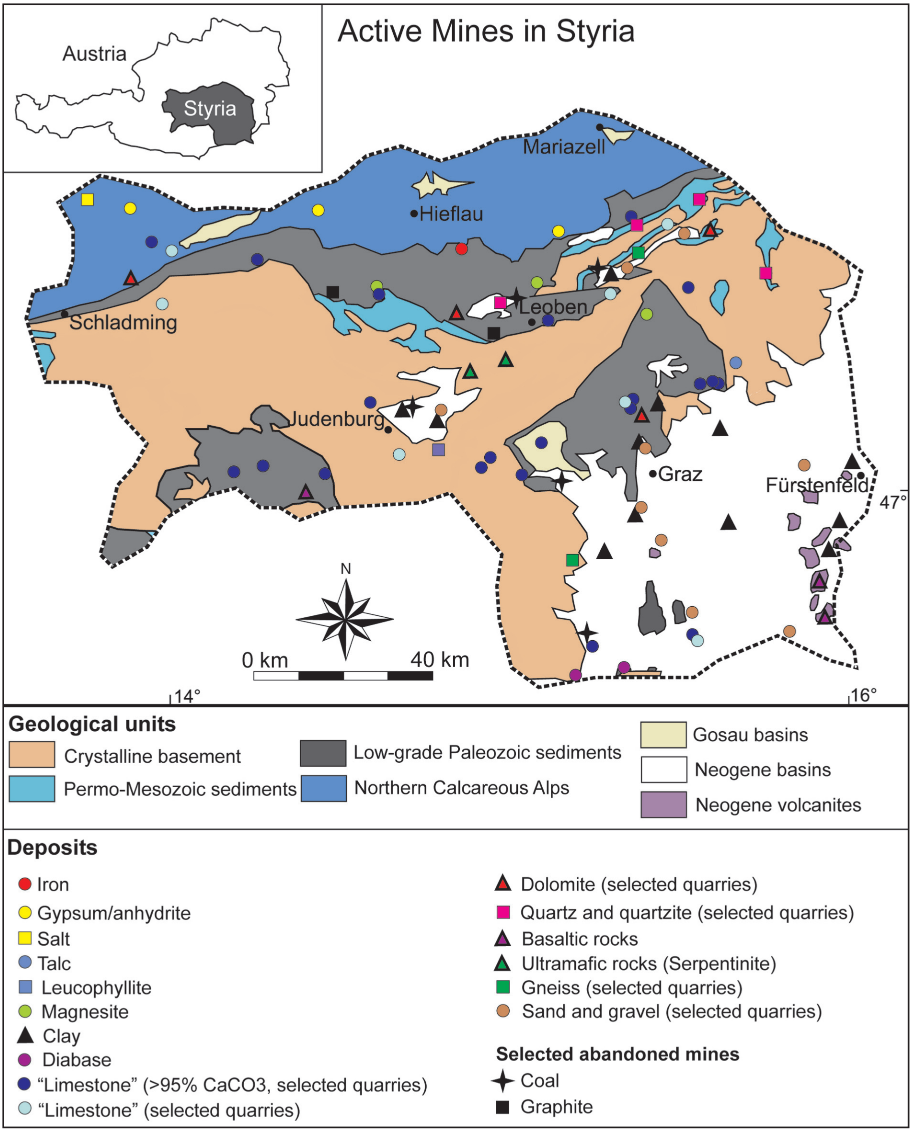

Fig. 17: Simplified geological map of Styria with locations of active mines (data from Österreichisches Montanhandbuch, 2008).

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Magnesite

Magnesite of economic importance only occurs in the low-grade Paleozoic units. They host a number of Veitsch-type sparry magnesite deposits. Austria´s largest magnesite mine in Breitenau/Hochlantsch is located in the lower nappe system (Laufnitzdorf facies) of the Paleozoic of Graz (Fig. 9). With a production of 385 500 t crude magnesite in 2007, the Breitenau mine produced nearly 50 % of Austria´s total magnesite production. The other Styrian magnesite mines are located in the Veitsch Nappe of the Greywacke Zone near Wald/Schoberpass and St. Katharein/Laming (4 mines). Detailed geological and geochemical information on the "Veitsch type" magnesite deposits in the Greywacke Zone can be found in Ebner & al. (2004). With a total production of 555183 t, Styria produced 67 % of the total Austrian magnesite production in 2007.

Carbonates ("limestone" and dolomite)

Deposits of "limestone" occur in different geologic units in Styria. In Fig. 17, the "limestone" mines are divided in those which are assigned as "bergfrei" (i.e. containing more than 95 % $CaCO_3$) and those which do not fulfil this criterion. Most of the mines are located in the low-grade Paleozoic units (Paleozoic of Graz, Greywacke Zone and Gurktal nappes). However, "limestone" deposits also occur in other geologic units like the Styrian Basin, the Northern Calcareous Alps and the Crystalline Basement (including their Permo-Mesozoic cover). In the Crystalline Basement the "limestones" are metamorphosed and should therefore be named as marbles (for that reason the term "limestone" was put in quotation marks). Dolomite of economic importance mainly occurs in the low-grade Paleozoic units, but also in the Northern Calcareous Alps and the Permo-Mesozoic cover of the Crystalline Basement. In total, 5796159 t of "limestone" and 484206 t of dolomite were mined in Styria in 2007.

Clay

Clay pits occur in the sedimentary sequences of the Neogene basins (Styrian Basin, Fohnsdorf Basin, Mürz valley). Several pits in these basins mined 605708 t of clay in 2007.

Diabase

Diabase, which is defined as a low-grade metamorphosed basaltic rock, is mined in two quarries at the southern Styrian border (Lieschengraben near Oberhaag and Radlpass). Both are located in low-grade Paleozoic units of the Gurktal nappe system. Styria produced 898407 t of diabase in 2007.

Quartz and quartzite

The bulk of the quartzite mines are located in the Permo-Mesozoic cover of the Crystalline basement in northeastern Styria. The quarry located near Trofaiach mines quartz from the low-grade Greywacke Zone. 204311 t of quartz/quartzite were mined in Styria in 2007, which is about two third of the total Austrian production.

Basaltic and ultramafic rocks

Mines for basaltic rocks are located in Neogene volcanites of the Styrian Basin in southeastern Styria (e.g.: Klöch) and in the Gurktal nappes. Ultramafic rocks (serpentinite, dunite) are mined in the area of Kraubath, where they occur in ophiolite-like sequences of the Speik-Complex (Silvretta-Seckau nappe system). In 2007, 1607969 t of basaltic rocks and 1142770 t of ultramafic rocks, which corresponds to 85 % and 62 % of the total Austrian production, respectively, were mined.

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Gneiss

Gneiss is mined in several quarries in two areas, near Stainz and near St. Marein/Mürztal. Both areas are located in the crystalline basement, but in different units. In the area of Stainz, gneisses from the Koralpe complex (Koralpe-Wölz nappe system, see chapter 3.1.1) is mined. In the area of St. Marein, the quarries are located in the Silvretta-Seckau nappe system. In total, 72388 t of gneiss were mined in 2007.

Sand and gravel

Sand and gravel deposits of economic importance occur in fillings of the Neogene basins (most of them in the Styrian Basin) and in Quaternary sediments. There are more than 20 quarries mining sand and gravel in Styria with a total production of 1 573 347 t in 2007.

6. Final remarks

Styria has a rich and diverse geological history, and the mineral resources mined in Styria are an important economic sector in the province. The three Styrian universities which offer studies in Earth Sciences are ideally located to learn more about the geological formation and evolution of that fascinating region on our doorstep.

Acknowledgement

The joint Doctoral School of Earth Sciences in combination with GASS (Graz Advanced School of Science) and UZAG (Universitätszentrum für angewandte Geowissenschaften Steiermark) is thanked for financial support of the field trip 2009. R. Schuster (GBA Vienna) is thanked for many discussions and a thorough review of this article. R. Bakker, H.-J. Gawlick, S. Matthäi and W. Kurz are thanked for attending and leading parts of the field trip. F. Ebner, H.-J. Gawlick, G. Hoinkes, R. Sachsenhofer and W. Vortisch are thanked for support and advice during writing. All PhD students that attended the workshop are thanked for their interest and support.

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