

Raman spectroscopy of carbonaceous material thermometry in the uppermost Austroalpine units, Eastern Alps – paleogeographic and tectonic implications

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Abstract

Raman spectroscopy of carbonaceous material (RSCM) estimates peak metamorphic temperatures in structural top units of the Eastern Alps (Steinach nappes, Gurktal nappes, Graz Paleozoic, Carboniferous of Nötsch, Kreuzeck-Goldeck-Gailtal Nappe, Diabase Zone of the North-Karawanken Range) and in their tectonic units below (Schneeberg Complex and Ötztal Nappe below the Steinach nappes, Heiligengeistklamm Nappe below the Gurktal nappes, Waxenegg Nappe below the Graz Paleozoic). The data are based on a standardized temperature calibration and describe the thermal structure of displaced tectonic units which were adjacent segments of the western Tethyan shelf during Permomesozoic times. In a west- to east profile through the Eastern Alps, RSCM data from the Koralpe-Wölz and Ötztal-Bundschuh nappe systems (Brenner area, Gurktal and Nock area, Remschnigg area, Grazer Bergland, Drau Range, North-Karawanken Range) show consistent peak metamorphic temperatures of 570–410 °C. Great similarities are found between the Steinach and Gurktal nappes. A thermal imprint of their post-Variscan (Pennsylvanian) molasse sediments is lower than 300 °C. Similar RSCM temperatures are found in Pennsylvanian sediments of the Graz Paleozoic and in the Sausalpe, Remschnigg and Sausal sections of the Gurktal nappes, suggesting a similar burial depth during later times. The thermal structure of the Graz Paleozoic is characterized by an upright temperature trend within the nappe stack, by a thermal anomaly in the southeastern segment, and detachments disturbing the metamorphic pattern at the eastern margin. Permomesozoic burial heating of the Drau Range is constrained by upward decreasing RSCM temperatures. Temperatures <160 °C are estimated in the Carnian Raibl Formation. This pattern is overprinted in the central segment of the Gailtal Alps by a thermal anomaly with temperatures >200 °C in the Carnian stratigraphic level. It is suggested that the temperature gap at the base of the Drauzug-Gurktal Nappe System is related to low-angle detachments formed during post-orogenic collapse. Here, also RSCM temperatures increase locally.

1. Introduction

The highest tectonic elements of the Eastern Alps comprise units composed of Paleozoic (meta)sediments and (meta)volcanics that are derived from the Adriatic micro-continent and metamorphosed at various grades during the Variscan (Late Devonian, Carboniferous) and/or Permian-Triassic tectono-metamorphic events (see reviews

in Neubauer et al., 1999; Schuster et al., 2006; Schuster and Stüwe, 2008; Knoll et al., 2023). In major parts, they are overlain by Pennsylvanian to Permian molasse sediments followed by sediments of the western Tethyan shelf during Mesozoic times (see reviews in Neubauer et al., 2022 and Kurz et al., 2024). The Eoalpine (Cretaceous) metamorphic overprint is low (greenschist facies) or even

missing (Hoinkes et al., 1999). The corresponding structural units appear fragmented in modern map view (Tonale Nappe, Meran-Mauls nappe stack, Steinach nappes, Lienz Nappe, Kreuzeck-Goldeck-Gailtal Nappe, “Carboniferous of Nötsch”, Gurktal nappes, North-Karawanken Range and the Graz Paleozoic, from west to east, Figure 1) but based on their positions in the hanging wall of the Eoalpine high-pressure belt they were assigned to the Upper Austroalpine Drauzug-Gurktal Nappe System by Schmid et al. (2004).

Several paleogeographic reconstructions were proposed for the post-Variscan evolution of the western Tethyan shelf (Bechstädt, 1978; Schmidt et al., 1991; Haas et al., 1995; Handler et al., 1997; Lein et al., 1997; Gawlick et al., 1999; Schuster and Frank, 1999; Ebner et al., 2008; Vozárová et al., 2009; Haas et al., 2020; Neubauer et al., 2022). All these models share a common tectonic framework with a continuous dissection of a formerly continuous shelf area (e.g., Froitzheim et al., 2008). Permo-Triassic lithospheric extension dismembered the Variscan belt and yielded to the formation of the Neotethys in the Middle to Late Triassic. The Tethys was fragmented during rifting and subsequent opening of the Penninic ocean in Jurassic times.

Upper Jurassic to Cretaceous (up to Coniacian/Santonian) convergence and closure of the Neotethys followed by collision within the Adriatic microcontinent (Stüwe and Schuster, 2010) induced the formation of the Austroalpine nappe stack, which assembled fragments of the western Tethyan shelf into the Drauzug-Gurktal Nappe System in the uppermost position (Schmid et al., 2004, Fig. 1). During Cretaceous-Paleogene subduction of the Alpine Tethys and following continental collision, the Drauzug-Gurktal Nappe System was at the top of the upper plate (Schmid et al., 2004). Late Oligocene to Miocene extensional and strike-slip tectonics induced lateral block displacements that further dispersed the structural top units of the Eastern Alps (see review of Kurz et al., 2024).

Paleogeographic correlations have been proposed for the rocks of the Drauzug-Gurktal Nappe System. During Mesozoic times, the Drau Range had a common depositional area with the Southalpine Lombardian Basin and the western segments of the Northern Calcareous Alps (Schmidt et al., 1991; Haas et al., 1995). Haas et al. (2020) postulated a proximity of the Gurktal nappes and Graz Paleozoic to the Southalpine units, whereas Neubauer et al. (2022) positioned those units further to the north in a “Norc Domain”.

The mentioned paleogeographic views are based on sedimentological and stratigraphical analyses (Schmidt et al., 1991; Haas et al., 1995; Neubauer et al., 2022, cum. lit.) as well as geochronology of detrital minerals (Neubauer et al., 2007; Haas et al., 2020; Neubauer et al., 2024, cum. lit.). The post-Variscan metamorphic imprint of all the mentioned units is dependent on the constraints of the Permomesozoic burial history (e.g., Rantitsch et al., 2020). In particular, overburden thickness and heat-flow

history control the degree of organic metamorphism (i.e., the chemical and microstructural transformation of immature organic matter over time to graphite) in a specific stratigraphic level, which is dependent on the paleogeographic and tectonic setting of the studied sedimentary basin (see the review of Yalcin et al., 1997). In particular, as shown by Rantitsch and Rainer (2003), the analysis of vitrinite reflectance data contributes to a better paleogeographic understanding of the western Tethyan shelf. However, even if vitrinite reflectance tracks organic metamorphism in the diagenetic stage well, it loses its sensitivity in the stage of very-low grade metamorphism (Rantitsch et al., 2020). Raman spectroscopy of carbonaceous material (RSCM) thermometry therefore provides an alternative (see review of Henry et al., 2019). RSCM reliably estimates peak metamorphic temperatures from the sensitive change of the microstructural order of carbonaceous matter enclosed in metasediments, covering the zone of very-low- to medium-grade metamorphism, and thus images the thermal structure of an orogen in a depth range which includes all major thrust sheets as well as the basal units of thick cover sequences. At best, an RSCM database is completed by pressure estimates and age dating (e.g. Hollinetz et al., 2022, 2024). Hence, large gaps of RSCM temperatures accompanied by a pressure gap (Hollinetz et al., 2024) at the eastern margin of the Graz Paleozoic may be interpreted as the signature of extensional ductile shear zones at the basis of the Drauzug-Gurktal Nappe System called the “Austroalpine Detachment System” (Hollinetz et al., 2024, Fig. 1).

In this paper, we provide a comprehensive set of RSCM temperature estimates for the Drauzug-Gurktal Nappe System, both from the basement and the Pennsylvanian-Paleogene cover. We targeted the well constrained continuous tectonic and stratigraphic profiles in the Steinach nappes, the Gurktal nappes, the Graz Paleozoic, the Lienz Nappe, the Kreuzeck-Goldeck-Gailtal Nappe, the Dobratsch Nappe and the North-Karawanken Range. For deeper insights, underlying units of the Drauzug-Gurktal Nappe System were also investigated. This comprises the Ötztal Nappe (Ötztal-Bundschuh Nappe System) below the Steinach nappes, as well as several units from the Koralpe-Wölz Nappe System, namely the Schneeberg Complex (differing interpretations regarding its tectonic position exist; cf. Sölva et al., 2005; Klug and Froitzheim, 2022), the Heiligengeistklamm Nappe below the Gurktal nappes and the Waxenegg Nappe below the Graz Paleozoic. We also include new estimates from already published samples and review the data of Rantitsch et al. (2020). All study data are based on a common temperature calibration, thus enabling a quantitative data view, improving significantly the preliminary temperature collection of Hoinkes et al. (1999). This allows us to describe the thermal structure of the Drauzug-Gurktal Nappe System and shed new light on the original geometry of the dismembered western Tethyan shelf. This also helps to further quantify the temperature jump associated with the Austroalpine Detachment System.

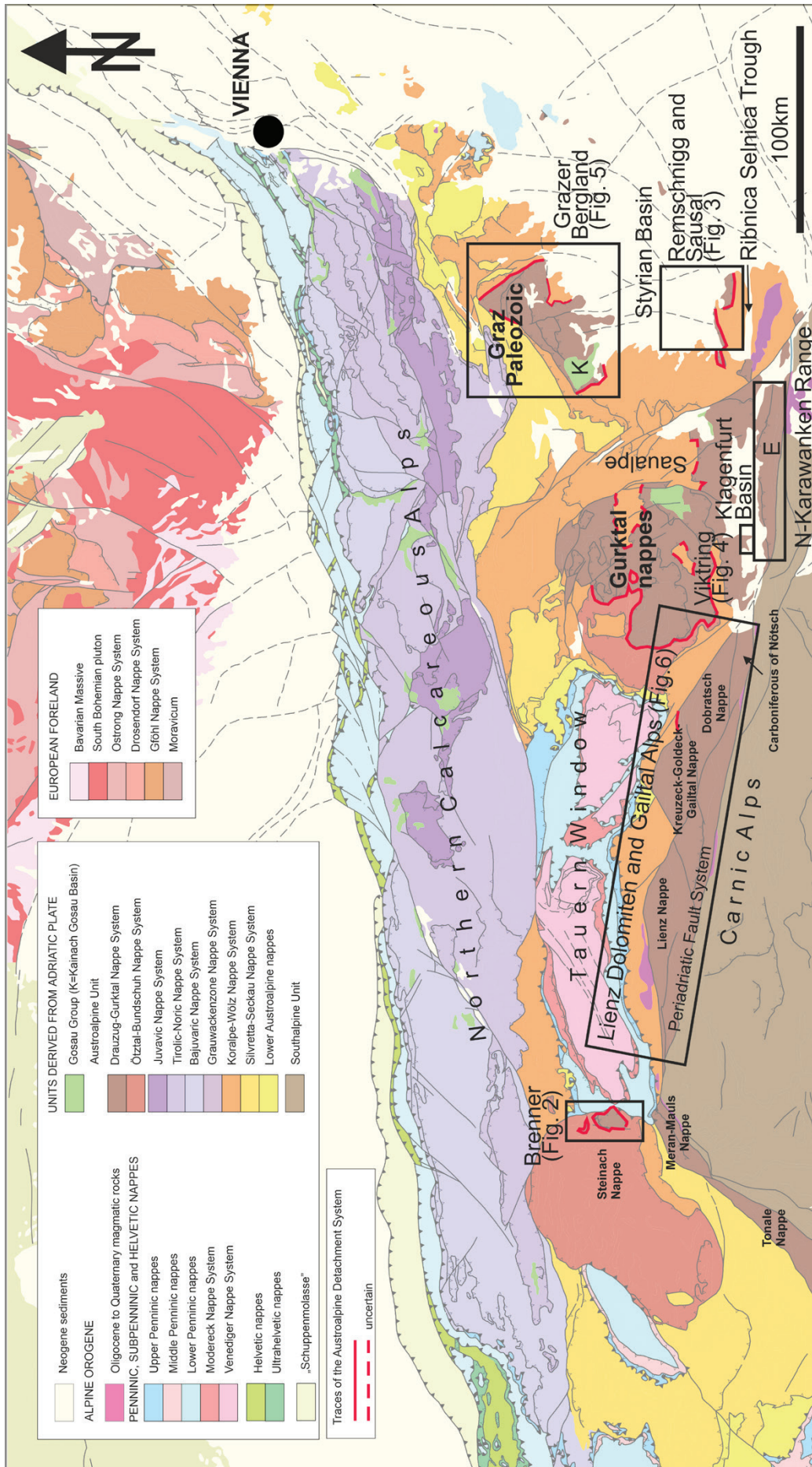


Figure 1: Tectonic map of the Eastern Alps and adjacent units based on maps.geosphere.at (last access June 2026) with tectonic interpretation after Schmid et al. (2004). Rectangles indicate the investigated areas. Units of the Gailtal Alps and North-Karawanken Range (E=Eisenkappel) are parts of the Drau Range. Traces of the Austroalpine Detachment System (Hollinetz et al., 2024) after own observations and Neubauer et al. (1995), Koroknai et al. (1999), Fügenschuh et al. (2000), Wiesinger et al. (2006), Krenn et al. (2008), Huet (2018), Rantitsch et al. (2019), Hollinetz et al. (2020), Griesmeier et al. (2024), Iglseder (2025).

2. Geological setting

The Drauzug-Gurktal Nappe System shows a W-E extension of more than 400 km in the southern part of the Eastern Alps. Together with the underlying Ötztal-Bundschuh Nappe-System and the Transdanubian Range in the eastern continuation it is interpreted to represent nappes derived from the Eoalpine (Cretaceous) upper plate (Schmid et al., 2004), because all these units are overlying the Eoalpine high-pressure belt (Koralpe-Wölz Nappe System) and are characterized by an upright metamorphic field gradient. The individual nappes of the Drauzug-Gurktal Nappe System consist of pre-Alpine metamorphosed basement rocks and post-Variscan Pennsylvanian-Paleogene cover sequences in variable portions. The basement experienced tectonometamorphic overprints during the Cambro-Ordovician, Late Devonian-Carboniferous (Variscan) and Permian events at different metamorphic grades. The Late Jurassic to Paleogene Alpine overprint, also affecting the cover sequences, reached greenschist-facies conditions at maximum (Hoinkes et al., 1999; Froitzheim et al., 2008). In map view (Fig. 1), the Drauzug-Gurktal Nappe System forms a more or less continuous belt directly north of the Periadriatic Fault System, as well as some outliers further north overlying nappes of the Ötztal-Bundschuh and Koralpe-Wölz nappe systems.

The Drauzug-Gurktal Nappe System consists of several geographically isolated units throughout the Eastern Alps (Fig. 1), which are briefly described here. (1) The Tonale Nappe (Trentino-South Tyrol and Lombardy) is correlated to the deepest nappe of the Meran-Mauls nappe stack (Roda et al., 2018; Pomella et al., 2022). (2) The Meran-Mauls nappe stack (Trentino-South Tyrol) consists of basement rocks metamorphosed in the Variscan and Permo-Triassic events with intercalated very-low to low grade metamorphic Permo-Triassic cover sediments (Pomella et al., 2022). (3) The Steinach nappes (Brenner area, Tyrol and Trentino-South Tyrol) are composed of a pre-Variscan basement and a Pennsylvanian post-Variscan cover sequence (Reiser et al., 2019). Mesozoic cover sediments are additionally exposed in the Blaser Nappe (Reiser et al., 2019). (4) The Gurktal nappes (Styria and Carinthia) display a similar architecture to the Steinach nappes, with a much thicker Carboniferous to Cenozoic cover (Iglseider, 2025). (5) The Graz Paleozoic (Styria) is composed of basement nappes and a post-Eoalpine cover sequence of Upper Cretaceous to Neogene age (Fritz et al., 1991; Gasser et al., 2010). (6) The Lienz Nappe (East Tyrol, Carinthia) displays a complete Permian to Cretaceous succession. (7) The Kreuzeck-Goldeck-Gailtal Nappe (East Tyrol, Carinthia) contains Variscan metamorphic basement units which experienced only a mild Eoalpine overprint (Schuster et al., 2015; Griesmeier et al., 2019). It additionally shows Permian to Triassic sediments that transgressively overlie the Goldeck Complex (Schuster et al., 2015; Griesmeier et al., 2019). (8) The Dobratsch Nappe (Carinthia) contains Carboniferous sediments (Carboniferous of Nötsch, Schönlaub, 1985) that are lo-

cally exposed below a transgressive contact evidencing a stratigraphic position below Permomesozoic sediments. (10) In the North-Karawanken Range (Carinthia, Slovenia), a Permian to Jurassic sedimentary sequence tectonically overlies the Paleozoic “Eisenkappel Diabase Zone” (Loeschke and Weber, 1973) and the “Eisenkappel Crystalline” with the Permian Karawanken plutonic belt (Miller et al., 2011). The Permomesozoic unit of the Lienz Nappe, the Dobratsch Nappe and the North-Karawanken Range form the so-called “Drau Range Permomesozoic”. The investigated units (Fig. 1) are characterized in more detail below.

2.1. Brenner area

In the Brenner area (Fig. 1), the Schneeberg Complex (Koralpe-Wölz Nappe System) is represented by graphitic micaschists, metacarbonates and amphibolites. It was affected by an Eoalpine metamorphic overprint under amphibolite-facies conditions between 105 and 95 Ma (550–600 °C and 0.8–1.0 GPa; Konzett and Hoinkes, 1996; Sölva et al., 2005; Pedevilla and Tropper, 2012; Tual et al., 2025).

The Ötztal Nappe (Ötztal-Bundschuh Nappe System) above is composed of polymetamorphic metasediments, metabasites and orthogneisses, overlain by the transgressive Permian to Jurassic cover of the “Brenner Mesozoic”. The crystalline basement experienced Variscan metamorphism under amphibolite-facies conditions (Hoinkes et al., 1982; Frank et al., 1987; Thöni, 1981, 1999; Schulz et al., 2019). At the base of the “Brenner Mesozoic”, Permian to Triassic metaconglomerates and quartzite are followed by Anisian carbonates (Steinalm Formation) and dark carbonates of the Ladinian-Carnian Partnach Formation (Brandner et al., 2003), interfingering with massive Ladinian and Norian dolomite platforms, separated by a characteristic horizon of silvery grey to black graphitic schists and yellowish dolomitic carbonates (Carnian Raibl Formation). At the top of the succession, highly deformed Triassic to Jurassic calcareous schists, carbonates, quartzites and phyllites are summarized as “Metamorpher Kalkkomplex” (sensu Kübler and Müller, 1962). Consistent with thermobarometric data from the basement (Tropper and Hoinkes, 1996; Tropper and Recheis, 2003; Raso et al., 2025), the “Brenner Mesozoic” was metamorphosed to 450–530 °C at 0.35–0.40 GPa during the Eoalpine event in the Cretaceous (Dietrich, 1983; Frank et al., 1987) and later exhumed below a Cretaceous detachment (Fügenschuh et al., 2000).

In the hanging wall of the detachment, the Blaser and Steinach nappes are parts of the overlying Drauzug-Gurktal Nappe System (Rockenschaub et al., 2003; Schmid et al., 2004; Reiser et al., 2019). The Blaser Nappe comprises Middle Triassic to Cretaceous carbonates with basal slivers of Carboniferous to Permian sediments and quartzphyllites (Tollmann, 1963, cum. lit.). It represents the Mesozoic cover of the Steinach nappes, detached from its Lower Triassic and pre-Mesozoic base. South of the Gschnitz

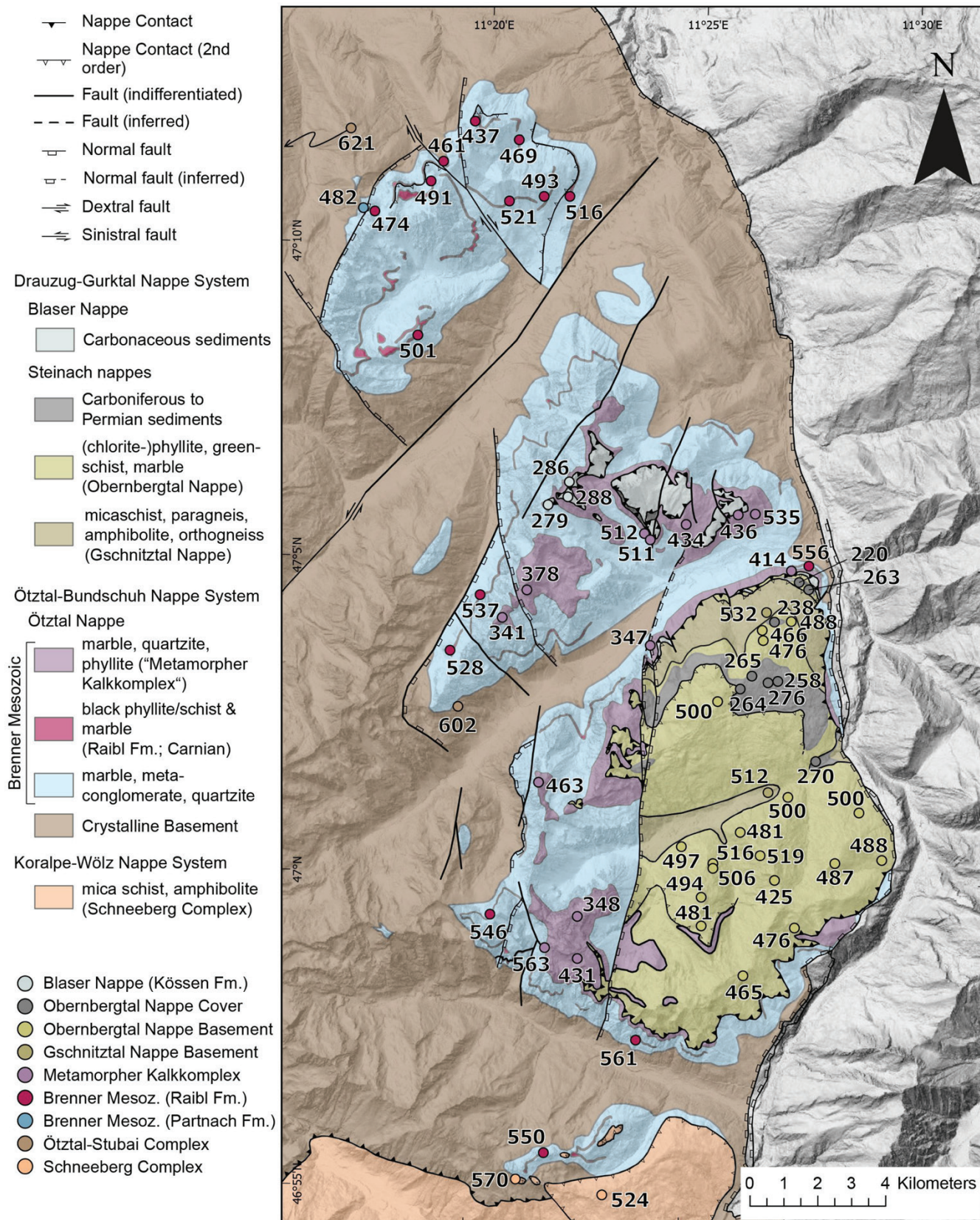


Figure 2: RSCM temperatures (°C) from the Brenner area west of the Tauern Window (not shown). Colored dots represent sample location with color code identical to legend. Geologic map modified from maps.geosphere.at (last access June 2026). Hillshade from basemap.at.

Valley, the nappe is exposed in a narrow zone between the Ötztal and Steinach nappes. The latter consists of a pre-Variscan crystalline basement and a Carboniferous to Permian cover ("Carboniferous of Nösslach"; Krainer, 1990; Rockenschaub et al., 2003; Priewalder and Rockenschaub, 2007). Rockenschaub and Nowotny (2009) separated a micaschist-dominated Gschnitztal Nappe from an overlying phyllite-dominated Obernbergtal Nappe with both nappes indicating Variscan metamorphism of upper greenschist facies conditions and a low-grade overprint (below 300 °C, Rockenschaub et al., 2003). First RSCM data of Lünsdorf et al. (2012) indicated a maximum burial temperature of 300 °C (vitrinite reflectance data showing up to 350 °C) of anthracite bearing Carboniferous cover sediments atop the Obernbergtal Nappe. A transition from Variscan to Late Cretaceous $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite ages (82–95 Ma) is reported from southernmost parts of the Steinach nappes, indicating a gradually increasing thermal overprint of approximately 400 to 450 °C towards the basal contact with the Ötztal Nappe (Reiser, 2008). The tectonic contact with the "Brenner Mesozoic" shows folding (see profiles in Reiser et al., 2010).

2.2. Gurktal nappes

The geological setting of the Gurktal nappes (Fig. 1) largely resembles the setting of the Steinach nappes on the other side of the Oligocene-Miocene Tauern Window (Tollmann, 1963; Schmid et al., 2013). The Gurktal nappes tectonically overlie the Bundschuh Nappe of the Ötztal-Bundschuh Nappe System. Similar to the Brenner area, a Permian to Jurassic sedimentary cover ("Stangalm Mesozoic") was deposited on top of the Bundschuh basement. The Gurktal nappes consist of the "Basal Micaschist Unit", Murau, Ackerl, Pfannock, Königstuhl, and Stolzalpe nappes from bottom to top (Iglseider, 2025). The individual nappes are characterized by different types of early Paleozoic basement rocks and are overlain by remnants of various cover sediments with a stratigraphic range from Pennsylvanian to Eocene (Iglseider, 2025). A RSCM study (Rantitsch et al., 2020) estimated peak temperatures of ca. 410–560 °C in the "Stangalm Mesozoic" of the Bundschuh Nappe, 470–540 °C in the Murau Nappe, 210–240 °C in the Pfannock Nappe, 250–330 °C in the Königstuhl Nappe, 300–320 °C in the basement of the Stolzalpe Nappe, and 230–260 °C in Pennsylvanian sediments (Stangnock Formation) of the Stolzalpe Nappe cover. Vitrinite reflectance and clay mineralogical data evidence an upward decreasing temperature trend in the Permomesozoic sediments (Rantitsch and Russegger, 2000). The reconstructed thermal history includes Variscan metamorphism in the Bundschuh, Pfannock, and Stolzalpe nappes, an increase of the heat-flow during post-Variscan times, and metamorphism during Eoalpine thrusting (Rantitsch et al., 2020).

South of the Lake Wörthersee, low-grade metamorphic (von Gosen et al., 1987) Permian clastics and Lower Triassic dolomites occur in a tectonically isolated posi-

tion ("Mittelkärntner Triaszug" of Kahler, 1953; see also Claassen et al., 1987). In the Viktring area (Fig. 1), Paleozoic metapelites also crop out. Here, they are imbricated with the Permomesozoic sequence and overlie a quartz-phyllite basement (Schünemann et al., 1982). Based on lithostratigraphic and tectonic arguments, von Gosen (1989) suggested that those units tectonically belong to the Gurktal nappes. Iglseider (2019) assigned them to the Basal Micaschist Unit. Eastwards, Murau and Stolzalpe nappe units crop out below Neogene and Quaternary sediments of the Klagenfurt Basin and at the southern slope of the Sausalpe Range (Wiesinger et al., 2006).

Further east, the Remschnigg and Sausal ranges rise below the Neogene sediments of the Styrian Basin and Ribnica Selnica Trough (Fig. 1). A subsurface map (Schreilechner et al., 2026) suggests a pre-Neogene continuity. The units of the Remschnigg Range are interpreted as the easternmost segment of the Gurktal nappes (Neubauer, 1987; Huet, 2018). According to Huet (2018) and map compilations (maps.geosphere.at, last access June 2026) they include from bottom to top amphibolite-facies rocks of the Heiligengeistklamm Nappe (Koralpe-Wölz Nappe System), Paleozoic metasediments of the Murau Nappe, as well as Ordovician (?) to Devonian sediments and volcanics of the Stolzalpe Nappe (Drauzug-Gurktal Nappe System). The stratigraphic top of the Stolzalpe Nappe is formed by a post-Variscan sequence of Pennsylvanian (Stangnock Formation) and Cisuralian (Werchzirm Formation) molasse sediments as well as Norian carbonates (Hauptdolomit Formation), which are covered in turn by Late Cretaceous Gosau sediments. The contact between the Stolzalpe and Heiligengeistklamm nappes is a top-to-the ENE ductile shear zone (Huet, 2018). The Stolzalpe Nappe is also exposed in a small rise in the Styrian Basin, forming the Sausal Range north of the Remschnigg (maps.geosphere.at, last access June 2026). Here, pre-Variscan sediments and volcanics are locally overlain by the Stangnock Formation (Huet, 2018).

2.3. Graz Paleozoic

The Graz Paleozoic (Fig. 1) is built by several nappes assembled during Eoalpine nappe stacking (Fritz, 1988). The Gasen, Schöckel and Gschnaidt nappes overlie nappes of the Koralpe-Wölz Nappe System at its eastern margin (Schuster et al., 2014). They are overlain in more central parts of the Graz Paleozoic by the Hochlantsch and Rannach nappes (Gasser et al., 2010). In an alternative concept, Fritz et al. (1991) divided the nappe stack into the Schöckel Nappe, the Lauffnitzdorf Nappe, the Kalkschiefer (Gschwendt) Nappe, and the Rannach and Hochlantsch nappes at the top. The nappe stack is buried below the Late Cretaceous Kainach Gosau Basin (Neubauer et al., 1995; Kurz and Fritz, 2003), sealing the nappe contacts. Neogene sediments cover the Graz Paleozoic in the south (Styrian Basin) and in the central part (Passail Basin). Along the northwestern margin, the basal thrust has been overprinted by a sinistral strike-slip sys-

Nappe System	Nappe	Formation/Litho- dem/Complex	Temperature °C	Pressure Gpa	Reference	Temperature °C	Pressure Gpa	Time Ma	Reference	Temperature °C	Pressure Gpa	Time Ma	Reference
Drauzug-Gurktal Nappe System	Laufnitzdorf N.	Hackensteiner Fm	510-580	0.8	6	375-425	0.3-0.6	119.2±1.2	3, 6, 3, 6	229.3±2.4			2
	Gschneid N.	Glöselhof Ld								475	0.4	261.3±8.4	3, this study
	Schöckel N.	Hirschkoegel Ld								500-530	0.2-0.4	275.2±6.2	3, this study
		Schöckel Fm											
	Gasen N.	Raasberg Fm											
		Heilbrunn Fm	450-500	0.6	1	440-480	0.4-0.8	108.8±6.6					
Koralpe-Wölz Nappe System	Waxenegg N.	Rossegg C	580±20	0.8	4	550	1.0-1.1	87.3±1.2	3	560	0.4	283-256	3, this study
								76.8±0.8	6				
	Radegund N.	Rappold C	580		1	580-620	0.8-1.2	78.7±0.8	5, 6			275±11	5
	Exenberg N.	Wölz C				550±30	0.1	88±10	5			267±10	5

Table 1: Eoalpine (Cretaceous) and Permian pressure-temperature-time data from the Graz Paleozoic and underlying units from Bojar et al. (2001: 1), Henjes-Kunst et al. (2014: 2), Hollinetz et al. (2024: 3), Krenn et al. (2008: 4), Rögglä (2007: 5), Schantl et al. (2015: 6).

tem during Late Cretaceous to Eocene subsidence of the Kainach Gosau Basin (Neubauer et al., 1995). At the south-eastern margin, the footwall thrust was overprinted by a polyphase fault system of the same age (Krenn et al., 2008).

The Graz Paleozoic comprises Silurian to Carboniferous shelf sediments (Flügel, 2000; Gasser et al., 2010; Piller, 2014). Basal siliciclastics and basic metavolcanics are overlain by Devonian to Mississippian shallow to deep-water sediments (predominantly carbonates), and a Bashkirian shallow-water sequence at the top. They were metamorphosed to a very-low- to low-grade rank (Hasenhüttl and Russegger, 1992). Problems in the understanding of the timing of the metamorphic history were raised due to missing post-Variscan cover sequences and a lack of modern geochronological data, which prevent a clear distinction between Variscan and Eoalpine events (see the review of Gasser et al., 2010). Major progress was achieved however, by (1) mapping RSCM temperatures in the Schöckel Nappe, detecting a metamorphic field gradient (Rantitsch et al., 2005), (2) deciphering the tectonic and fluid evolution along the eastern margin of the Graz Paleozoic constraining Eoalpine tectonics (Bojar et al., 2001; Krenn et al., 2008), (3) establishing a tectonic concept explaining the sedimentary facies architecture of the nappe stack (Gasser et al., 2010), and (4) presenting modern petrological and geochronological data from the tectonic deep nappes (Rögglä, 2007; Henjes-Kunst et al., 2014; Schantl et al., 2015; Hollinetz et al., 2024; Tab. 1). As a result, Permian and Eoalpine metamorphism in units underlying the Graz Paleozoic, and thermal effects due to Late Cretaceous exhumation of units are now well constrained. In contrast, there are no clear hints for a Variscan overprint, but indications are given by K/Ar and Rb/Sr mixing ages of white micas (Gasser et al., 2010), and by sedimentological and paleontological evidence of Carboniferous tectonics (Ebner, 1976). The sedimentary record of the Graz Paleozoic shows similarities to the Bükk and Drina Ivanica units of the Pannonian and Dinaric realms respectively, which were located at the distal shelf

of the Neotethys ocean (Ebner et al., 2008; Vozárová et al., 2009). Those units lack a Variscan imprint and were probably situated in the foreland of the Variscan orogen belt.

2.4. Drau Range

Permian to Cretaceous cover sequences of the Drauzug-Gurktal Nappe System are exposed by an almost complete stratigraphic record in the Lienz Dolomiten Range, Gailtal Alps, and North-Karawanken Range (Figure 1). Individual tectonic units (Lienz Nappe, Dobratsch Nappe, Kreuzeck-Goldeck-Gailtal Nappe sensu Schuster et al., 2015 and North-Karawanken Range) defined by Lein et al. (1997) are separated by thrusts and major Miocene strike-slip faults. Mississippian sediments are exposed at the base of the Dobratsch Nappe ("Carboniferous of Nötsch"; Schönlaub, 1985) at the southern margin of the Drau Range Permomesozoic. Whereas over wide areas, Permomesozoic units tectonically overlie the Variscan basement, a stratigraphic contact to the post-Variscan cover has been mapped in the Goldeck Range (Schuster et al., 2006). Here, the Strieden, Gaugen and Goldeck complexes together with the Drau Range Permomesozoic at the top expose a section through the Permomesozoic middle and upper crust, characterized by Variscan upper greenschist and Permo-Triassic HT-LP metamorphism in the basement (Schuster et al., 2001, 2015; Griesmeier et al., 2019). Permian to Lower Triassic cover sediments indicate very-low grade metamorphic conditions (Niedermayr et al., 1984). The Permomesozoic stratigraphical record includes Permian to Early Triassic red beds (Alpine Buntsandstein Formation), Anisian shallow-water carbonates, Ladinian to Carnian platform carbonates (Wetterstein Formation), Ladinian intraplateau sediments (Partnach Formation), Carnian mixed carbonates and siliciclastics (Raibl Formation), Norian lagoonal dolomites, Rhaetian basinal shales (Kössen Formation), Liassic (Hettangian) to Lower Cretaceous (Valanginian) hemipelagic basin sediments, and Aptian to Albian flysch sediments (Bechstädt et al., 1976; Bech-

städt, 1978; Schmidt et al., 1991; Haas et al., 1995). Former work to decipher the thermal history of this unit included Kübler-Index data (Niedermayr et al., 1984), Conodont Alteration Indices (Lein et al., 1997), clay mineralogical data (Rantitsch, 2003a), vitrinite reflectance data (Rantitsch, 2001; Rantitsch and Rainer, 2003), fluid inclusion data (Niedermayr et al., 1984; Rantitsch et al., 1999; Rantitsch, 2003b), and organic geochemical data (Bechtel et al., 2001). The peripheral segments of the Drau Range (Lienz Dolomiten Range, eastern Gailtal Alps, North-Karawanken Range) show vitrinite reflectance values explained by Permomesozoic sedimentary burial (Rantitsch, 2001; Rantitsch and Rainer, 2003). Furthermore, a broad vitrinite reflectance anomaly was detected in the central Gailtal Alps (Rantitsch, 2001), explained by an overprinting thermal event. Melcher et al. (2023) included lead-zinc mineralization as an important event of the reconstructed thermal history.

3. Samples

In this study, new RSCM data from the Schneeberg Complex, Ötztal Nappe, Blaser Nappe, and Steinach nappes (Brenner area), Stolzalpe and Heiligengeistklamm nappes (Remschnigg and Sausal), Graz Paleozoic (Grazer Bergland), as well as Lienz, Dobratsch and Kreuzeck-Goldeck-Gailtal nappes (Gailtal Alps, Goldeck, and Kreuzeck Mountains) are presented. Data from the Viktring area together with data from the North-Karawanken Range (Eisenkappel area) and the area in between are used to pinpoint the tectonic affiliation of the “Mittelkärntner Triaszug” in the Viktring area and to investigate the thermal imprint at the south-eastern margin of the Drauzug-Gurktal Nappe System. All samples are dark colored metapelites and carbonates. To use a common calibration frame, data from the Graz Paleozoic include new estimates from samples already analyzed by Rantitsch et al. (2005). The Drau Range data include samples from the vitrinite reflection study of Rantitsch (2001), correlating two parameters of organic metamorphism.

4. Methods

The presented temperature data are based on Raman spectroscopy of carbonaceous material (RSCM), applying the IFORS method of Lünsdorf et al. (2017) as explained in Rantitsch (2024):

RSCM investigates the interaction of laser light with carbonaceous material (CM) in inelastic scattering giving a spectrum, which assesses the state of structural order (see Lünsdorf, 2016 for a review). The CM order is related irreversibly to peak metamorphic temperatures (see Henry et al., 2019 for a review). CM from the metasediments of this study was concentrated by an acid (HCl and HF) treatment of crushed sample material. A Horiba Labram HR Evolution instrument, equipped with a 100 mW Nd:Yag (532 nm) laser, a confocal microscope (100x

objective with a 0.80 numerical aperture and a confocal hole aperture of 100 μm), a 1800 g/mm grating, and a Peltier cooled CCD detector was used to collect Raman spectra. Filters to minimizing the output laser power to <1mW were used to avoid any sample damage. The wavenumbers were calibrated with the Rayleigh scattering (0 cm^{-1}), and a silicon wafer (520.7 cm^{-1}). 20 spectra per sample over the 700–2000 cm^{-1} spectral region were collected, evaluated by the IFORS software of Lünsdorf and Lünsdorf (2016), which excludes subjectivity in curve-fitting (Lünsdorf et al., 2014), and characterized by median spectral parameters of Lünsdorf et al. (2017). In particular, the D-STA parameter (total area, scaled by the maximum intensity in the D-band region) reliably describes the evolution of dispersed organic matter during coalification and graphitization (Lünsdorf 2016, Lünsdorf and Lünsdorf 2016; Lünsdorf et al., 2017). Metamorphic peak temperatures were calculated from a calibration function established by spectral data collected on standard samples (Lünsdorf et al., 2017), as described above.

All data are presented in the supplementary Tables 1–4. The given uncertainty of the temperature estimates of 25–30 °C (supplementary tables) is controlled primarily by the uncertainty of the (petrologically determined) uncertainty of the used calibration sample set (Lünsdorf et al., 2017).

Vitrinite reflection is used to correlate the study data from the Drau Range with an additional parameter of organic metamorphism. It is a widely applied index of organic metamorphism, used to assess the molecular order of organic matter in coal and organic-rich pelites from the percentage of reflected light measured on vitrinite macerals (e.g. Pusz et al., 2014).

5. Results

5.1. Brenner Area (Schneeberg Complex, Ötztal Nappe, Blaser Nappe, and Steinach nappes)

Two samples from different structural levels of the Schneeberg Complex yield peak temperatures of 524 ± 34 and 570 ± 29 °C. Sample 21MR036 was taken from garnet-bearing graphite-phyllites intercalated with calcite marble and hornblende schists from a tectonically emplaced lens on top of carbonates of the “Brenner Mesozoic”, whereas 19MR-007-001 was sampled from monotonous garnet and graphite bearing phyllites in a central position.

Samples from the Ötztal Nappe were collected in the crystalline basement and the Permomesozoic cover. Two samples of the pre-Mesozoic crystalline of the Ötztal Nappe indicate a thermal peak at about 600 °C. The dataset from the “Brenner Mesozoic” comprises samples mainly from the schists and phyllonites of the Raibl Formation (with one sample coming from the Partnach Formation). The basal rocks of the “Brenner Mesozoic” were metamorphosed (with few local deviations) at c. 440–570 °C with a southward increasing temperature

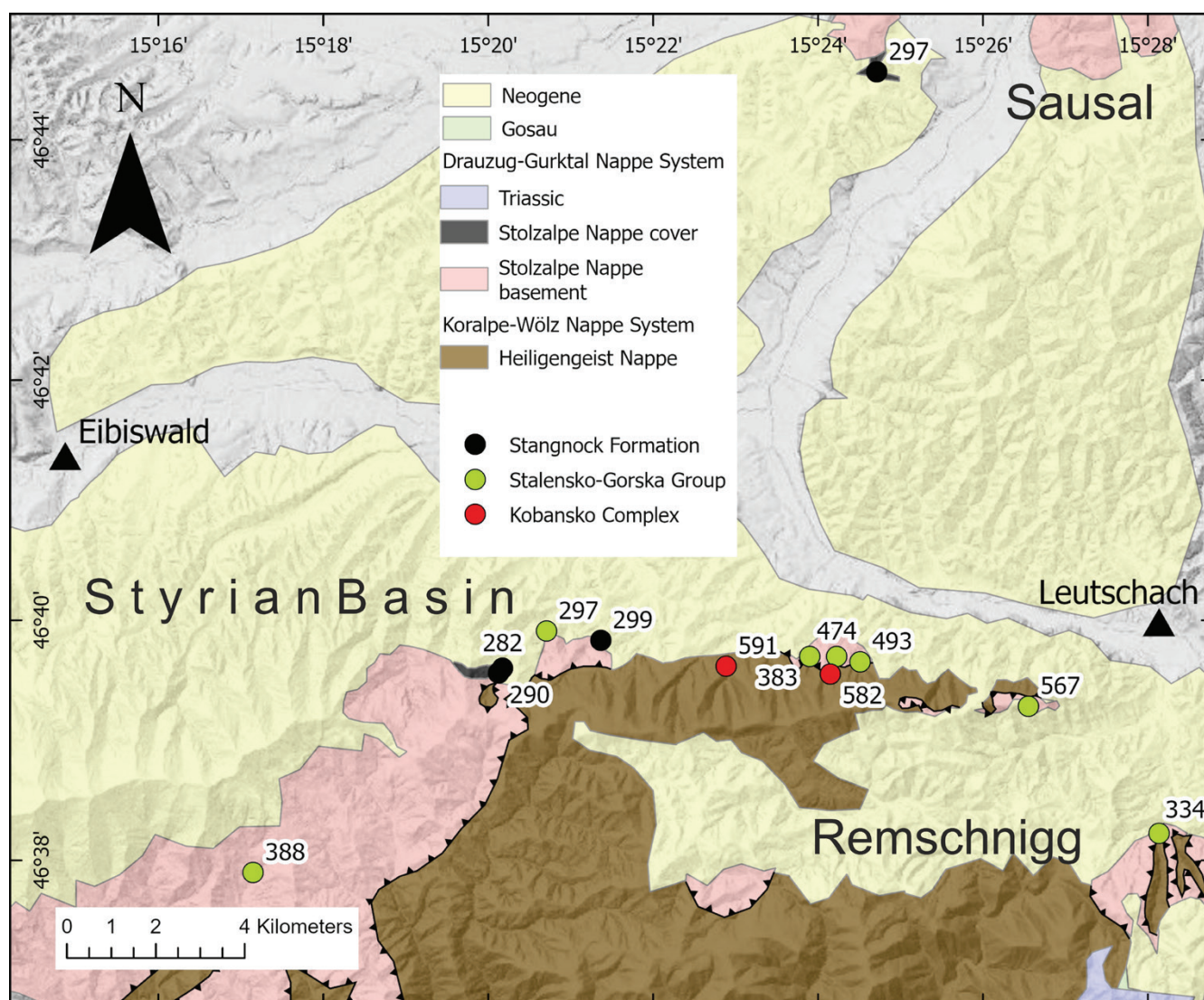


Figure 3: RSCM temperatures (°C) in the Remschnigg and Sausal ranges. Geologic map simplified from maps.geosphere.at (last access June 2026) and the “Basic geological map of Slovenia 1:100 000” (Geological Survey of Slovenia, <https://ogk100.geo-zs.si/>, last access June 2026). The hillshade is from basemap.at. The Pennsylvanian Stangnock Formation is the post-Variscan cover of the Stalensko-Gorska Group, which overlies tectonically the Kobansko Complex of the Koralpe-Wölz Nappe System. Colored dots represent sample location with color code identical to legend.

trend (supplementary Tab. 1, Fig. 2). Samples from various lithologies of the “Metamorpher Kalkkomplex” yielded a larger thermal range of 340–560 °C.

The dataset from the Steinach nappes is grouped into the Gschnitztal Nappe, the Obernbergtal Nappe and its Carboniferous to Permian cover. Samples from the crystalline basement of the Obernbergtal Nappe show a range from 466 to 519 °C with one outlier, a graphitic quartzite from a southern part of the Obernbergtal Nappe which gave a temperature of 425 °C. Two samples from the Gschnitztal Nappe show a thermal overprint around 500 °C. Samples from the Carboniferous to Permian cover of the Obernbergtal Nappe provide a range of 240 to 276 °C. However, two samples from Carboniferous to Permian cover sediments in a tectonic sliver near Steinach show slightly lower temperatures of 220 and 260 °C.

In the Blaser Nappe three samples of the Kössen Forma-

tion in the surrounding of the Kesselspitze peak (2.728 m) indicate a thermal overprint of c. 290 °C (supplementary Tab. 1, Fig. 2).

5.2. Remschnigg, Sausal, and Viktring areas (Gurktal nappes)

RSCM data (supplementary Tab. 2, Fig. 3) map a metamorphic break between the Heiligengeistklamm and Stolzalpe nappes. Temperatures of c. 570–580 °C are estimated in the Heiligengeistklamm Nappe, whereas the Stolzalpe Nappe is characterized by temperatures of c. 300–390 °C, without difference between pre- and post-Variscan strata. SW of Leutschach, two samples just above the thrust between the Heiligengeistklamm and Stolzalpe nappes record significantly higher temperatures of c. 475–495 °C (Fig. 3).

Samples from the Viktring rocks reveal RSCM temperatures between c. 530 °C and 580 °C (supplementary Tab. 2, Fig. 4). Data between c. 460 °C and 480 °C from Paleozoic schists of the tectonic hanging wall indicate a metamorphic break in-between. A further hiatus is observed at the thrust contact to Permian clastics and Lower Triassic dolomite, characterized by RSCM temperatures of ca. 310 °C (Fig. 4).

East of Viktring, a sample from the Stolzalpe Nappe yielded temperature of ca. 360 °C (supplementary Tab. 2). Samples from the Phyllite Unit of the Saualpe (correlated to the Murau Nappe by Wiesinger et al., 2006) reveal 544 and 591 °C (supplementary Tab. 2).

5.3. Grazer Bergland (Graz Paleozoic)

The RSCM temperature (supplementary Tab. 3) maps presented in Figure 5 cover the entire Graz Paleozoic, including parts of the deeper nappes at the eastern margin. Samples from the Waxenegg Nappe (Koralpe-Wölz Nappe System) show temperatures of c. 550–570 °C. In the Graz Paleozoic, c. 520 °C to 560 °C are measured in the basal Gasen Nappe. For the Schönberg Formation of the Schöckel Nappe, the map indicates a concentric isotherm pattern with a temperature maximum of c. 520 °C at the southeastern margin. In this area, an estimate of 539 °C in the stratigraphically lower Raasberg Formation and temperatures of c. 450–500 °C in samples of the stratigraphically higher Hirschkogel Lithodeme constrain a stratigraphic upward trend of decreasing temperatures (see Hollinetz et al., 2024). Metamorphic temperatures higher than 500 °C were already proposed for the overlying Gschnaidt Nappe due to the occurrence of garnet and ductile dolomite marbles (Schantl et al., 2015). At the northern margin, the tectonically deepest parts (Kalkschiefer Nappe sensu Fritz et al., 1991) show temperatures of c. 480 °C to 520 °C. Samples from the higher nappes (Laufnitzdorf and Kalkschiefer nappes sensu Fritz et al., 1991 and the overlying Hochlantsch Nappe) are characterized by upward decreasing temperatures of c. 360 °C to 300 °C, indicating a temperature gap of c. 150 °C towards the Gasen Nappe beneath. In the south, c. 290–320 °C is measured in the Rannach Nappe. Samples from the western margin of the Graz Paleozoic indicate RSCM temperatures higher than 550 °C.

5.4. Drau Range

RSCM temperatures from the Goldeck and Kreuzeck Mountains range between c. 540 and 600 °C (Fig. 6, supplementary Tab. 4), which agrees with previous estimates based on petrology (Schuster et al., 2001; Griesmeier et al., 2019). A slice of Permian metasediments squeezed in a negative flower structure along a shear zone (Griesmeier et al., 2019) at Gnoppnitztörl yields a temperature of 375 °C. A further sample from the “Eisenkappel Crystalline” of the North-Karawanken Range yields 500 °C (supplementary Tab. 4). Significantly lower temperatures of 315–330

°C were estimated in samples from the adjacent Paleozoic “Eisenkappel Diabase Zone” (supplementary Tab. 4). The “Carboniferous of Nötsch” at the southern margin of the Gailtal Alps yielded a temperature of ca. 260 °C.

RSCM temperature estimates from the Drau Range Permomesozoic (supplementary Tab. 4) offer deeper insight into the thermal structure of the Drauzug-Gurktal Nappe System cover section. The map pattern (Figure 6) shows stratigraphically upward decreasing values, obvious also if thermal indices are plotted in vertical pseudosections of representative key areas (Fig. 6c). As a particular feature, the data outline an area of high temperatures centered at the northern margin of the Gailtal Alps (Fig. 6). A maximum temperature of 250 °C is estimated in Permian sediments close to the basal tectonic boundary in the center of the anomaly. The temperatures in Triassic strata decrease continuously towards the southeast, approaching 160 °C in the Raibl Formation of the eastern Gailtal Alps, the lower calibration limit of the used method. This temperature corresponds to a vitrinite reflectance of ca. 1.0 %Ro (Fig. 6). Consequently, in the eastern segment of the Drau Range including the North-Karawanken Range (Rantitsch and Rainer, 2003), the Raibl Formation was heated below 160 °C. A slightly higher temperature of c. 160–220 °C characterizes the same stratigraphic unit in the Lienz Nappe.

6. Discussion

The presented RSCM temperature dataset covers most tectonic units of the Drauzug-Gurktal Nappe System and several nappes below (Fig. 7). These were segments of the Tethyan shelf from Triassic to Late Jurassic times that experienced a long and complex geological history (e.g., Froitzheim et al., 2008; Kurz et al., 2024). The lower Paleozoic units of most of the studied units experienced a Variscan (Carboniferous) tectonometamorphic event and major parts were also heated during a period of crustal anatexis during Permian to Early Triassic times (Schuster and Stüwe, 2008; Knoll et al., 2023). In post-Variscan times they were buried below Permomesozoic cover sediments. Exceptions are the Graz Paleozoic and the underlying nappes of the Koralpe-Wölz Nappe System where the first documented imprint is Permian in age. Dissection of the margin started in the latest Jurassic. Eoalpine (Cretaceous) thrusting and Paleogene to Neogene extension further displaced the former continuous facies belt. For deciphering Eoalpine thermal imprint we first focus on post-Variscan cover sediments to exclude potential pre-Alpine thermal imprint. Second, we report on temperature ranges within individual nappes and across individual nappes to see the effect of Eoalpine tectonics.

6.1. The thermal imprint of the Drauzug-Gurktal Nappe System cover

The cover sections in the Austroalpine Unit are post-Variscan sequences on top of the Austroalpine crys-

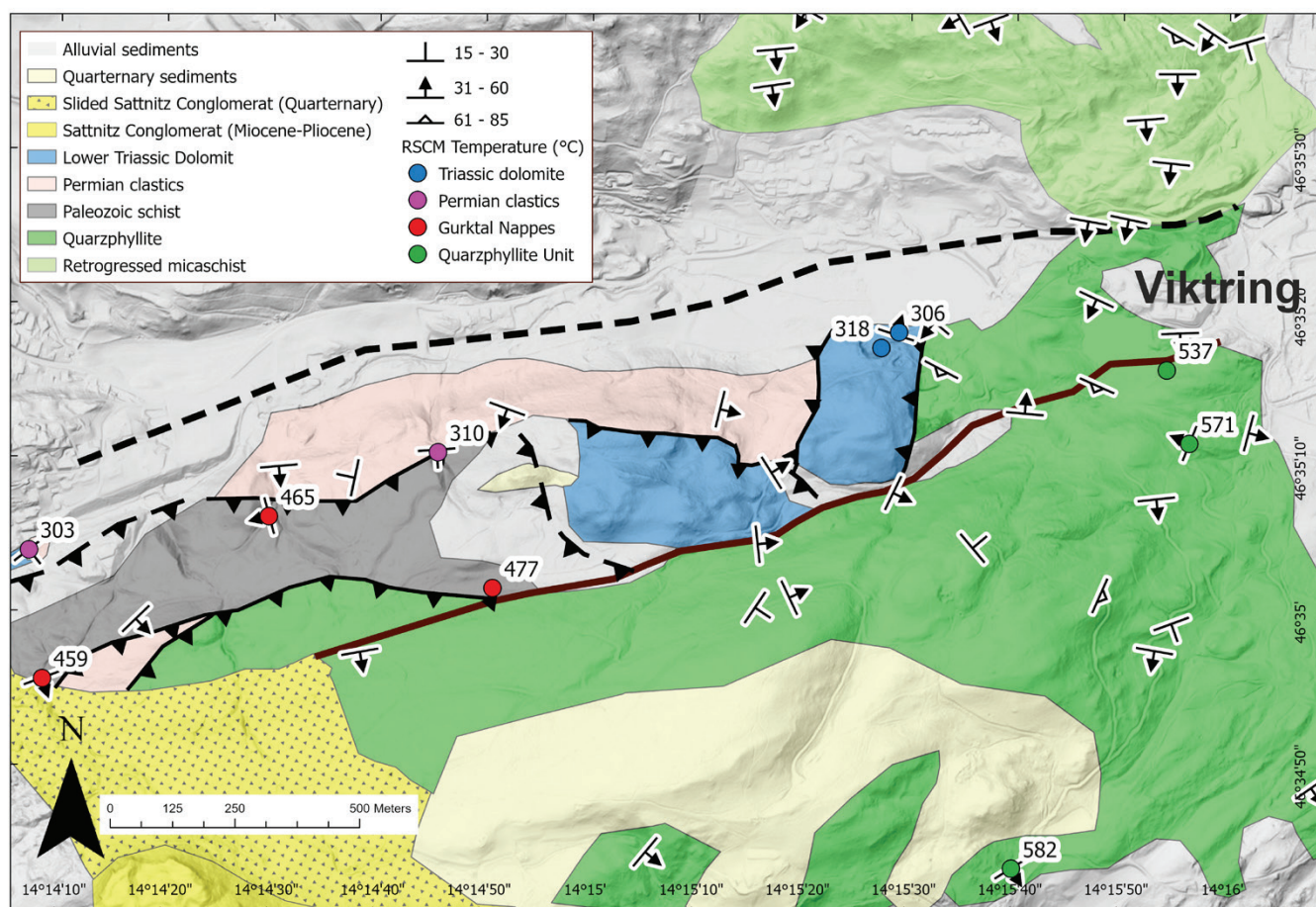


Figure 4: RSCM temperatures (°C) in the Viktring area. The hillshade is from basemap.at. Colored dots represent sample location with color code identical to legend.

talline. All the rocks from these units investigated here are Pennsylvanian to Triassic and could have potentially experienced a thermal overprint related to the Permian extensional event, the Eoalpine orogenic event and/or later orogenic events. We consider the imprint of each event from youngest to oldest.

A large enigmatic thermal anomaly is seen in the central Gailtal Alps (Fig. 6). Crosscutting relationships with stratigraphic boundaries and Eoalpine tectonic structures point to a post-Cretaceous overprint of the Permomesozoic sequence. Oligocene magmatism might provide an explanation (Rantitsch et al., 1999; Rantitsch, 2001), related age data of metamorphism are however missing.

The data from the cover sequence of the Ötztal Nappe constrain Eoalpine lateral and vertical thermal gradients. "Horizon-consistent" temperature data from the Raibl Formation yield a thermal increase from approx. 440 °C in the north to 570 °C in the south. These temperature estimates are in good agreement with published data from calcite-dolomite thermometry (Dietrich, 1983; Frank et al., 1987) and thermobarometric data from post-Variscan basic intrusions (Raso et al., 2025). The geometric pattern corresponds to an Eoalpine ESE-ward increasing thermal overprint. However, since most of the presented

samples are not aligned along a WNW-ESE trending section, the results only represent a small part of the overall gradient. The temperature range determined in the "Brenner Mesozoic" is similar to the one in the "Stangalm Mesozoic s.l." (410–560 °C, Fig. 7, Rantitsch et al., 2020), also from the Ötztal Bundschuh Nappe System. The data from the "Metamorpher Kalkkomplex" reveal a large thermal range of about 220 °C that does not conform to the ESE-directed thermal gradient of the basal parts of the "Brenner Mesozoic". This anomalous thermal pattern may be related to a previously recognized shear zone in this area (Fügenschuh et al., 2000) and its interpretation is discussed later.

Although often considered "non-metamorphic", the Blaser Nappe experienced an Eoalpine imprint just below 300 °C. Permian to Carboniferous sediments from a tectonic sliver south of the Gschnitz Valley yield roughly similar thermal conditions of 220–260 °C. Thermal data from the Permian to Carboniferous cover of the Obernbergthal Nappe evidence a thermal overprint of 240–280 °C, showing good agreement with RSCM data from Lünsdorf et al. (2012). Together with vitrinite reflectance data from Lünsdorf et al. (2012), the Eoalpine overprint of the Blaser Nappe and the cover of the Steinach nappes is limited to less than 350 °C. These temperatures are similar

to those of the corresponding Pennsylvanian to Triassic units in the Gurktal nappes (210–330 °C, Fig. 7, Rantitsch et al., 2020). RSCM temperatures of c. 200 to 300 °C have also been measured in the Permian of the “Drau Range Permomesozoic”, in the “Carboniferous of Nötsch” (in the lower range of the conditions determined by Zanoni et al., 2022), in the Permian and Triassic rocks of Viktring as well as in the Stangnock Formation of the Remschnigg and Sausal areas. All these temperatures are considered to be linked to the Eoalpine orogenic event. The higher temperatures of c. 330 to 360 °C in the Königstuhl Nappe and the Permo-Mesozoic of Viktring indicate metamorphism at a slightly higher grade.

As RSCM data of this study as well as other temperature indicators (Rantitsch and Russegger, 2000) from the Permo-Mesozoic cover constrain an upright temperature gradient (Figure 6), burial heating during Mesozoic to Cenozoic times is evidenced. The RSCM temperature of the “Carboniferous of Nötsch” also fits into this trend (Rantitsch, 1995). The onset of post-Variscan subsidence was influenced by a high heat-flow related to Permo-Triassic lithospheric extension, which has been verified by thermal subsidence modeling of the cover (Rantitsch et al., 2020) and is consistent with a wealth of data from rocks below (Knoll et al., 2023, and references therein).

6.2. The thermal imprint of the Drauzug-Gurktal Nappe System basement

The case of basement units is more difficult to deal with, as they could additionally have experienced Variscan metamorphism. In the Schneeberg Complex, the RSCM temperature range of 520–570 °C is consistent with published estimates for the Eoalpine imprint, which is the only metamorphic event that has been identified in this unit so far (Konzett and Hoinkes, 1996; Sölva et al., 2005; Pedevilla and Tropper, 2012; Tual et al., 2025). This range is therefore considered as Eoalpine.

RSCM data of 600 to 620 °C from the Ötztal Nappe surpass the Eoalpine thermal overprint, particularly in the northwestern part of the study area (Raso et al., 2025). We therefore interpret these results as Variscan peak temperatures, as they are just slightly higher than the established Variscan temperature estimates of 550–600 °C (e.g. Tropper and Hoinkes, 1996; Thöni et al., 2008; Schulz et al., 2019). In the crystalline basement of the Steinach nappes, syn- to post-Variscan $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite ages (311–321 Ma; Rockenschaub et al., 2003) allow the attribution of the RSCM temperatures (470–530 °C) to the Variscan orogeny. Only in the southernmost, basal parts of the Obernbergtal Nappe, where Eoalpine thermal conditions were sufficient to fully reset $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite ages (Reiser, 2008), the unequivocal distinction between Eoalpine and Variscan overprint is made more difficult. RSCM temperatures from the Goldeck and Kreuzeck Mountains ranging between c. 540 and 600 °C (supplementary Tab. 4) are in agreement with previous Variscan estimates based on petrology (Schuster et al.,

2001; Griesmeier et al., 2019) and therefore considered as Variscan.

Because of missing post-Variscan cover strata and the complex geometry of the nappe stack, the data from the Graz Paleozoic and underlying units are of particular interest. Despite incomplete stratigraphic evidence, the thermal imprint of the (Carboniferous) top strata of the Rannach Nappe might be explained by Carboniferous to Eocene sedimentary burial as described above. RSCM temperatures of those sediments resemble the temperatures from post-Variscan molasse sediments, outcropping in the Sausal and Remschnigg Ranges south of it (see above). The RSCM temperature estimates of the Waxenegg and Gasen nappes are in accordance with data of Bojar et al. (2001) and Schantl et al. (2015). Poly-metamorphism in the Waxenegg Nappe (Koralpe-Wölz Nappe System) is dated as Permian and Eoalpine (Schantl et al., 2015; Hollinetz et al., 2024). The Gasen Nappe at the northeastern margin of the Graz Paleozoic shows RSCM temperatures of c. 500–550 °C. Data from the overlying Schöckel Nappe indicate here a metamorphic break. Small nappe fragments at the northern margin of the Graz Paleozoic show consistent temperatures. Major parts of the Schöckel Nappe are characterized by a RSCM temperature field gradient with a temperature maximum of ca. 520 °C at its southern margin and a temperature minimum of ca. 300 °C at its northern margin. The Rannach and Hochlantsch nappes show consistent RSCM temperatures of c. 290–320 °C. The break in metamorphism between Schöckel Nappe and Rannach Nappe (detected already by Neubauer, 1989) at the Leber Fault (Fig. 5) is explained by the local Permian overprint of the Schöckel Nappe (Hollinetz et al., 2024), not seen in the overlying Rannach Nappe. Extraordinarily high temperatures are observed in the west, at the contact with underlying rocks (see also Rantitsch and Lünsdorf, 2016). Their tectonic interpretation is discussed later.

6.3. The temperature gap between basement and cover

As the grade of Variscan metamorphism, the thickness of the Permomesozoic sedimentary overburden, as well as the imprint of Eoalpine tectonics may provide paleogeographic evidence, RSCM temperatures from the Variscan basement are compared to values estimated from the post-Variscan cover rocks (Fig. 7). The relationships observed within a specific unit provide insight into the relative strength of metamorphic events (Variscan vs. post-Variscan metamorphism). Furthermore, the comparative view of the study data (Fig. 7) including the investigated Koralpe-Wölz and Ötztal-Bundschuh nappe systems provides another approach visualizing former paleogeographic relationships.

Three types of pre- to post-Variscan basement units are distinguished (Fig. 7). The basement of the Ötztal, Bundschuh, Steinach and Kreuzeck-Goldeck-Gailtal areas experienced greenschist to amphibolite facies meta-

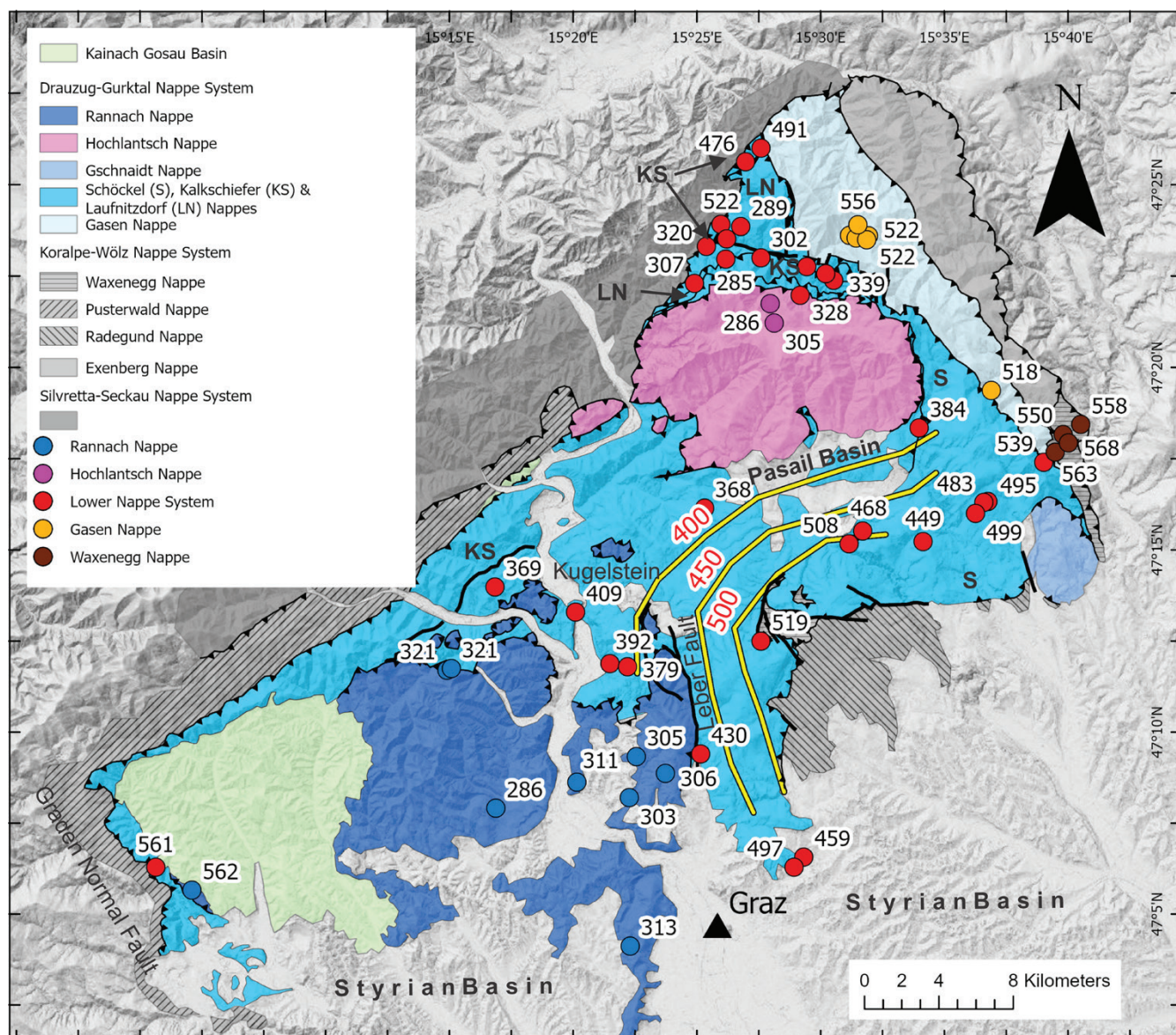


Figure 5: RSCM temperatures (°C) in the Graz Paleozoic. Colored dots represent sample location with color code identical to legend. The map includes RSCM data from samples of Rantitsch et al. (2005) based on a calibration valid for all map data and shows data of Hollinetz et al. (2024). Geologic map simplified from maps.geosphere.at (last access June 2026) using the tectonic model of Gasser et al. (2010). Fritz et al. (1991) discriminated the Schöckel Nappe, Kalkschiefer Nappe and the Laufnitzdorf Nappe of the “Lower Nappe System”. Hillshade is from basemap.at. Isotherms (yellow lines) contour the RSCM temperatures estimated for the Schönberg Formation. A slightly higher temperature than the mapped isotherms at the Kugelstein locality is explained by extensive shearing (Fritz, 1988) of the analyzed sample.

morphism during the Variscan orogeny. In contrast, the basement of the Stolzalpe Nappe only experienced lower greenschist facies conditions at the same time. The third group composed of the metasediments of the Graz Paleozoic has no evidence of Variscan metamorphism, but instead recorded sedimentation of clastic material produced by the Variscan orogeny in Carboniferous flysch-like sediments (Neubauer et al., 2007).

A gap of RSCM temperature between the basement and the cover is recorded in most investigated nappes (Fig. 7). This first holds for the Ötztal and Bundschuh nappes in the footwall of the Drauzug-Gurktal Nappe System. In the Drauzug-Gurktal Nappe System, a gap

of 150 to 300°C is evidenced between crystalline basement and cover in the Steinach nappes. At the base of the Kreuzeck-Goldeck-Gailtal Nappe in the Drau Range (Schuster et al., 2001), a Variscan temperature of ca. 560 °C is estimated for the garnet-bearing Gaugen Complex, which is higher than 375 °C in the overlying Permian metasediments squeezed in a negative flower structure along a shear zone at Gnoppnitztörl (Griesmeier et al., 2019). A similar pattern occurs between the basement of the Goldeck Complex (c. 560 °C) and its Permomesozoic cover (150–230 °C). The RSCM temperature of 500 °C in the “Eisenkappel Crystalline” of the North-Karawanken Range also indicates a temperature gap with respect to

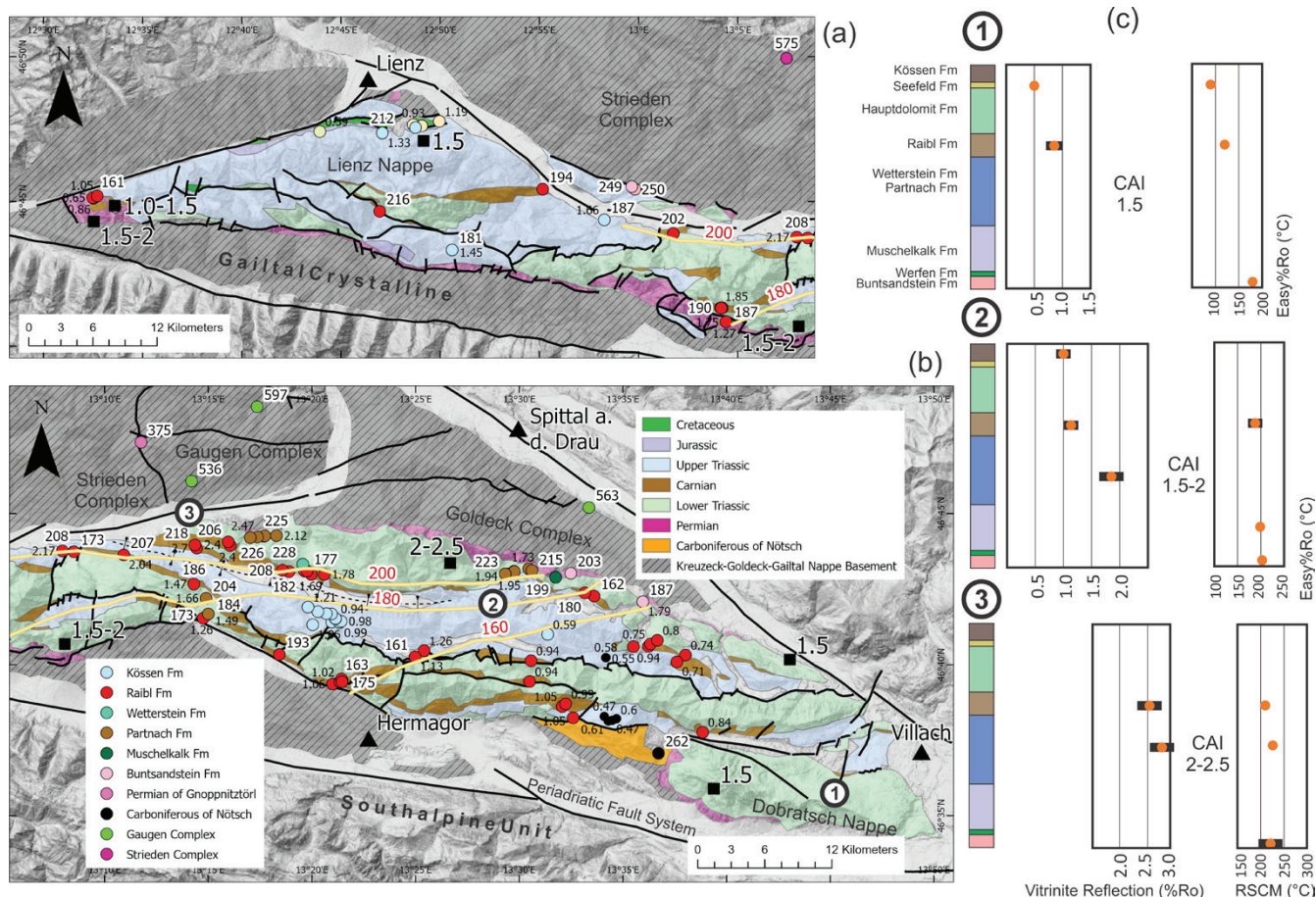


Figure 6: RSCM temperatures (°C) estimated in different stratigraphic levels (point colors) with contoured field gradient (yellow lines) for the Carnian Raibl Formation in the western (a) and eastern (b) Drau Range, extended by vitrinite reflectance data (small numbers, rising numbers indicate higher temperatures, see c) of Rantitsch (2001) and the CAI data (black squares) of Lein et al. (1997). The circled numbers 1–3 refer to the stratigraphic pseudosections of ca. RSCM data from the units below are also shown. Geologic map simplified from maps.geosphere.at (last access June 2026). Hillshade is from basemap.at. (c) Vitrinite reflection (%Ro) and modelled burial temperatures (Easy%Ro) from Rantitsch (2001), Conodont Alteration Index (CAI) data of Lein et al. (1997) and RSCM temperatures of this study in stratigraphic pseudosections of the Drau Range Permomesozoic, representative for three key areas (see b for the profile area locations) showing stratigraphic temperature trends which increase from the eastern segment of the Drau Range (section 1) to the central segment (section 3).

the low-grade cover. A slightly lower gap occurs in the Stolzalpe Nappe with 300–320 °C in the basement and 230–260 °C in Pennsylvanian cover sediments (Rantitsch et al., 2020). Notice that this gap cannot be determined by field or microscope observations, showing how insightful the RSCM method can be. Finally, the Paleozoic and Mesozoic metasediments of Viktring are thrust upon Eoalpine metamorphosed rocks (Neubauer et al., 2018). They are strongly imbricated and therefore of uncertain tectonic position. In respect to their peak metamorphic temperatures, there is no correspondence to lower values of adjacent Stolzalpe Nappe outcrops and higher values of adjacent outcrops of the Phyllite Unit of the Saualpe (Murau Nappe). Data from basement rocks correspond to data from the Basal Micaschist Unit of the Saualpe with both Permian and Eoalpine mineral assemblages (Moser, 2025). However, the contact to the Paleozoic and Mesozoic metasediments above is also characterized by a temperature hiatus that could be similar to those described above. All these gaps indi-

cate that in the mentioned units, the grade of Variscan metamorphism was higher than the grade of Eoalpine metamorphism.

In contrast, no temperature gap between cover and basement could be determined in the Carnic Alps, South-Karawanken Range, Dinarides (Rantitsch and Rainer, 2003; Rainer et al., 2009, 2016; Rantitsch, 2024) and in the Stolzalpe Nappe of the Remschnigg and Sausal areas (Fig. 7), thus providing a hint to relate those units with the Graz Paleozoic to the Southalpine unit (Gollner et al., 1987; Massari et al., 2024). This is particularly interesting as, on the one hand, the units of Carnic Alps and South-Karawanken Range were initially adjacent to those of the North-Karawanken Range and, on the other hand, the Stolzalpe Nappe presents a temperature gap in the Gurktal Alps. These differences together with the three types of basement units in Drauzug-Gurktal Nappe System mentioned above indicate that the continental crust was already strongly segmented in units with very different characteristics with respect to the Variscan imprint

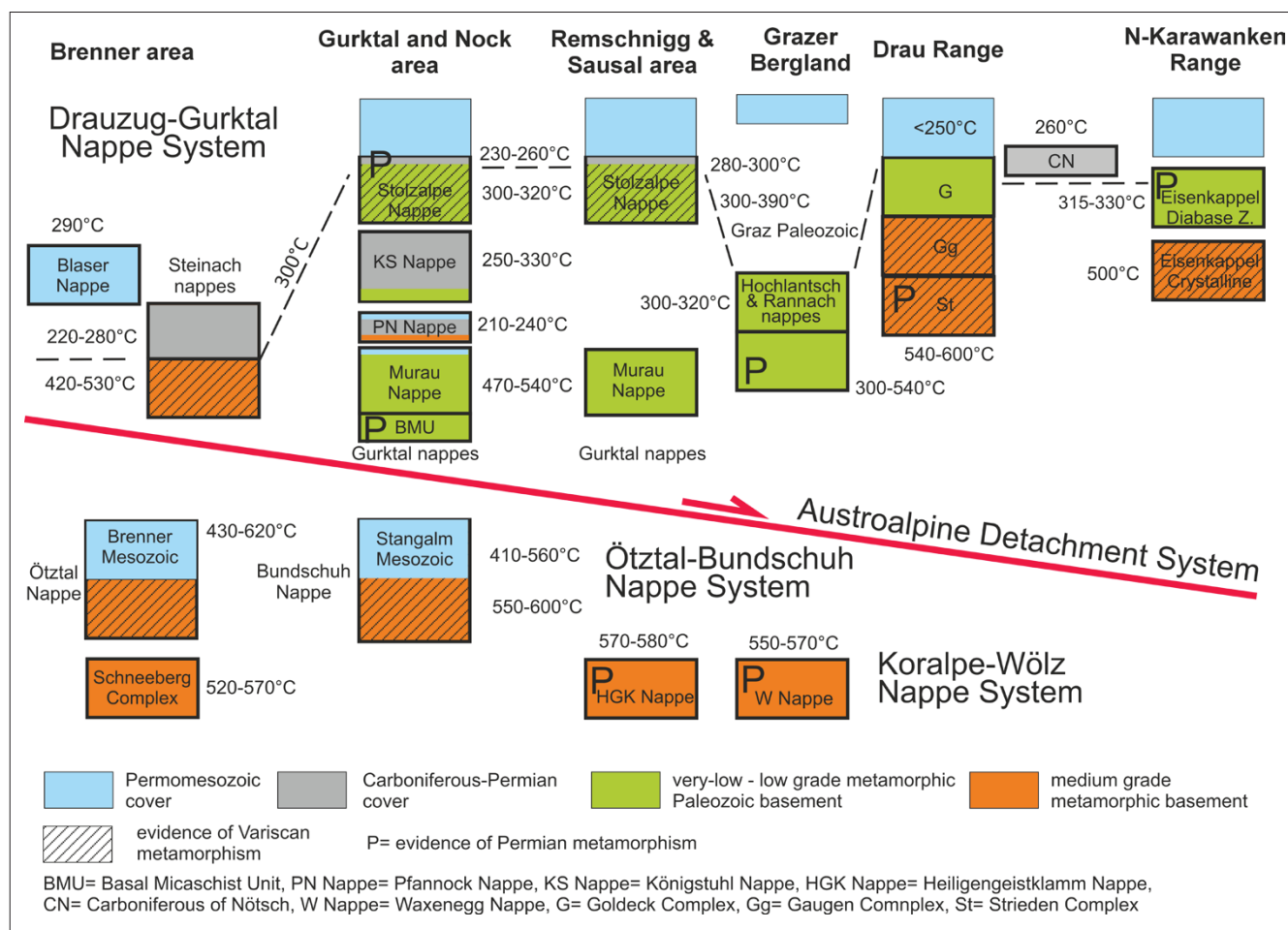


Figure 7: Compilation of RSCM temperatures in the Drauzug-Gurktal Nappe System and tectonic units below from west to east. The shown 300 °C isograd indicates the temperature attained during Permomesozoic burial. The position of the Austroalpine Detachment System (Hollinetz et al., 2024) is indicated by a red line at the base of the Drauzug-Gurktal Nappe System.

at the end of the Variscan orogeny. This implies that correlations of tectonic units involved in the Eoalpine nappe stack solely based on the basement nature might not be robust.

6.4. The temperature gap at the base of the Drauzug-Gurktal Nappe System

RSCM thermometry provides major insights into the late stages of Eoalpine tectonics within the Drauzug-Gurktal Nappe System, particularly when temperatures are linked to a geodynamic event. By comparing Eoalpine peak temperatures between the units of the Drauzug-Gurktal Nappe System and those in the Ötztal-Bundschuh and Koralpe-Wölz nappe systems, a temperature gap is reconstructed. Note that this gap is evidenced by peak temperatures that are actually Variscan (e.g., in the Brenner area) or Permian (e.g., between Graz Paleozoic and units below). Discarding the Murau and Königstuhl nappes as well as the basal parts of the Oberrnberg Nappe for the moment, the temperature gap in the Brenner area, the Gurktal Alps, the Remschnigg and

Sausal area and the Grazer Bergland is comprised between 150 and 300 °C (Fig. 5).

Such a gap has already been discussed in studies of Hoinkes et al. (1999), Koroknai et al. (1999), Rantitsch et al. (2020), and Hollinetz et al. (2024). It is systematically related to localized deformation at the base of the Drauzug-Gurktal Nappe System, with evolution from ductile to brittle in the footwall as well as brittle-ductile and brittle deformation in the hanging wall. When characterized, the kinematics is top-to-the-northeast-to-south-east (Neubauer et al., 1995; Froitzheim et al., 1997; Koroknai et al., 1999; Fügenschuh et al., 2000; Huet, 2015, 2018; Schorn and Stüwe, 2016; Griesmeier et al., 2019), which is the opposite direction to nappe stacking (Ratschbacher and Neubauer, 1989; Ratschbacher et al., 1989; Kurz and Fritz, 2003). Available geochronological constraints and systematic evidence for lower-grade overprint indicate that deformation in the footwall post-dates the Eoalpine peak of metamorphism (Ratschbacher and Neubauer, 1989; Ratschbacher et al., 1989; Kurz and Fritz, 2003). Furthermore, exhumation occurred coevally with the formation of post-orogenic Gosau basins (Neu-

bauer et al., 1995; Kurz and Fritz, 2003; Wiesinger et al., 2006). All the features are characteristic of low-angle detachments formed during post-orogenic collapse (Wernicke, 1981; Lister and Davis, 1989; Jolivet et al., 2004). Building on Hollinetz et al. (2024), we conclude that the temperature gap is related to a mountain belt scale detachment system called “Austroalpine Detachment System” (Fig. 7). The temperature gap is also accompanied by a pressure gap of at least 0.5 GPa (Hollinetz et al., 2024), which roughly corresponds to half of the thickness of a continental crust in a state of lithostatic pressure. Assuming a typical low-angle normal fault geometry, this yields a minimum displacement of 45 km (Hollinetz et al., 2024), which would apply to the whole “Austroalpine Detachment System”.

There are “thermal anomalies” to this pattern. Indeed, units that recorded relatively high temperatures occur at the base of the Drauzug-Gurktal Nappe System. Parts of the Obernbergtal Nappe, the Murau Nappe and contact units in the Remschnigg area experienced Eoalpine temperatures of up to ca. 500 °C comparable to those of the footwall of the “Austroalpine Detachment System” (Fig. 7). Similarly, extraordinarily high temperatures are observed along the Upper Cretaceous shear system (Neubauer et al., 1995) separating the Graz Paleozoic from rocks below (see also Rantitsch and Lünsdorf, 2016). The Königstuhl Nappe and the Stolzalpe Nappe east of Viktring also display relatively high temperatures. These units are interpreted as basal slivers of the Drauzug-Gurktal Nappe System that were exhumed together with the footwall. This highlights the complexity of deformation along several branches of the “Austroalpine Detachment System”, which is similar to detachment systems well characterized in the Basin-and-Range province, Aegean realm, and the Tauern Area (Wernicke, 1981; Lister and Davis, 1989; Jolivet et al., 2004; Brichau et al., 2007; Jolivet et al., 2010; Grasemann et al., 2012; Spalding et al., 2025). Note that these thermal anomalies are not related to structural anomalies, as the deformation pattern and kinematic of the individual detachments are similar (Neubauer et al., 1995; Froitzheim et al., 1997; Koroknai et al., 1999; Fügen-schuh et al., 2000; Huet, 2015, 2018).

7. Conclusions

The good agreement between the temperatures from RSCM thermometry and the peak temperature estimates available from the literature highlights the robustness of the method and interpretations.

In a west- to east profile through the Eastern Alps, RSCM data from the Koralpe-Wölz and Ötztal-Bundschuh nappe systems (Brenner Area, Gurktal and Nock Mountains, Remschnigg, and Grazer Bergland) show consistent peak metamorphic temperatures of 570–410 °C. A lower temperature range is attained in their Mesozoic cover sediments (Brenner Mesozoic and Stangalm Mesozoic) constraining the Eoalpine metamorphic imprint. New RSCM data from the Drauzug-Gurktal Nappe System give

insight into the thermal structure of the highest tectonic unit of the Eastern Alps. They describe peak metamorphic temperatures within the Blaser Nappe, Steinach nappes, Gurktal nappes (Sausal, Remschnigg, and Viktring areas), Graz Paleozoic, and Drau Range. In several locations, the presented dataset allows the discrimination of Variscan and Eoalpine peak temperatures. The data describe a consistent imprint of post-Variscan molasse sediments in the Steinach and Gurktal nappes, resembling also the imprint of the same stratigraphic horizon within the Southalpine Carnic Alps. The metamorphic imprint of the Carboniferous top strata of the Graz Paleozoic is also the same. Basement-cover relations constrain a metamorphic hiatus between pre- and post-Variscan strata in the Steinach nappes and at the northern margin of the Drau Range Permomesozoic, contrasting a missing hiatus in the Remschnigg-Sausal area and Southern Alps. RSCM data from the Graz Paleozoic indicate an upright metamorphic gradient within major parts of the nappe stack and a RSCM temperature anomaly in the Schöckel Nappe. Sedimentary burial of the Drau Range Permomesozoic is constrained by RSCM temperatures <250 °C in Permian base strata. A RSCM temperature map outlines a Cenozoic thermal anomaly in the central segment of the Gailtal Alps.

Based on the study data, we suggest that the temperature gap at the base of the Drauzug-Gurktal Nappe System is related to low-angle detachments formed during post-orogenic collapse. Here, also RSCM temperatures increase locally.

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