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ORIGINAL PAPER

# Internal structural geometry of the Paleozoic of Graz

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**Abstract** The Paleozoic of Graz is an isolated nappe complex of about 1,500 km$^2$ size and belongs to the Austroalpine units of the eastern European Alps. Despite more than 500 publications on stratigraphy, paleontology and local structure, many aspects of the internal geometry of this complex as a whole remained unclear. In this contribution, we present integrated geological profiles through the entire nappe complex. Based on these profiles, we present (1) a simplified lithological subdivision into 13 rock associations, (2) a modified tectonostratigraphy where we consider only two major tectonic units: an upper and a lower nappe system and in which we abandon the traditionally used facies nappe concept, and (3) a modified paleogeography for the whole complex. Finally, we discuss whether the internal deformation of the Paleozoic of Graz is of Variscan or Eo-Alpine age and which of the published models best explain the tectonic evolution of the Paleozoic of Graz.

**Keywords** Paleozoic of Graz · Eastern Alps · Austria · Geological profiles · Structural geology

## Introduction

The Paleozoic of Graz is a 30 × 50 km-sized nappe complex of mostly low-grade carbonates, schists and metavolcanics of Paleozoic depositional ages. Together with other low-grade Paleozoic sedimentary units such as the Gurktal Thrust System and the Greywacke Zone it builds up large parts of the Upper Austroalpine units of the eastern European Alps (Fig. 1a). The Paleozoic of Graz is surrounded by and lies on top of crystalline rocks that experienced high-grade metamorphism in the Permian and the Cretaceous (Oberhänsli et al. 2004; Schuster and Stüwe 2008). It is discordantly overlain by a small Cretaceous Gosau basin and by the Neogene Styrian basin (Fig. 1b). As such, the Paleozoic of Graz records many of the sedimentological, tectonic and metamorphic events that formed the eastern Alps since the early Paleozoic. Stratigraphy, paleontology, internal structure and metamorphism of the Paleozoic of Graz were extensively studied over the past 180 years and resulted in over 500 publications (e.g., Schwinner 1925; Clar 1935; Boik 1950; Flügel and Hubmann 2000 and references therein). However, no geological profiles of the *entire* Paleozoic of Graz are published. As a consequence, many aspects of the internal structure of the complex are poorly understood.

In this study, we present integrated geological profiles of the entire Paleozoic of Graz, which we constructed on the basis of a simplified lithological subdivision of the complex. Using these profiles, we discuss the internal structure of the Paleozoic of Graz and present a modified tectonostratigraphy for the complex. Within this, we discern only two major nappe systems separated by a single thrust: the Rannach thrust. Based on these results, we then discuss the age of internal deformation and metamorphism as well as models proposed in the literature for the final emplacement of the Paleozoic of Graz onto the surrounding crystalline basement.

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## Geological setting

The Paleozoic of Graz consists of Silurian to Carboniferous, poly-phase deformed, diagenetic to greenschist facies

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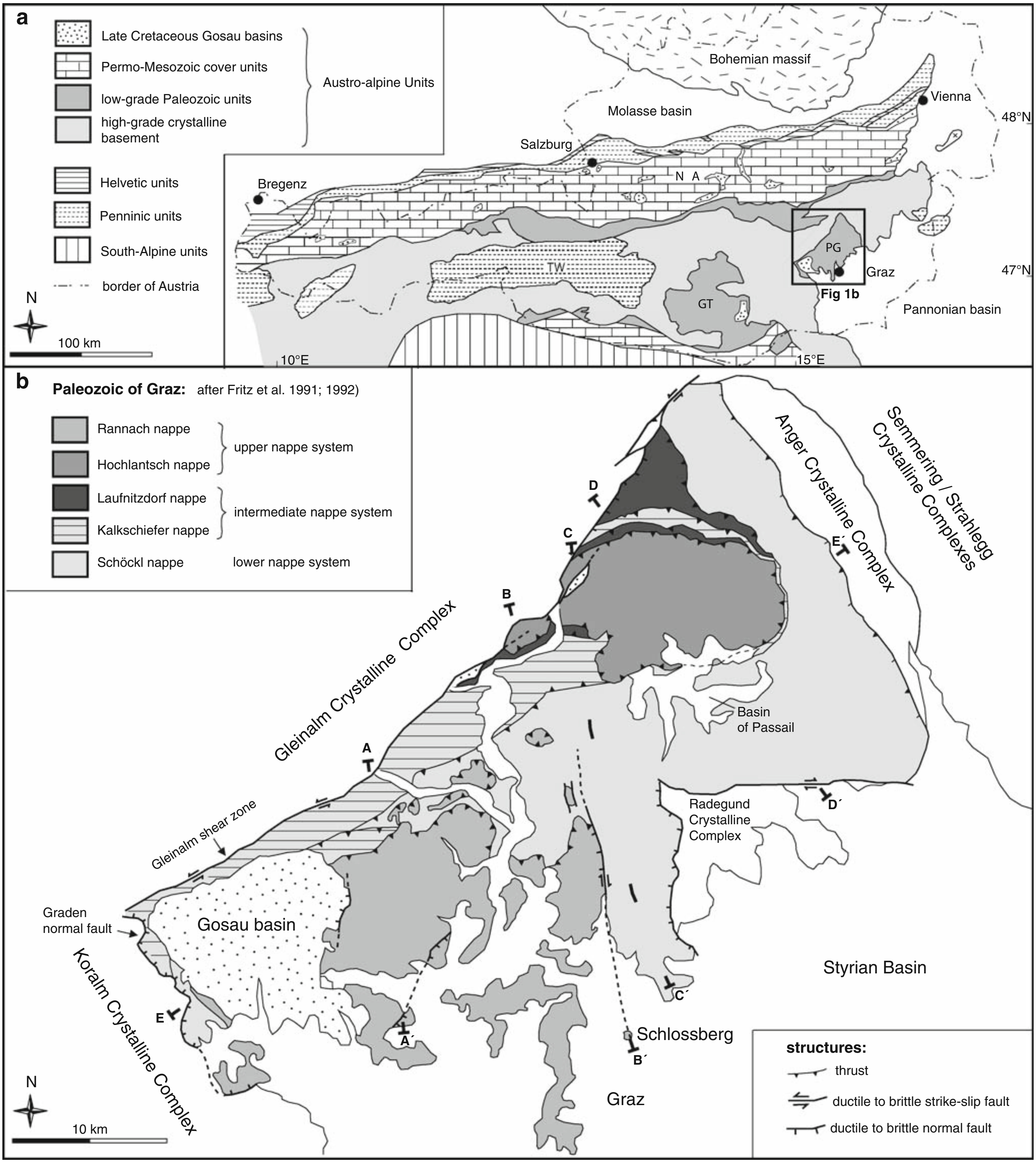


**Fig. 1** **a** Geological sketch map of the eastern Alps. *PG* Paleozoic of Graz, *GTS* Gurktal Thrust System, *TW* Tauern Window, *GW* Grauwacken Zone, *NCA* northern Calcareous Alps. **b** Tectonic map of the Paleozoic of Graz after Fritz et al. (1991). Profile traces from Fig. 4 are indicated

rocks. In the literature, five sedimentary facies associations are discerned: The Rannach, Hochlantsch, Laufnitzdorf, Kalkschiefer and Schöckl facies. Each facies has been ascribed to one tectonic nappe (Fig. 1b; Fritz et al. 1991, 1992; Ebner et al. 2000). These nappes are attributed to an upper (Rannach and Hochlantsch), an intermediate (Laufnitzdorf and Kalkschiefer) and a lower nappe system (Fig. 1b; Fritz et al. 1992). In general, deformation intensity is lowest in the upper nappe system and highest in the lower nappe system. The fact that the same names have

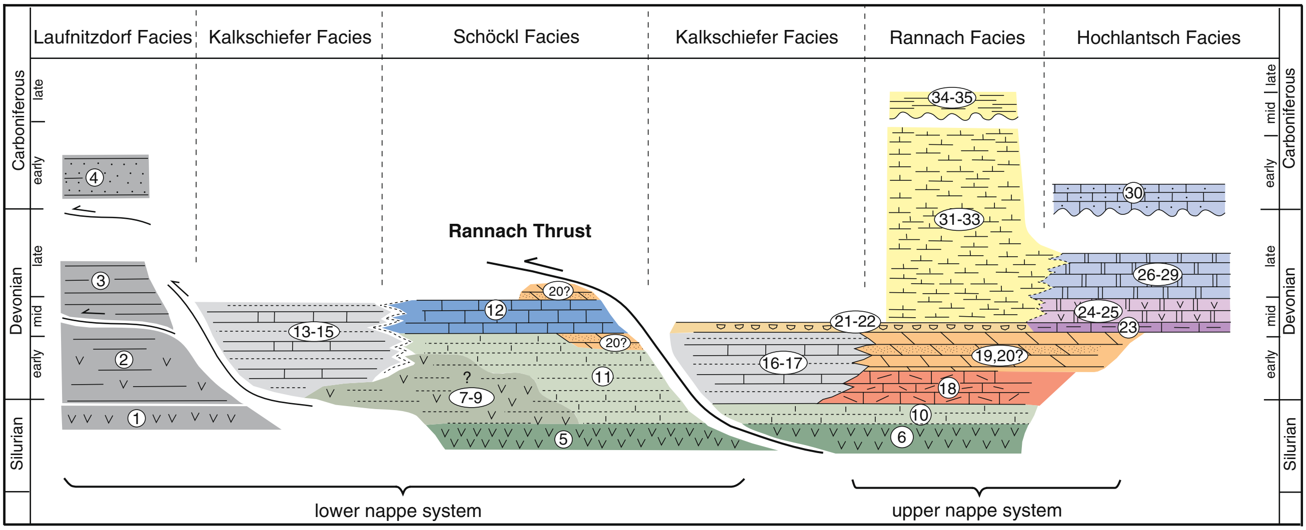


**Fig. 2** Stratigraphic relationships as observed today in the major tectonic units of the Paleozoic of Graz. Formation numbers: *1* Hackensteiner Fm, *2* St. Jakob Fm, *3* Harrberger Fm, *4* Dornerkogel Fm, *5* Taschen Fm, *6* Kehr Fm, *7* Semriach Phyllite Fm, *8* Heilbrunn Phyllite Fm, *9* Hirschkogel 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. Drawn according to Flügel and Hubmann (2000), Hubmann and Messner (2007) and the results of this study

been applied to both sedimentary facies as well as tectonic units led to some confusion in the literature, because some of the facies occur in more than one tectonic nappe.

The borders of the Paleozoic of Graz consist of ductile to brittle shear zones including the sinistral Gleinalm Shear Zone in the northwest (Neubauer 1988a; Neubauer et al. 1995), the Graden normal fault in the southwest (Rantitsch and Mali 2006) and the un-named ductile to brittle normal and strike slip faults against the Radegund Crystalline in the south and the Anger Crystalline in the northeast (Krenn et al. 2008; Fig. 1b). The Paleozoic of Graz is discordantly overlain in its southwestern part by a late Cretaceous (~85–65 Ma) Gosau basin (Fig. 1b). This basin contains a basal, reddish conglomerate, limestone, marls and a >1,000 m thick sequence of sand, silt and claystones. These sediments show an evolution from a coarse alluvial facies, through a lacustrine shallowwater facies, to a marine delta system (Neubauer et al. 1995; Ebner and Rantitsch 2000). Clasts in the basal conglomerate are derived from the northern Calcareous Alps, the southern Alps, the Paleozoic of Graz as well as reworked clasts from the Gosau itself. Interestingly, clasts from the surrounding crystalline basement are missing. The transport direction of the sediments was mainly from north and northeast (Gollner et al. 1987; Ebner and Rantitsch 2000). In the south, both the Gosau basin and the Paleozoic of Graz are discordantly overlain by the Neogene Styrian basin. Sedimentation in this basin took place between the lower Miocene and the Pliocene (~19–1.8 Ma; Piller et al. 2004).

Detailed stratigraphical and paleontological work in the Paleozoic of Graz led to the definition of 35 sedimentary formations (Fig. 2; Flügel and Hubmann 2000). The oldest rocks are Silurian, volcano-clastic sediments, which are interpreted to be the result of intracontinental rifting (Fritz and Neubauer 1988; Loeschke 1989). From the Early Devonian on, several distinct facies associations developed. Rocks in the Rannach and Hochlantsch nappes represent the most proximal facies. Early Devonian sandy limestones and dolomites, deposited in a coastal environment, are overlain by Middle Devonian platform carbonates and Late Devonian to Carboniferous pelagic limestones. Erosion and carstification occurred in the Late Devonian and Early Carboniferous (Fig. 2; Flügel and Hubmann 2000; Ebner et al. 2000; Hubmann and Messner 2007). Rocks in the Kalkschiefer and Laufnitzdorf nappes and in the Schöckl nappe experienced epizonal to greenschist facies metamorphism. The internal stratigraphy of those nappes is therefore less well known. The Laufnitzdorf nappe contains carbonates, radiolarites, clay- and sandstones of Devonian age, which were deposited in a pelagic environment. The Kalkschiefer nappe consists of a uniform sequence of marls, limestones and sandstones of Devonian age. In the Schöckl nappe, the Silurian volcano-clastic rocks are overlain by dark-gray carbonates and black schists, which were probably deposited in a euxinic basin. They are in turn overlain by Middle Devonian platform carbonates (Fig. 2; Flügel and Hubmann 2000; Ebner et al. 2000). The Schöckl nappe also contains large amounts of greenschist facies phyllites and chlorite schists of unknown age (Fig. 2, Fm 10–12). However, their close association with Silurian volcano-clastic rocks and Early Devonian black schists make a pre-Middle-Devonian age probable.

Metamorphic conditions in the Paleozoic of Graz were revealed by illite crystallinity, vitrinite reflectance and Raman spectroscopy (Hasenhüttl 1994; Russegger 1996; Rantitsch et al. 2005). In the upper nappe system, estimated metamorphic temperatures lie in the range of 200–300°C. In the intermediate and lower nappe system, rocks of the Laufnitzdorf nappe show temperatures below 300°C, and rocks of the Kalkschiefer and Schöckl nappes above 300°C. Raman spectroscopy revealed a temperature aureole roughly parallel to the normal faults along the northeastern, southern and southwestern margins of the Paleozoic of Graz (Rantitsch et al. 2005). At the southwestern margin, metamorphic temperatures rise over only a few kilometers from <250°C in the Gosau basin to ~500°C in the Paleozoic of Graz and 500–600°C in the Koralm Crystalline (Rantitsch et al. 2005). Krenn et al. (2008) calculated conditions of ~500–600°C and ~6–9 kbar at the northeastern border to the Anger Crystalline. Surprisingly, there is no temperature aureole parallel to the northwestern margin to the Gleinalm Crystalline, where temperatures in the crystalline also reached ~500°C.

## Simplified lithological subdivision

In order to construct integrated structural profiles for the entire Paleozoic of Graz it is necessary to reduce the 35 formations described by Flügel and Hubmann (2000) to much fewer distinct rock associations (Fig. 2). Each of the rock associations defined here is displayed in one color in Fig. 2 and contains one or more formations. We assembled (a) formations that are identical in age and sedimentary facies but occur in different tectonic units, and (b) formations that are part of a continuous sedimentary sequence but vary slightly in composition. The following groupings are performed to obtain rock associations, which are displayable on the scale of the profiles:

– *Dark gray (Fm–Fm 4)* The Hackensteiner (Fm 1), St. Jakob (Fm 2), Harrberger (Fm 3), and Dornerkogel (Fm 4) formations correspond to the Laufnitzdorf group of Flügel and Hubmann (2000). They all occur only in the northern part of the Paleozoic of Graz. Formations 1–3 build a Silurian to late Devonian sequence of pelagic, fine-grained clastic sediments intercalated with volcanic ashes and limestones. Their ages overlap; they received their different names mainly from different workers who observed them in different places and different structural positions. The Dornerkogel formation (Fm 4) is lithologically different: it consists of coarser-grained silt and sandstones, which were deposited as turbidites. Detrital micas in this formation are of Variscan age and it is therefore interpreted as a Flysch deposit in front of the Variscan orogen (Neubauer et al. 2007). However, because it occurs only in the northernmost part of the Paleozoic of Graz in close proximity and probably in sedimentary contact with Fm 1, we assembled it together with Fm 1–3.
– *Dark green (Fm 5–Fm 6)* The Taschen (Fm 5) and Kehr (Fm 6) formations are both basic metavolcanic rocks of Silurian age. They occur geographically in different regions: near Taschen in the central part, and near Kehr in the western part of the Paleozoic of Graz (Fig. 3). They occur in two different structural levels: the Kehr formation in the upper Rannach nappe and the Taschen formation in the lower Schöckl nappe. The Taschen formation has a slightly higher metamorphic grade than the Kehr formation. Despite these geographical, structural and metamorphic differences, their lithology and age are very similar and we therefore assume them to be originally part of the same rock association.
– *Intermediate green (Fm 7–Fm 9)* The Semriach (Fm 7), Hirschkogel (Fm 8) and Heilbrunn (Fm 9) formations correspond to the Passail group of Flügel and Hubmann (2000). They are all greenschist facies, sericite and chlorite-bearing phyllites of unknown age. However, their close proximity to the Taschen, Schönberg and Schöckl formations make a Silurian to Early Devonian age probable. They are grouped based on their position within the sedimentary succession and their lithological similarity. The Semriach and Hirschkogel formations occur both in the region of Semriach and the Heilbrunn formation crops out in a structurally lower level parallel to the eastern border of the Paleozoic of Graz (Fig. 3).
– *Light green (Fm 10–Fm 11)* The Kötschberg (Fm 10) and Schönberg (Fm 11) formations are both dark limestones and black schists. They occur in sedimentary contact on top of the Kehr and Taschen formations, respectively. Grouping them followed the same logic as grouping the Kehr and Taschen formations (Fm 5–6).
– *Blue (Fm 12)* The Schöckl formation (Fm 12) consists of a peculiar blue–white banded limestone of several 100 m thickness. This limestone is lithologically very distinct. It is therefore not grouped with other formations.
– *Light gray (Fm 13–Fm 17):* The Kogler (Fm 13), Hochschlag (Fm 14), Hubenhalt (Fm 15), Bameder (Fm

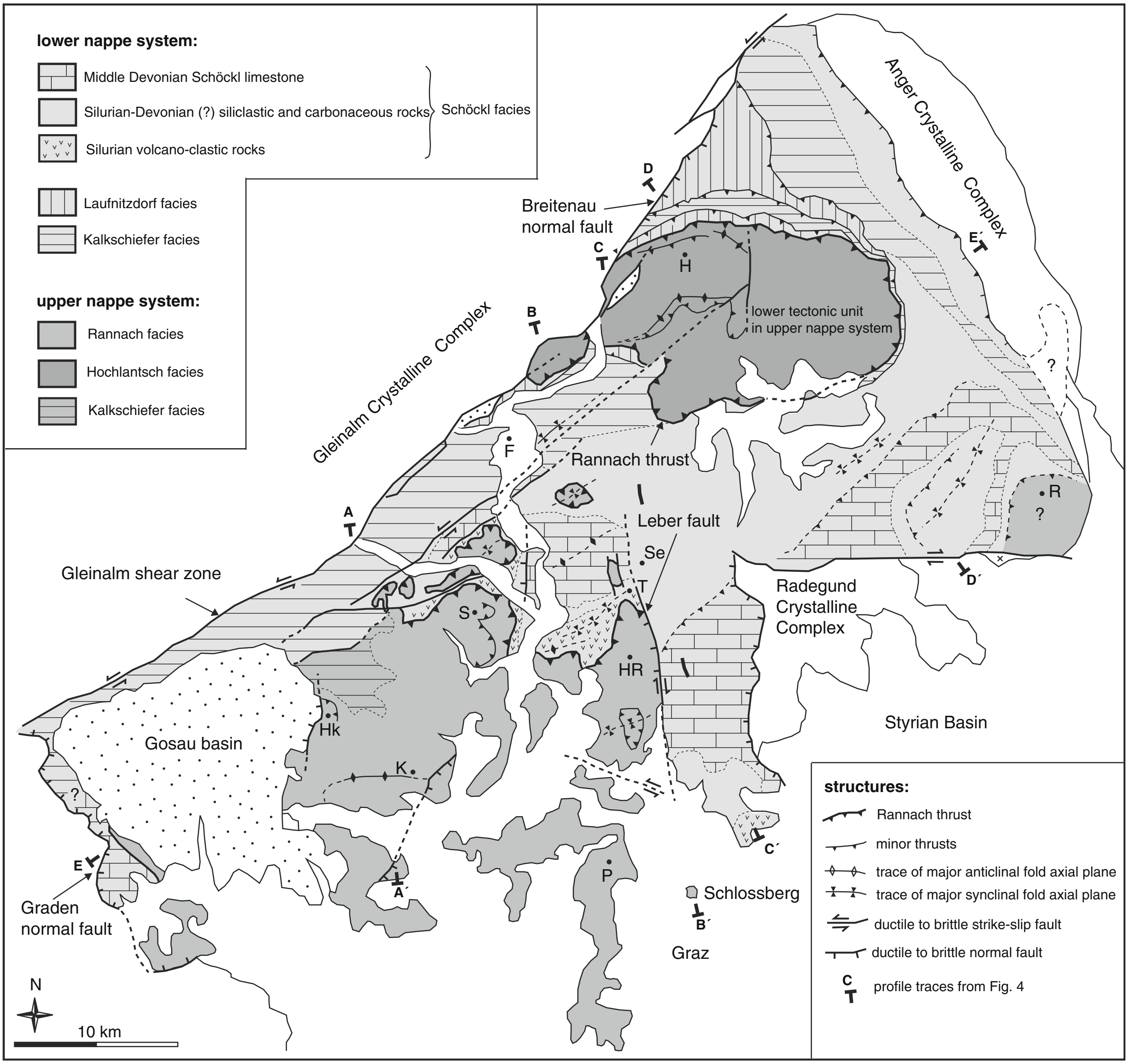


**Fig. 3** Structural map of the Paleozoic of Graz. The profile traces of Fig. 4 are indicated. Locations mentioned in the text are: *Hk* Höllererkogel, *S* Schartnerkogel, *HR* Hohe Rannach, *T* Tannebenstock, *F* Frohnleiten, *H* Hochlantsch, *R* Raasberg, *P* Plabutsch, *T* Taschen, *K* Kehr, *Se* Semriach

16) and Heigger (Fm 17) formations are what has traditionally been referred to as Kalkschiefer facies. They are layered calcareous schists, slaty limestones and minor clay-, silt- and sandstones of early to middle Devonian age. They occur all over the Paleozoic of Graz in different tectonic positions and are internally folded and imbricated. Their different formation names mainly originate from their occurrence in different geographical areas and tectonic levels. Because they are lithologically and stratigraphically similar, we assembled them into one group.

– *Dark orange (Fm 18)* The Parmasegg formation (Fm 18) is a distinct rock association consisting of coastal crinoidal limestones, sandy marls and minor silt- and sandstones with a thickness of up to 200 m. It is therefore left ungrouped.
– *Medium orange (Fm 19–Fm 20)* The Flösserkogel formation (Fm 19) consists of early diagenetic, yellow dolomites, limestones and sandstones. It reaches 500–1,000 m thickness and builds up substantial parts of the upper Rannach and Hochlantsch nappes. The Raasberg Fm (Fm 20) occurs around Raasberg (Fig. 3) and

consists of highly deformed and metamorphosed dolomites, limestones and sandstones. Its stratigraphic and tectonic position is unclear (Fig. 2; Flügel and Hubmann 2000). However, because it consists of very similar rocks as the Flösserkogel Fm and because it is located on top of the Schöckl Fm, we group it together with the Flösserkogel Fm and interpret it as a sheared relict of the upper nappe system on top of the lower nappe system.

- *Light orange (Fm 21–Fm 22)* The Plabutsch (Fm 21) and Draxler (Fm 22) formations are dark, fossil-rich limestones intercalated with marls and claystones of well-defined middle Devonian age. They occur in two different geographic locations, but are grouped for their lithological and age equivalence.
- *Dark purple (Fm 23)* The Osser formation (Fm 23) is lithologically similar to Fm 21 and Fm 22, but contains less fossils, is more marly, much more deformed and of slightly higher metamorphic grade. It is therefore kept separate and is not grouped.
- *Light purple (Fm 24–Fm 25)* The Tyrnauer Alm (Fm 24) and Rotmüller (Fm 25) formations consist of limestones, sand- and siltstones and intercalated volcanics. They occur in close geographic proximity in the upper Hochlantsch nappe and are of the same age; they are therefore grouped together.
- *Light blue (Fm 26–Fm 30)* The Zachenspitz (Fm 26) and Hochlantsch (Fm 27) formations build up a classical carbonate platform sequence of late Devonian age with massive to bedded light-gray limestones constituting the major cliffs of the Hochlantsch massif. The Schweinegg (Fm 28) and Fahrneck (Fm 29) formations are both very local occurrences of fossil-rich limestones only tens of meters in thickness. Both have previously been suggested to correspond to the Zachenspitz and/or Hochlantsch formations and they are therefore grouped with them here. The Bärenschütz formation (Fm 30) only occurs locally south of Hochlantsch (Fig. 3) where it discordantly overlies Fm 27. It consists of bedded limestones and is significantly younger than formations 26–29, but it is grouped with them here as it is too small to feature as a mappable association of its own.
- *Yellow (Fm 31–Fm 35)* The Kollerkogel (Fm 31), Steinberg (Fm 32) and Sanzenkogel (Fm 33) formations are all variegated, pelagic limestones and shales of late Devonian to Carboniferous age. Each formation is less than 100 m thick, and they all occur in an undisturbed stratigraphic sequence in the upper Rannach nappe. The Höchkogel (Fm 34) and Hahngraben (Fm 35) formations are separated from the others by an erosional unconformity. They consist of limestones and shales and contain detrital mica of Variscan age. They are therefore—similar to the Dornerkogel Fm (Fm 4)—interpreted as Variscan flysch deposit (Neubauer et al. 2007). However, they are very thin and are therefore grouped together with formations 31–33.

In summary, Fig. 2 shows the simplified stratigraphic relationships as they are observed today in the Paleozoic of Graz in the different tectonic units. The groupings we performed show clearly the first-order stratigraphic features that are typical for this complex. The sedimentation started with Silurian metavolcanic rocks. In the early and middle Devonian, platform carbonates and sandy coastal deposits interfinger with fine-grained siliclastic sediments, and volcanic layers point to an ongoing volcanic activity. In the late Devonian, the environment changes from a platform setting to more pelagic sedimentation, which, interrupted by two erosional unconformities, continued up to the Carboniferous and finished with the deposition of flysch-type clastic sediments. The paleogeographical implications of these observations are discussed below.

## Structural geometry

Using this simplified lithological subdivision, we assembled a structural map (Fig. 3) and constructed a series of geological profiles through the entire nappe complex (Fig. 4). The topography for the profiles was extracted from a digital elevation model. Geological information such as detailed maps, local profiles, drill hole data and written descriptions of structure and stratigraphy was taken from many detailed publications listed in Flügel and Hubmann (2000) and the published geological map sheets 133 Leoben, 134 Passail, 135 Birkfeld, 162 Köflach, 163 Voitsberg, 164 Graz and 165 Weiz of the 1:50,000 map series of the Geological Survey of Austria, which are available for download at http://www.geologie.ac.at/. The traces from the profiles in Fig. 4 are indicated in Figs. 1 and 3. Profiles A–D run N–S to NW–SE and are chosen to be perpendicular to the major fold axis orientation in the Paleozoic of Graz. Profile E runs SW–NE and is parallel to the late Cretaceous stretching direction reported by Krohe (1987), Neubauer et al. (1995) and Krenn et al. (2008).

### Rannach thrust

The most prominent tectonic feature in the Paleozoic of Graz is the thrust at the base of the Rannach and Hochlantsch nappes (Figs. 3, 4, profiles B–E). The thrust, here called Rannach thrust, can be traced through much of the Paleozoic of Graz and separates rocks of the Rannach, Hochlantsch and Kalkschiefer facies above from rocks of

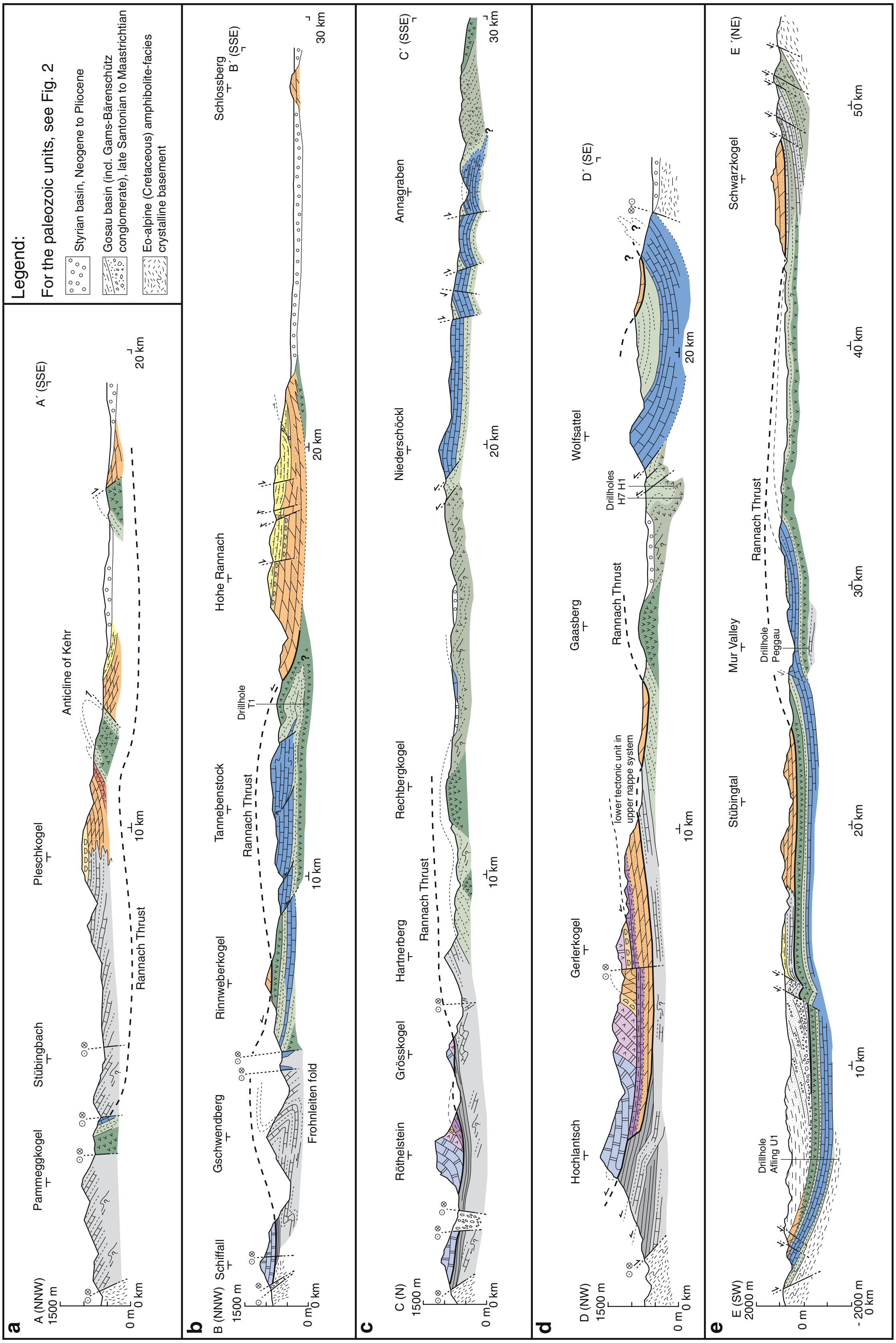


**Fig. 4** Geological profiles through the Paleozoic of Graz. No vertical exaggeration. Informations on drill holes T1, H7 and H1 are from Weber (1990), on drill hole Peggau from Fritz (1986) and on drill hole Afling U1 from Kröll and Heller (1978)

the Kalkschiefer, Schöckl and Laufnitzdorf facies below. The thrust itself is best exposed in the central part of the Paleozoic of Graz. Below Schartnerkogel (Fig. 3), it separates the relatively undeformed, low-grade rocks of the Rannach facies from highly deformed, greenschist facies rocks of the Schöckl facies. The thrust itself is a several meters thick, high strain zone at the base of the Parmasegg formation (Fritz 1988, 1991). It contains asymmetric pressure shadows around pyrite which show a stretching lineation that progressively turns from E–W to SE–NW with generally top-west to top-northwest shear sense. Below Hohe Rannach (Fig. 4, profile B), the thrust separates the rocks of the Rannach facies from the highly deformed greenschist facies rocks of the Schöckl facies. The thrust consists of an up to 100 m thick sheared zone with strongly interleaved rock slices of the Laufnitzdorf and Rannach facies (Neubauer 1989). Similarly, sheared Laufnitzdorf facies rocks occur below the Rannach thrust at Schiffall and Röthelstein (Fig. 4, profiles B–C). Below Schiffall, Grösskogel and north of Gaasberg (Fig. 4, profiles B–D), the Rannach thrust cuts straight through highly folded units of the Schöckl and Kalkschiefer facies; it therefore represents a thrust that is younger with respect to the internal deformation of the lower nappe system.

In other parts of the Paleozoic of Graz, the location of the Rannach thrust is less obvious. In the northwestern part north of Höllererkogel and Stübingbach (Figs. 3, 4, profile A), rocks of the Kalkschiefer and Schöckl facies are juxtaposed against rocks of the Rannach and Kalkschiefer facies along steep, semi-brittle sinistral strike slip zones (Fritz 1991). The original geometry of the Rannach thrust is therefore obliterated. In the southwest around Kehr, the oldest rocks of the Rannach facies crop out in a southeast-verging antiform, but a thrust zone that could correspond to the Rannach thrust is not exposed (Neubauer 1991). In the northeastern part around Hochlantsch (Fig. 3), the location of the Rannach thrust is obvious: it occurs below Schiffall, Röthelstein and Grösskogel (Fig. 4, profiles B–C). In the north of Hochlantsch, the undeformed and low-grade Hochlantsch formation is thrust over imbricated and highly deformed Kalkschiefer and Laufnitzdorf facies rocks and the Rannach thrust is clearly developed. However, south of Gerlerkogel (Fig. 4, profile D) a tectonic unit of higher deformed rocks consisting of the Flösserkogel and Osser formations (Fm 19 and 23) reveals a similar metamorphic grade as the underlying Kalkschiefer and Laufnitzdorf facies rocks and the Rannach thrust could therefore be also located on top of this unit (Hasenhüttl 1994). Because the Flösserkogel and equivalents of the Osser formation are elsewhere clearly located above the Rannach thrust, we interpret this tectonic unit as a local thrust inside the upper nappe system. The Raasberg formation occurs in the southeastern part around Raasberg on top of and sheared together with rocks of the Schöckl facies (Fm 20; Figs. 3, 4; profile D). We interpret it as an equivalent of the Flösserkogel formation and therefore as a small relict of the Rannach Thrust Zone on top of Schöckl facies rocks.

Despite some local difficulties in determining the location of the Rannach thrust, it is a major first-order tectonic boundary in most of the Paleozoic of Graz. It splits the Paleozoic of Graz into an upper nappe system and a lower nappe system, which differ from each other significantly in deformation style and metamorphic grade. Rocks of different sedimentary facies occur both above and below this thrust: Rannach, Hochlantsch and Kalkschiefer facies rocks above; Schöckl, Kalkschiefer and Laufnitzdorf facies rocks below.

### Upper nappe system

Deformation in the upper nappe system above the Rannach thrust is characterized by large-scale open folds, local imbrications and steep brittle faults. Variable fold axis orientations occur, but the general trend of the axes is E–W to NE–SW. A prominent fold example is the southeast-verging anticline of Kehr (Fig. 4, profile A; Neubauer 1991). Other large-scale folds occur in the Hochlantsch massif (Fig. 4, profile D; Gollner and Zier 1985). The Hochlantsch massif consists of two smaller thrust sheets, which we both assign to the upper nappe system: an upper, less deformed unit that contains formations 26–30 and a lower, more deformed unit consisting of formations 19 and 23. Smaller local imbrications in the upper nappe system are known from the east of Schartnerkogel (Fig. 3; Fritz 1991), from the south of Hohe Rannach (Fig. 4, profile B) and around Höllererkogel (Fig. 3). Steep, brittle normal and strike slip faults crosscut the whole upper nappe system.

### Lower nappe system

Deformation in the lower nappe system is much more intense and differs in style from the deformation in the upper nappe system. The Schöckl facies rocks in the lower nappe system are intensely deformed and show a penetrative foliation with a pronounced, asymmetric E–W stretching lineation with top-W shear sense. At micro- to meso-scale, two generations of isoclinal folds occur: (1) isoclinally folded quartz veins, which have the penetrative foliation as axial plane foliation, and (2) isoclinal folds of the penetrative foliation itself with a spaced second cleavage developed at the hinges. The stretching lineation is folded around these second-generation folds (Agnoli 1987; Fritz 1988, 1991; Reisinger 1988; Neubauer 1989, 1991).

Apart from this strong deformation at micro- and meso-scale, also large-scale repetitions of stratigraphy occur. In the northern part, rocks of the Kalkschiefer and Laufnitzdorf facies are imbricated and thrust on top of each other. At the eastern border of the Paleozoic of Graz, phyllites of the Heilbrunn formation (Fm 9), calcareous schists of the Hochschlag formation (Fm 8), phyllites of the Semriach formation (Fm 7) and limestone of the Schöckl formation (Fm 12) lie on top of each other (Fig. 4, profile E). In the central part of the Paleozoic of Graz, the Schöckl formation is symmetrically underlain and overlain by the Taschen (Fm 5) and Schönberg (Fm 11) formations (e.g., south of Tannebenstock, south of Annagraben and below Schartnerkogel; Figs. 3, 4). Schwinner (1925) interpreted this repetition of stratigraphy as the result of multiple thrusting. Clar (1933) and Boik (1950) proposed the existence of large-scale isoclinal folds with the Schöckl formation in the core of the folds. The symmetric occurrence of the same lithologies below and above the Schöckl formation, as well as isoclinal folds at micro- and meso-scale point to the possible existence of such large-scale folds. That is why we draw this possibility in Fig. 4, profiles B–D, Figs. 5, 6d. However, hinges of such possible large-scale folds are nowhere exposed and no proofs for overturned sequences in the inverted limbs such as top–bottom criteria are known. In addition, it is not known if the repetition of stratigraphy occurred prior to, contemporaneously with, or after the formation of the penetrative foliation, the stretching lineation and the two generations of micro- to meso-scale isoclinal folds.

These isoclinally folded and foliated rocks are further overprinted by open to tight, NW to SE-verging folds with a steep axial planar crenulation cleavage and NE–SW trending axes. These folds are associated with brittle fore- and backthrusts. Rocks underlying the basin of Passail (Fig. 4, profile C) as well as the northern border of the Schöckl limestone (Fig. 4, profiles C and D) are strongly overprinted by such tight folds and thrusts. The large-scale open synform south of Wolfsattel belongs to this generation of folds (Fig. 4, profile D).

## Modified tectonostratigraphy and paleogeography

Our tectonostratigraphic interpretation is displayed in Fig. 6. In this interpretation, the structure of the Paleozoic

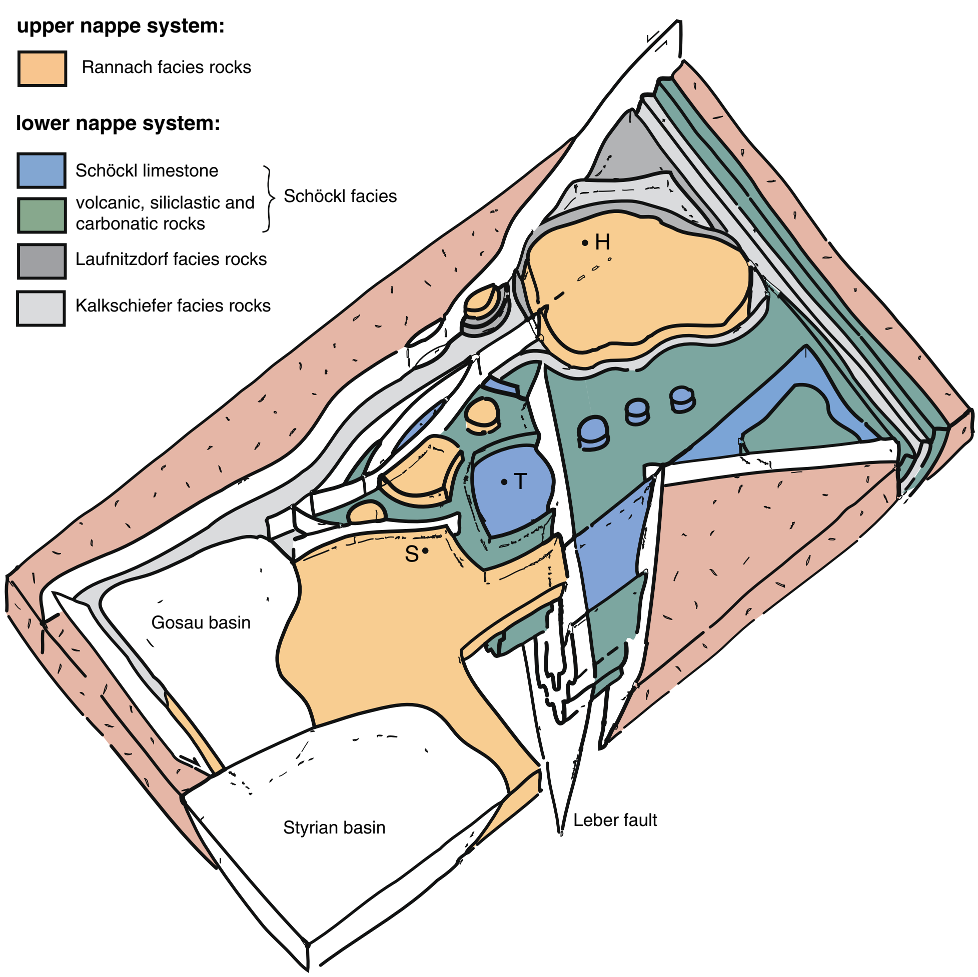


**Fig. 5** 3D Sketch of the Paleozoic of Graz. Location abbreviation as in Fig 3

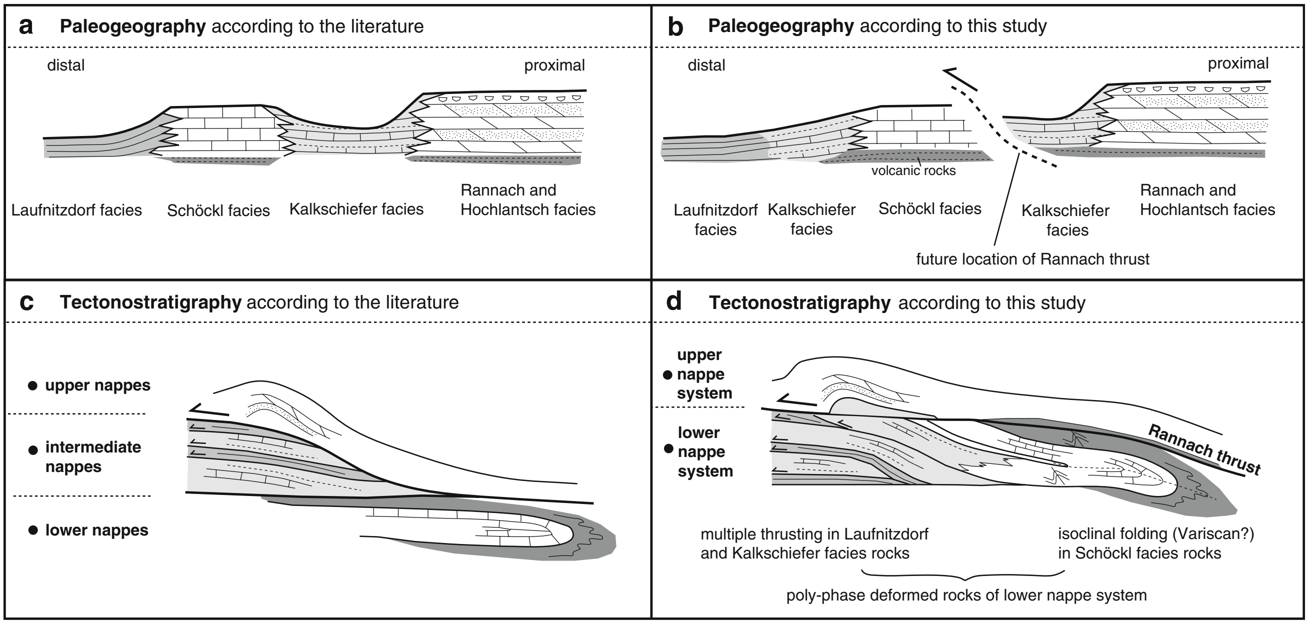


**Fig. 6** **a** Simplified tectonostratigraphy as presented by Fritz et al. (1991, 1992). **b** Simplified tectonostratigraphy as proposed in this study. **c** Simplified paleogeography as proposed by Hubmann (1993). **d** Simplified paleogeography as proposed in this study

of Graz is described in terms of an upper, less deformed nappe system, which is separated by the Rannach thrust from a lower, more deformed and generally higher metamorphic nappe system. The upper nappe system consists of weakly deformed Rannach, Hochlantsch and Kalkschiefer facies rocks. The lower nappe system consists of complex and poly-phase deformed Laufnitzdorf, Kalkschiefer and Schöckl facies rocks, where several repetitions of stratigraphy occur. The reason for this large-scale repetition of stratigraphy is not well known and could be either thrusting or isoclinal folding.

Our tectonostratigraphy differs from the one previously published in the literature. Traditionally, the Kalkschiefer and Laufnitzdorf facies rocks were attributed to an intermediate nappe system (Figs. 1b, 6c; Fritz et al. 1991, 1992). However, no first-order tectonic boundary such as the Rannach thrust is observed between the Kalkschiefer and Laufnitzdorf facies rocks on one side and the Schöckl facies rocks on the other side. A close investigation of existing maps and our profiles reveals that the Kalkschiefer facies rocks lie stratigraphically on top of the Schönberg formation (Fm 11) and laterally replace rocks of the Schöckl formation (Fm 12). This can be seen, for example in Fig. 4, profile C, south of Hartnerberg. Rocks of the Schöckl formation are nowhere overthrust by rocks of the Kalkschiefer and Laufnitzdorf facies and a tectonic boundary between them (except for late steep sinistral strike slip faults on Fig. 4, profile B) is not known. We therefore prefer to interpret the Kalkschiefer and Laufnitzdorf facies rocks as lateral facies equivalents of the Schöckl formation and not as an own intermediate tectonic nappe system.

Traditionally, tectonic nappes in the Paleozoic of Graz (and in other low-grade sedimentary units of the Alps) have been defined on the basis of sedimentary facies with each identified facies being ascribed to an own tectonic nappe. In the Paleozoic of Graz, the terms Laufnitzdorf, Kalkschiefer, Schöckl, Rannach and Hochlantsch have been used interchangeably for sedimentary facies as well as for tectonic units. Here, we have shown that rocks of the Kalkschiefer facies occur both in the upper and lower nappe system. It is therefore confusing to use the term Kalkschiefer nappe in a tectonic sense because it is not explicit. Similarly, the terms Rannach and Hochlantsch nappes do not really describe tectonic units, but different facies associations occurring on the same tectonic level, namely in the upper nappe system. We therefore propose to only use upper and lower nappe system in a tectonic context.

The analysis of the profiles also leads to a slightly modified paleogeography for the Paleozoic of Graz. Such a paleogeographical model has to explain that (a) the Kalkschiefer facies rocks occur in the lower nappe system and are closely imbricated with Laufnitzdorf facies rocks and (b) the Kalkschiefer facies rocks occur in the upper nappe system in sedimentological contact with Rannach facies rocks. Hubmann (1993) proposed the arrangement displayed in Fig. 6a for the Middle Devonian. In this scenario, the Rannach and Hochlantsch facies represent a proximal, coastal facies, which is separated from the Schöckl limestone by a Kalkschiefer facies basin. The pelagic

Laufnitzdorf facies directly borders the Schöckl limestone toward a more pelagic environment. This scenario makes it difficult to explain the close imbrication of Kalkschiefer and Laufnitzdorf facies rocks that is observed today in the northern part of the Paleozoic of Graz. The Kalkschiefer facies rocks would have needed to overthrust the Schöckl limestone in order to get adjacent with the Laufnitzdorf facies rocks. We therefore propose a modified arrangement, which does not require such a complicated deformation (Figs. 2, 6b). We suggest that there were two basins of Kalkschiefer facies rocks that flanked the Schöckl facies on both sides and were therefore, in part, adjacent to the Laufnitzdorf facies rocks. This is sedimentologically reasonable as the Kalkschiefer facies represents an intermediate facies between the pelagic Laufnitzdorf facies and the carbonate platform of the Schöckl facies. However, the two Kalkschiefer facies basins are postulated entirely on tectonic considerations. A second difference between the model proposed by Hubmann (1993) (Fig. 6a) and the model proposed here (Fig. 6b) is that we do not directly link the stratigraphy we observe in the upper tectonic nappe system with the stratigraphy in the lower tectonic nappe system. We do not know how much displacement occurred along the Rannach thrust and if the two nappe systems were directly adjacent during sedimentation or not. The stratigraphy in the two nappe systems shows some differences: Whereas in the upper nappe system dolomitic, carbonaceous, sandy and marly sediments dominate, the lower nappe system is dominated by fine-grained siliclastic rocks and more pelagic sediments. However, both nappe systems share the volcanic rocks at the base. In fact, these basal volcanic rocks may have served as a detachment horizon for the later Rannach thrust.

Despite these modifications in the paleogeographical interpretation and the uncertainities that remain due to later deformation, we suggest that the Paleozoic of Graz nicely fits into other larger-scale models for the paleogeographical evolution of the Austroalpine during the Paleozoic. In the Silurian, the Paleozoic of Graz was located at the northern border of Gondwana, where spreading led to volcanism and the deposition of volcano-clastic rocks. In the Devonian, the Paleotethys opened and shallowwater, carbonate platform and basin sediments were deposited, followed by deeper-water and more pelagic sediments in the upper Devonian. In the Carboniferous, a change from an extensional setting toward a compressional setting occurred with the deposition of flysch-type deposits, erosion and carstification. Similar evolutions are observed in several other low-grade Paleozoic units such as the Carnic Alps or the Greywacke Zone (e.g., Fritz and Neubauer 1988; Schönlaub 1992; Neubauer and Sassi 1993; Schönlaub and Histon 1999; von Raumer and Stampfli 2008).

## Tectonic evolution of the Paleozoic of Graz: a discussion

According to the profiles and structural map shown in Figs. 3 and 4, the internal geometry of the Paleozoic of Graz is best described in terms of an upper and a lower nappe system separated by the Rannach thrust. Deformation in the lower nappe system is dominated by a ductile penetrative foliation, isoclinal folds and an E–W stretching lineation. Deformation in the Rannach Thrust Zone is dominated by a stretching lineation that progressively turns from E–W to SE–NW. In both the lower and upper nappe systems open folds with NE–SW trending fold axes occur. Several brittle strike slip faults crosscut the Paleozoic of Graz, but major normal faults inside the complex are not known. The whole complex is bordered by a normal fault in the west, a strike slip fault in the northwest and several complex strike slip, normal and thrust faults in the south and east. In the following, we discuss what we know and do not know about the events, which led to this actual internal geometry of the complex.

### Age of internal deformation and metamorphism: Variscan or Eo-Alpine?

The internal deformation of the Paleozoic of Graz is loosely constrained by the Upper Carboniferous age of the youngest sediments incorporated into the deformed complex and by the Late Cretaceous Gosau basin, which unconformably overlies the deformed complex (Fig. 2). Within this large age bracket, both the Variscan (Carboniferous) and the Eo-Alpine (Cretaceous) orogeny occurred, which are both well known in large parts of the eastern Alps. *Variscan* deformation is documented for the Carnic Alps and the Greywacke Zone (Fig. 1a) by late Carboniferous to Permian rocks, which discordantly overlie deformed pre-late-Carboniferous sequences (Neubauer 1988b; Schönlaub and Histon 1999; Neubauer and Handler 1999). In the Carnic Alps, rocks of the same age as the Höchkogel and Hahngraben Fm (Fm 34–35) from the Rannach facies are incorporated into isoclinal, complex Variscan deformation (Schönlaub and Histon 1999, Figs. 7, 9). Correspondingly, in the Gurktal nappe system, Variscan deformation is indicated by Carboniferous $^{40}Ar/^{39}Ar$ muscovite ages from mylonites (Neubauer and Handler 1999). It is therefore possible that Variscan deformation also affected the Paleozoic of Graz. In the upper nappe system, a hint for Variscan tectonics in the Graz Paleozoic is evident from carstification of previous deep marine limestones (Sanzenkogel Fm) followed by deposition of clastic sediments containing Variscan mica (Hahngraben Fm; Fig. 2). Conversely, *Eo-Alpine* deformation is well documented in large parts of the eastern Alps by deformed Permo-Mesozoic sediments, for example below the Greywacke Zone or below the Gurktal nappe system (Ratschbacher 1986). In these zones, a similar

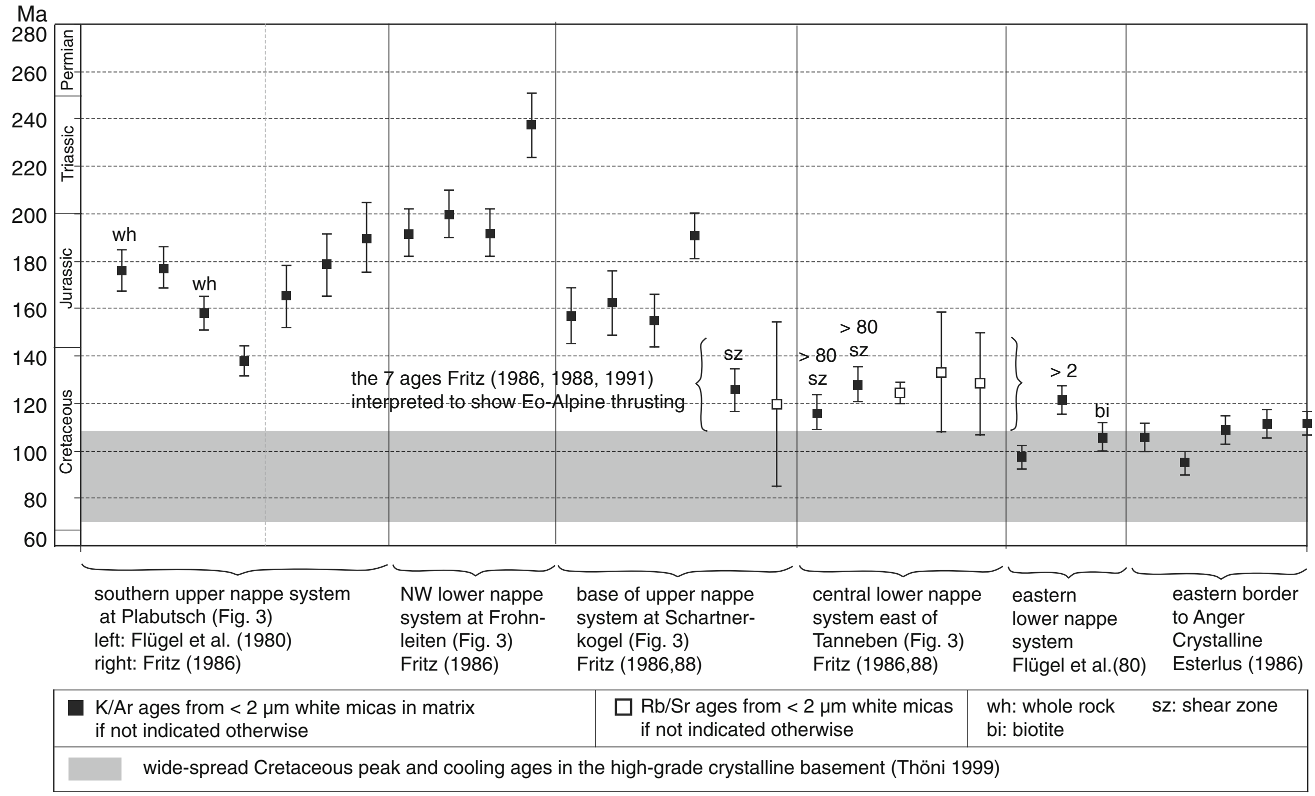


**Fig. 7** Geochronological ages from the Paleozoic of Graz (from Flügel et al. 1980; Fritz 1986, 1988, 1991; Esterlus 1986). Fritz (1986, 1988, 1991) interpreted the ages in the time interval 130–115 Ma as showing Eo-Alpine thrusting. However, the ages scatter over a larger time interval from 240 to 100 Ma and do not necessarily show the time of deformation (Thöni 1999); see also text for discussion. Time scale after Ogg et al. (2008)

top-W to top-NW thrusting as in the Paleozoic of Graz occurred, which may indicate that deformation in the Paleozoic of Graz is also of Eo-Alpine age. In addition, recent studies in the northern Calcareous Alps showed that the onset of Eo-Alpine thrusting in these units already started in the late Jurassic (ca 150 Ma: Frisch and Gawlick 2003; Gawlick and Schlagintweit 2006). This was most likely associated with closure of the Meliata oceanic basin, blueschist metamorphism of oceanic sediments and nappe imbrication of footwall units (Dallmeyer et al. 2008).

Unfortunately, Permo-Mesozoic sediments, used elsewhere in the eastern Alps to differentiate between Variscan and Eo-Alpine orogeny, are absent in the Paleozoic of Graz. So neither Variscan nor Eo-Alpine deformation can be proven in the Paleozoic of Graz with the help of sediments.

The age of the low-grade metamorphism in the Paleozoic of Graz is similarly controversial. Earlier studies suggested Silurian to Early Devonian rifting and volcanism (Hasenhüttl 1994) and the Variscan orogeny (e.g., Fritz 1986; Russegger 1996) as the causes of metamorphism. In view of the rising evidence for a Permian thermal event (Schuster and Stüwe 2008), Rantitsch et al. (2005) also suggested that the overall metamorphism of the Paleozoic of Graz could be the result of Permian burial. Fritz (1988, 1991) interpreted K/Ar and Rb/Sr ages from white micas in both pressure shadows and the matrix as being the result of an Eo-Alpine thrusting event around 125 Ma and concluded that all deformation in the Paleozoic of Graz took place during the Cretaceous. However, a plot of all published isotopic ages from the Paleozoic of Graz shows that they scatter over a large time interval from ~240 Ma down to ~90 Ma (Fig. 7) and that only a few ages lie in the range Fritz (1988, 1991) attributed to the age of deformation. A similar scatter of ages was recorded from other low-grade Upper Austroalpine units in the eastern Alps such as the base of the northern Calcareous Alps and the Greywacke Zone (Kralik et al. 1987; Thöni 1999). The interpretation of all these scattering ages is difficult: They could (a) represent mixed ages between an old, Variscan and a younger (~100 Ma) Eo-Alpine event; (b) be related to hot fluids circulating after Triassic–Jurassic spreading, or (c) represent crystallization ages during a Jurassic to Early Cretaceous deformation (Thöni 1999). In view of these difficulties in interpreting isotopic ages in low-grade rocks, we are not convinced that the few isotopic ages that lie in the range of 130–115 Ma in the Paleozoic of Graz are sufficient to conclude that all deformation in the Paleozoic of Graz took place during the Cretaceous. We suggest that the actual state of knowledge about deformation and metamorphism and the lack of a modern, detailed geochronological analysis of the region do not allow judging unequivocally which of the two major events (Variscan or Eo-Alpine) was (and to which extent) responsible for the actual internal geometry of the Paleozoic of Graz.

## Deformation along the borders in the Late Cretaceous and Tertiary

The Paleozoic of Graz is not only internally deformed and metamorphosed, but also spectacularly juxtaposed against high-grade crystalline units such as the Koralm Crystalline along its southwestern and the Gleinalm Crystalline along its northwestern borders (Fig. 1b). Several models have been proposed to explain the emplacement of the Paleozoic of Graz on top of these crystalline units. The following observations have to be included in these models:

- The Paleozoic of Graz is only ~1–2 km thick: the crystalline rocks below the Paleozoic of Graz were reached by a drill hole in the Gosau basin at a depth of only about 1,000 m below sea level (Kröll and Heller 1978; Fig. 4, profile E). Based on the very low-grade metamorphism of the uppermost units, it can be argued that the complex was never more than 5–8 km thick.
- Geochronological data from the surrounding crystalline units constrain the age of amphibolite to eclogite facies metamorphism to around 100–80 Ma and subsequent cooling to below 100°C to around ~60–50 Ma (Neubauer et al. 1995; Hejl 1997; Thöni 1999).
- Simultaneously to metamorphism and cooling, sedimentation occurred in the alluvial to marine Gosau basin on top of the Paleozoic of Graz. This suggests that exhumation of the crystalline units was not accompanied by major topography.
- The profiles in Fig. 4 show that the internal structure of the Paleozoic of Graz is dominated by compressional structures; apart from brittle normal and strike slip faults along the borders, extensional structures inside the Paleozoic of Graz are rare.
- The Paleozoic of Graz is bounded by several ductile to brittle fault zones. The north-western border toward the Gleinalm Crystalline is made up of a sinistral fault zone dipping 50–80° toward SSE and showing a stretching lineation dipping ~10° toward the NE (Neubauer 1988a; Neubauer et al. 1995). The southwestern border toward the Koralm Crystalline is a steep, brittle, NE-dipping normal fault (Graden normal fault), which overprints a gently NE dipping mylonitic foliation with a down-dip lineation and top-NE shear sense in the crystalline rocks (Krohe 1987; Rantitsch and Mali 2006). The eastern border to the Radegund Crystalline is made up of several 100 m broad zones of highly deformed rocks of the Paleozoic of Graz, which show both top-E and top-W shear sense (Krenn 2001). The southern border toward the Radegund Crystalline consists of a steep, brittle dextral strike slip fault (Krenn 2001). The northeastern border toward the Anger Crystalline is less pronounced and the metamorphic grade increases continuously. A tectonic foliation is developed, which dips 35–55° toward SW and shows both top-NE and top-SW shear sense. This foliation is overprinted by steep SW-dipping brittle normal faults (Neubauer 1981; 1982; Gsellmann 1987; Krenn 2001; Krenn et al. 2008).

Ratschbacher et al. (1991) interpret the mylonitic fault rocks found in several of the border faults as part of a single belt of mylonitic rocks, which underlie the Paleozoic of Graz. According to them, exhumation of the surrounding crystalline rocks took place due to a gravitational instability caused by the thickened Early Cretaceous orogenic wedge, and the entire nappe stack of the Paleozoic of Graz was sheared off from its basement along a basal, spoon-shaped high-strain zone toward the northeast. In contrast, Neubauer et al. (1995) proposed that the Glein- and Koralm Crystalline were exhumed in an overall transpressional setting in a sinistral wrench corridor, where the Paleozoic of Graz and the Gosau basin were located in a releasing bend of this corridor. This model does not require a connected shear zone at the base of the whole Paleozoic of Graz and interprets the extensional structures at the borders and the Gosau basin formation as a result of oblique shortening rather than gravitational collapse. Consistent with that, Rantitsch et al. (2005) modeled the thermal influence of the exhuming crystalline rocks onto the Paleozoic of Graz and the Gosau basin along the Graden normal fault and concluded that a normal fault, which roots in a flat lying detachment at ~20 km depth best fits the observations. Consequently, from a thermal point of view, no shallow flat lying detachment along the base of the Paleozoic of Graz is needed. Krenn et al. (2008) returned to the model proposed by Ratschbacher et al. (1991) and refined it to a two-stage process: in a first event, the Paleozoic of Graz extruded as a block together with the underlying crystalline rocks to the NE. In a second event the Paleozoic of Graz decoupled from the underlying crystalline rocks and pure extension led to the formation of normal faults at the borders, whereas the underlying crystalline rocks were ductilely stretched.

The models explaining the exhumation of the surrounding crystalline basement either invoke a continuous shear zone at the base of the Paleozoic of Graz (which decouples it from the underlying crystalline rocks) or brittle to ductile faults, which go much deeper than the actual base of the Paleozoic units. Considering the internal geometry of the Paleozoic rocks (Fig. 4), we suggest that decoupling along the base in an overall extensional setting (as suggested by Ratschbacher et al. 1991 and Krenn et al. 2008) is mechanically highly unlikely. If extension and stretching of the underlying crystalline basement occurred, the whole internal Paleozoic of Graz would have dismembered. In contrast, no substantial extensional structures are observed in the Paleozoic of Graz and the profiles in Fig. 4 suggest that there is a minimum of extensional strain. We therefore suggest that exhumation of the Kor- and Gleinalm Crystalline in an overall transpressional regime (as suggested by Neubauer et al. 1995) provides a good explanation that is consistent with the observations in the Paleozoic of Graz.

## Conclusions

Re-evaluation of an abundance of local literature and the compilation of this information in the form of integrated profiles lead to the following conclusions about the internal structure of the Paleozoic of Graz: (1) The 35 sedimentary formations defined by Flügel and Hubmann (2000) can be summarized into 13 distinct rock associations belonging to five different sedimentological facies termed the Laufnitzdorf, Kalkschiefer, Schöckl, Rannach and Hochlantsch facies. (2) The Paleozoic of Graz consists of an upper and a lower nappe system which are separated by a thrust, the Rannach thrust. Kalkschiefer, Rannach and Hochlantsch facies rocks occur in the upper nappe system, Kalkschiefer, Laufnitzdorf and Schöckl facies rocks occur in the lower nappe system. Upper and lower nappe system differ in deformation style and metamorphic grade. (3) In the literature, the same names were applied for both sedimentary facies as well as tectonic units. Because sedimentary facies and tectonic units do not correlate, this should be avoided. (4) The age of internal deformation remains badly constrained. Compared with other Paleozoic units of the eastern Alps, both Variscan and Eo-Alpine events may have contributed to the internal structure of the Paleozoic of Graz. (5) The exhumation of the surrounding crystalline basement during the Late Cretaceous led to deformation along the borders of the Paleozoic of Graz. For mechanical reasons, we favor models that invoke a deep-seated detachment in the crystalline rocks relative to models that invoke a shallow, flat-lying detachment at the base of the Paleozoic of Graz.

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