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Re-interpretation of the TRANSALP seismic section in the light of new tectonic subdivisions of the western Northern Calcareous Alps

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Abstract

In this study we present a reprocessed part of the TRANSALP seismic section between the Austrian-German border and the Ziller valley. It offers new insights into deep tectonic structures around the lower Inn valley, which are interpreted with the use of recently published tectonic classifications of the area. The lateral extension of the observed major structures is discussed with another deep cross section across the Kaisergebirge. This study demonstrates that Paleogene out-of-sequence thrusting locally controls the relationship between different tectonic units. Paleogene thrusts overprint pre-existing nappe boundaries, and were erroneously interpreted as Cretaceous nappe boundary. This is the case for the large, laterally persistent unit of the Tirolic Staufen-Höllengebirge- and Bajuvaric Lechtal nappes, which are separated by a Paleogene out-of-sequence thrust and the Oligo-Miocene Inntal Shear Zone. Consequently, this means to eliminate the concept of a tectonic subdivision solely based on in-sequence nappe stacking, and Triassic sedimentary facies distribution. We suggest to use a nomenclature also based on geometry of the Permo-Mesozoic cover nappes. Our proposed nappe classification leads to a newly defined Karwendel-Höllengebirge Nappe, occupying most of the middle to western Northern Calcareous Alps, incorporating the crystalline basement, which is in primary contact with the Permo-Mesozoic cover. The partly existing sedimentary contact to the basement further allows us to propose a new terminology on cover nappe systems in the Northern Calcareous Alps, getting rid of the terms Bajuvaric, Tirolic and Juvavic. Oligocene-Miocene thrusting and eastward extrusion along the Subtauern Ramp and steep strike-slip structures - like the Inntal shear zone – have further complicated the structure of the region, off-setting older in- and out-of-sequence structures, and finally exhuming basement units underneath the cover nappe stack south of the Inn valley.

1. Introduction

In this study, the reprocessed TRANSALP deep seismic survey in the Inntal segment and the resultant interpretation are used to discuss the overall tectonic structure of the foreland fold-and-thrust belt of the Eastern Alps. We question the established tectonic subdivision of the Northern Calcareous Alps and their basement, which creates logical and terminological problems (Rüffner and Bechstädt, 1995; Klug and Froitzheim, 2022; Ortner and Kilian, 2022). The newly proposed alternative subdivision originates from the western Eastern Alps. The intention is not to claim completeness for the entire NCA. However, we want to take this opportunity and initiate a discussion on a new tectonic subdivision of the Eastern Alpine foreland-fold and thrust belt. The objective is to promote a constructive exchange of opinions among researchers and to generate a meaningful debate.

The Northern Calcareous Alps (NCA) are the external fold-and-thrust belt of the Eastern Alps. The NCA are built by a Permo-Mesozoic sedimentary succession deposited on the north western Tethyan shelf (Mandl, 2000), on top of Variscan low-grade basement of the Adria Microplate north of the Meliata Ocean (Schmid et al., 2004). This succession was involved in thrusting, locally starting in Jurassic, however extensive nappe stacking started in the Early Cretaceous (135 Ma) (Schuster, 2015). Later the nappe stack was covered by Late Cretaceous to Eocene synorogenic sediments (Schuster, 2015; Ortner and Kilian, 2022). Understanding of the tectonic structures of the NCA and its basement are key for the use of the deeper subsurface, e.g., geothermal energy or storage projects. The TRANSALP seismic section between Munich and Treviso aimed to image the deep crustal structure of the Eastern Alps in the late 90s to early 2000s (Gebrande et al., 2001; Gebrande et al., 2002). It consequently became the foundation of many tectonic models, especially in the Alps of Tirol (Auer and Eisbacher, 2003; Lüschen et al., 2004; Lüschen et al., 2006; Ortner et al., 2006; Lammerer et al., 2008). These had impact on later, fundamental works, concerning the overall structure of the Eastern Alps (Schmid et al., 2004; Schmid et al., 2013; Schuster, 2015). In the following we present a new interpretation of a 40 km long segment of the TRANSALP line, located around the Inn valley, which was reprocessed and interpreted for geothermal exploration (Galler et al., 2023). A study published by Ortner et al. (2006) interpreted the original TRANSALP processing and is therefore held as a reference for new findings.

We additionally constrain the lateral extent of tectonic features by constructing another section east of the TRANSALP line, that is located in the area of the Kaisergebirge, where the prominent nappe boundary between the Tirolic and Bajuvaric nappe systems has previously been drawn. Our findings are discussed in the context of new tectonic subdivisions in the region (Huet et al., 2019; Kilian and Ortner, 2019; Ortner and Kilian, 2022). Therefore, we provide a more detailed section on the topic of nappe subdivision in the discussion.

2. Geological Setting

The Alps are the result of long-lasting convergence between the Adria Microplate and the European Plate since Late Jurassic. They expose units deriving from both continents as well as oceanic domains that were located in between. The investigated units, comprised of Permo-Mesozoic sediments and (low-grade) basement, belong to the Upper Austroalpine Unit, which derives from the northern margin of the Adria Microplate (Schmid et al., 2004; Froitzheim et al., 2008) (Fig. 1).

2.1. Stratigraphic and tectonic evolution

The stratigraphic succession exposed in the NCA (Fig. 2) starts in the Permian with continental and shallow marine siliciclastic and evaporitic deposits, which transgressively overlie (poly-) metamorphic Variscan basement (Mandl, 2000). Kilometre-thick shallow marine carbonate deposits dominate the sedimentary succession on the Tethys shelf from Middle Triassic to Jurassic, only being intercalated with thin clastic deposits (Tollmann, 1976b). The Austroalpine realm, located at the northern margin of the Adria Microplate, was separated from its European hinterland due to the opening of the Penninic Ocean that began in Jurassic (Froitzheim and Manatschal, 1996; Faupl and Wagreich, 2000; Mandl, 2000). In consequence, deep marine sequences deposited on the rifted passive margin southeast of the Penninic Ocean (Tollmann, 1976b).

At the same time, the south-eastern distal margin of the Austroalpine realm facing the Neotethys or Meliata Ocean was involved in a south-east dipping subduction zone, closing the Meliata Ocean and initiating north-westward thrusting of units now located in the NCA (Schmid et al., 2004). This first phase of thrusting took place in Callovian (Gawlick et al., 1999; Fernandez et al., 2025) to Oxfordian (Strauss et al., 2023) and brought Permian to Upper Triassic strata of the Lower Juvavic nappes onto deep marine Jurassic radiolarites. The cause of this event is still debated and the process might vary along-strike of the NCA (Mandl, 2000; Strauss et al., 2023; Fernandez et al., 2024). The established theory of allochthonous gravitational nappe movement of distal margin facies sediments into more proximal realms (Tollmann, 1987; Mandl, 2000) is put into question. In the central NCA, Jurassic deformation can be related to the closure of parautochthonous, intra platform basins, which formed by salt-tectonic processes (Fernandez et al., 2024; Fernandez et al., 2025). On the contrary, for the eastern NCA Strauss et al. (2023) suggested Jurassic thrusting being caused by inversion of a hyperextended distal Meliata margin. This Jurassic deformation however did not affect the western NCA, where initial thrusting started during Eoalpine orogeny, in Hauterivian to Barremian, which led to nappe stacking of the Tirolic onto the Bajuvaric nappe system (Mandl et al., 2017; Schuster, 2015). Generally characterized by northwest- to north-northwest-vergent fold-and-thrust structures and accompanied by northwest-striking steeply dipping transverse strike-slip faults (Eisbacher and Brandner, 1996; Ortner, 2003b). After Eoalpine orogeny, the NCA have traditionally been divided from base to top into the Bajuvaric, Tirolic and Juvavic nappe systems (Hahn, 1912; 1913a; 1913b; Tollmann, 1976b; 1985; Schmid et al., 2004; Schuster, 2015; Mandl et al., 2017) (Fig. 1).

In the basement of the Upper Austroalpine Unit, shortening is also associated with nappe formation at similar times, but Eoalpine shortening was followed by Late Cretaceous east-southeast-directed stretching (Froitzheim et al., 1994; Fügenschuh et al., 2000). In contrast, cover nappes of the western NCA experienced continuous shortening that changed from northwest-directed in Cretaceous, to northeast-directed in Paleogene (Eisbacher and Brandner, 1996; Ortner, 2001). Early Cretaceous nappe boundaries were folded during the Late Cretaceous, contemporaneous with the onset of sedimenta-

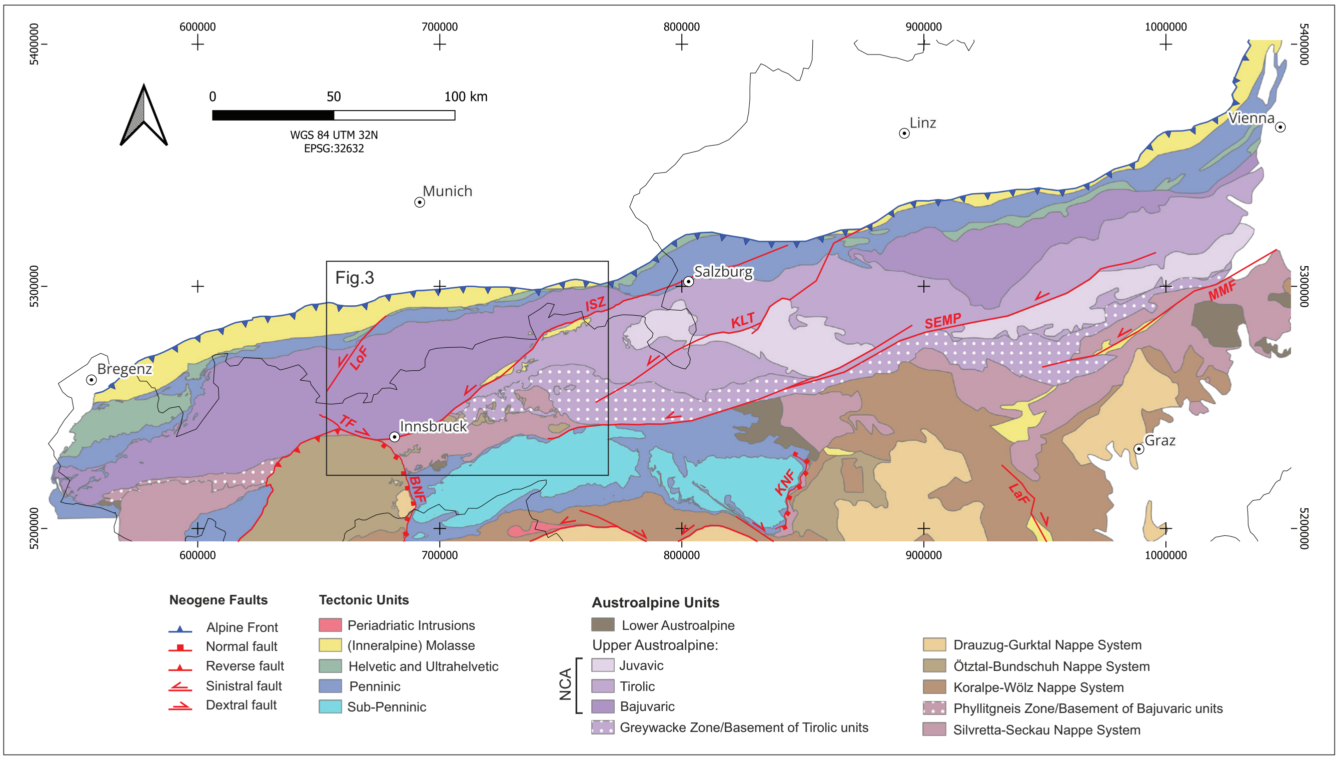

Figure 1: Tectonic map of the Eastern Alps with focus on the Northern Calcareous Alps (NCA) and the Austroalpine basement units south of the NCA. Tectonic subdivision following Schmid et al. (2004), western NCA following Ortner and Kilian (2022). Thin black solid line marks the border of Austria. BNF: Brenner Normal Fault, ISZ: Inntal Shear Zone, KLT: Königsee-Lammertal-Traunsee Fault, KNF: Katschberg Normal Fault, LaF: Lavanttal Fault, LoF: Loisach Fault, MMF: Mur-Mürztal Fault, NCA: Northern Calcareous Alps, SEMP: Salzachtal-Ennstal-Mariazell-Puchberg Fault, TF: Telfs Fault. Map modified from Linzer et al. (2002), Schmid et al. (2004), Schmid et al. (2013) and Ortner and Kilian (2022).

tion of the syntectonic Gosau Group that records syndepositional shortening documented by growth strata (Ortner et al., 2016; Ortner and Kilian, 2022). As the convergence between Adria and Europe proceeded, and the deformation front progressed in northwest- direction, the orogenic front reached the Piemont-Liguria branch of the Penninic Ocean in Cenomanian to Turonian (Eisbacher et al., 1990; Oberhauser, 1995). This initiated the subduction and accretion of Penninic units. The subduction of the Penninic Ocean lasted until Early to Middle Eocene (Froitzheim et al., 1994) consequently leading into continental collision in Late Eocene (Handy et al., 2010).

Late- to post-collisional processes in Oligocene-Miocene led to eastward extrusion of blocks of the orogenic wedge towards the Pannonian Basin. This was associated with major strike-slip faulting (Ratschbacher et al., 1991) as well as out-of-sequence thrusting. In the investigated area, the most prominent feature of lateral extrusion is the Inntal Shear Zone (ISZ) (Fig. 1). It is a sinistral strike-slip fault, located in the Inn valley and subparallel to it. The shear zone is kinematically linked with the Brenner Normal Fault south of Innsbruck and the Alpine Basal Thrust at the Alpine Front (Ortner, 2003b; Ortner et al., 2015). It obliquely cuts across the nappe stack of the NCA and the Penninic units (Ortner et al., 2006). The fault's multi-phase activity is also connected to the Subtauern Ramp (STR) (Ortner et al., 2006), which is discussed since the seismic detection of the ramp-structure beneath the Tauern Window by the TRANSALP Working group in 2002 (Gebrande et al., 2002; Lüschen et al., 2004). The ISZ is active at least since the Early Oligocene, as documented by soft sediment faults in Lower Oligocene sediments (Ortner and Stingl, 2001). The offset of the ISZ is estimated to be up to 40 km (Ortner, 2003b; Ortner et al., 2006). Other studies suggest larger offsets (Linzer et al., 2002).

2.2. The tectonic subdivision in the study area

The following tectonic subdivision is an updated classification following Schmid et al. (2004) (Fig. 1) on the local scale (Fig. 3). It is based on work from Huet et al. (2019) and Paulick et al. (2024) for basement nappes, and on Ortner and Kilian (2022) for the cover nappes.

According to Huet et al. (2019), the westernmost part of the Tirolic-Noric Nappe System contains the Staufen-Höllengebirge Nappe (SHN), the Windau Nappe and the Wildkogel Nappe (Fig. 3 and 4). These nappes are separated by Early Cretaceous, Eoalpine thrusts, however, only the uppermost, the SHN, comprises a pre-Variscan basement and a post-Variscan cover. The total extent of the above-mentioned nappes of the Tirolic-Noric Nappe System (the SHN, the Windau Nappe and the Wildkogel Nappe) in the study area is constructed based on lithostratigraphic criteria and the affiliation to Variscan com-

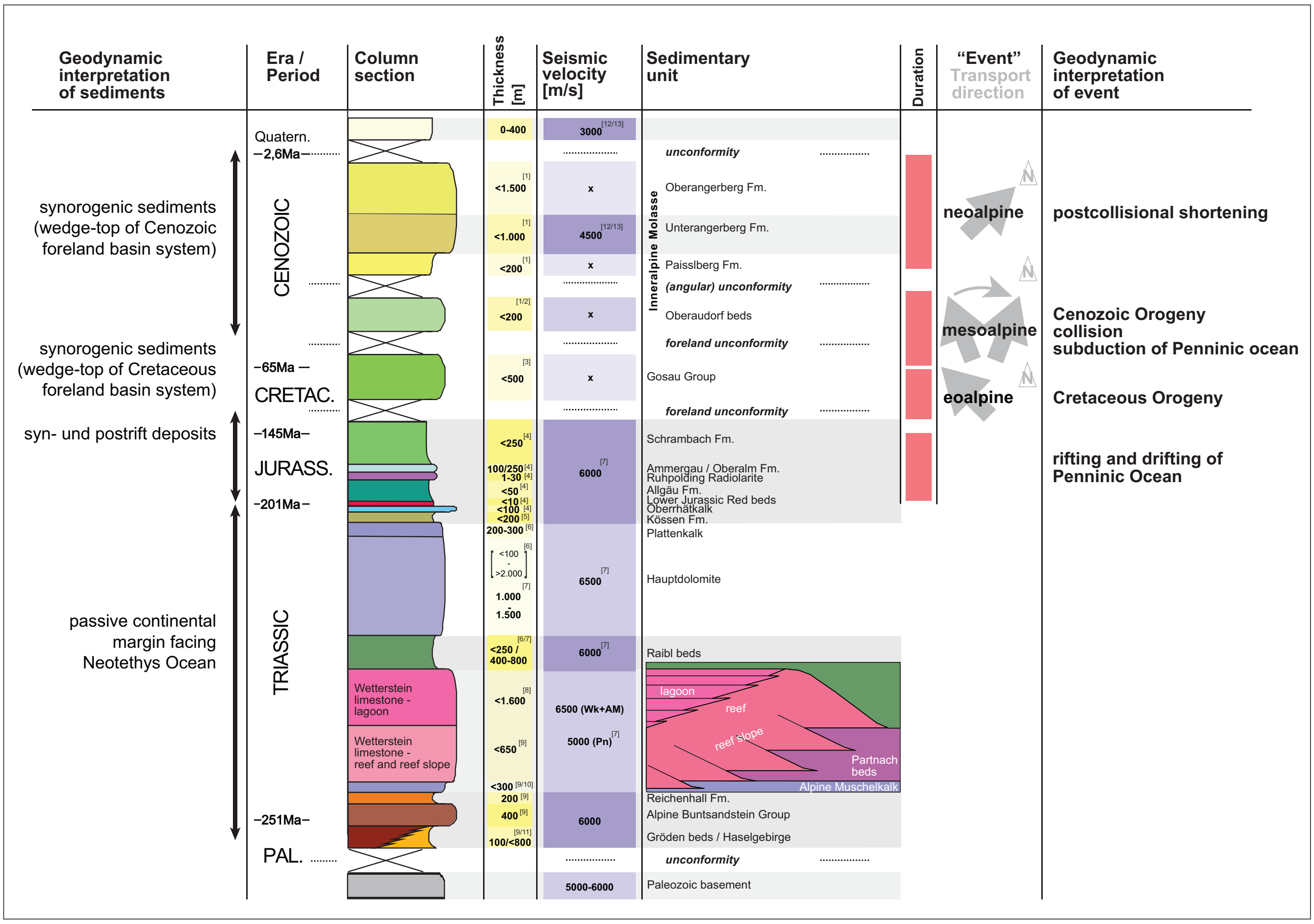

Figure 2: Simplified stratigraphic section of the rocks exposed in the NCA in the studied area. Thickness of units was used for the construction of deep cross sections. References: [1] (Ortner and Stingl, 2001), [2] (Schulz and Fuchs, 1991), [3] (Ortner, 2001), [4] (Töchterle, 2005), [5] (Golebiowski, 1991), [6] (Tollmann, 1976a), [7] (Bachmann et al., 1981), [8] (Kilian et al., 2021), [9] (Ortner and Reiter, 1999), [10] (Nittel, 2006), [11] (Schmidegg, 1951), [12] (Weber et al., 1990), [13] (Joanneum Research, 2000). Seismic velocity was used for the simplified depth conversion of the processed seismic data. Units without seismic velocity (x) are missing along the TRANSALP and not necessary for calculation. AM: Alpine Muschelkalk Group, Pn: Partnach beds, Wk: Wetterstein limestone.

plexes (Huet et al., 2019; Paulick et al., 2024) (see Fig. 4). Initially developed for the map sheet Neukirchen am Großvenediger of the Austrian Geological Survey, our study is extending this concept westward to cover the entire area between the ISZ, the Brenner Normal Fault and the Tauern Window (Fig. 3). The stratigraphic content of these three nappes is detailled below.

From top to bottom, the SHN consists of:
(1) A **Permo-Mesozoic cover** (see section 2.1. and Fig. 2).
(2) The **Wildseeloder Complex** containing the Middle-Ordovician Jausern Formation and metaignimbrite (Blasseneck Porphyry) (Söllner et al., 1991) as well as low-grade metamorphic Devonian siliciclastic and Silurian to Upper-Devonian carbonate.
(3) The **Hochhörndler Complex**, which is formed of low grade metamorphic siliciclastic rocks of the Löhnersbach and Schattberg formations (Lower Ordovician to Mississipian) with olistholiths of metaignimbrite, metacarbonate and greenschist occurring in stratigraphic position in the Wildseeloder and Glemmtal complexes.
(4) The **Glemmtal complex** with low grade metamorphic siliciclastic rocks of Löhnersbach and Schattberg formations (Lower Ordovician to Mississipian) together with metamorphosed ultramafic to mafic igneous and volcanosedimentary rocks (Cambrian to Mississipian).
(5) The **Uttendorf Complex** that is a tectonic mélange containing a broad range of lithologies in a matrix formed by metamorphic siliciclastic rocks, partly deriving from the Löhnersbach and Schattberg formations. This concept with four complexes formed of Palaeozoic rocks is based on the subdivision of Heinisch et al. (2015) and correspond to four Variscan tectonic units.

From top to bottom, the Windau Nappe is composed of:
(1) The **Glemmtal Complex** in a slightly more metamorphic state than its counterpart in the SHN (see above).
(2) The **Kellerjoch Orthogneiss** of Middle-Ordovician age (Tropper et al., 2016).
(3) The **Kreuzjoch Complex**, which is dominated by greenschist facies quartz phyllite, with subordinate quartzite, marble, greenschist and chlorite schist.

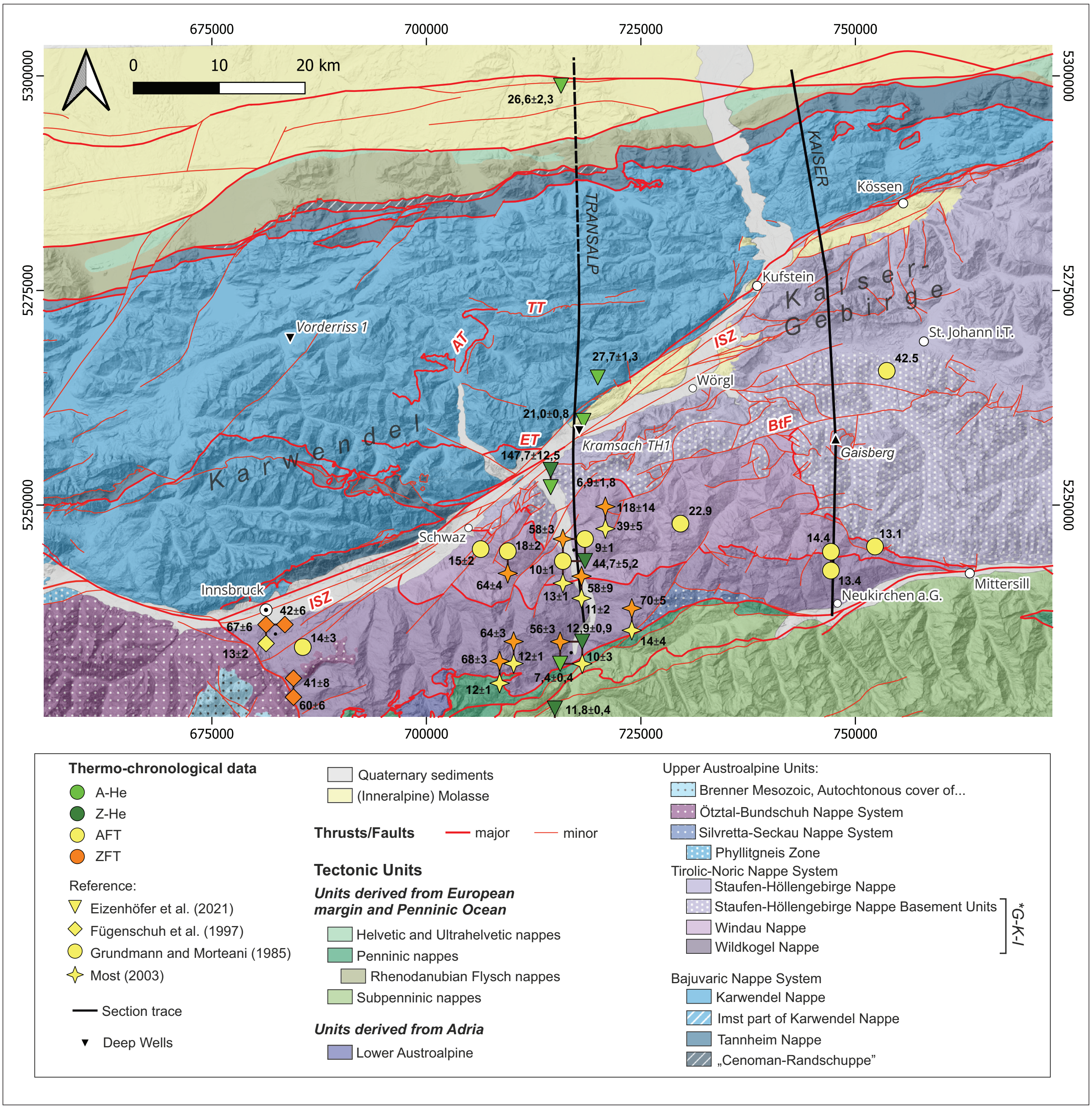

Figure 3: Updated tectonic subdivision used for this study, after Ortner and Kilian (2022) for the cover nappes exposed in the NCA, after Huet et al. (2019) and Paulick et al. (2024) for the basement units south of the Inn valley and Schmid et al. (2013) for the Tauern Window. Traces of cross sections shown are from TRANSALP and KAISER (see text for details). Solid trace line of TRANSALP marks the new processed part. Thermo-chronological data compiled from Grundmann and Morteani (1985), Fügenschuh et al. (1997), Most (2003), and Eizenhöfer et al. (2021). AT: Achental Thrust, BtF: Brixental Fault, ET: Eben Thrust, ISZ: Inntal Shear Zone, TT: Thiersee Thrust. *G-K-I* marks the extent of previously used units of Greywacke Zone, Kellerjoch Gneiss and Innsbruck Quartzphyllite Complex.

The Wildkogel Nappe is composed of the **Trattenbach Complex**, which consist of low- to middle grade mica schist, paragneiss and quartzite (Neoproterozoic to Carboniferous), locally with Lower to Middle Ordovician orthogneiss, amphibolite and marble (most likely Silurian to Devonian). It contains garnet-bearing rocks that are gathered in the Steinkogel Lithodem.

The previously used names for the basement units, the Western Greywacke Zone, the Kellerjoch Orthogneiss and the Innsbruck Quartzphyllite Zone, represent geological units with lithological similarities that do not define a tectonic nomenclature. This implies to abandon these unit names for formal tectonic subdivisions (Figs. 3, 4).

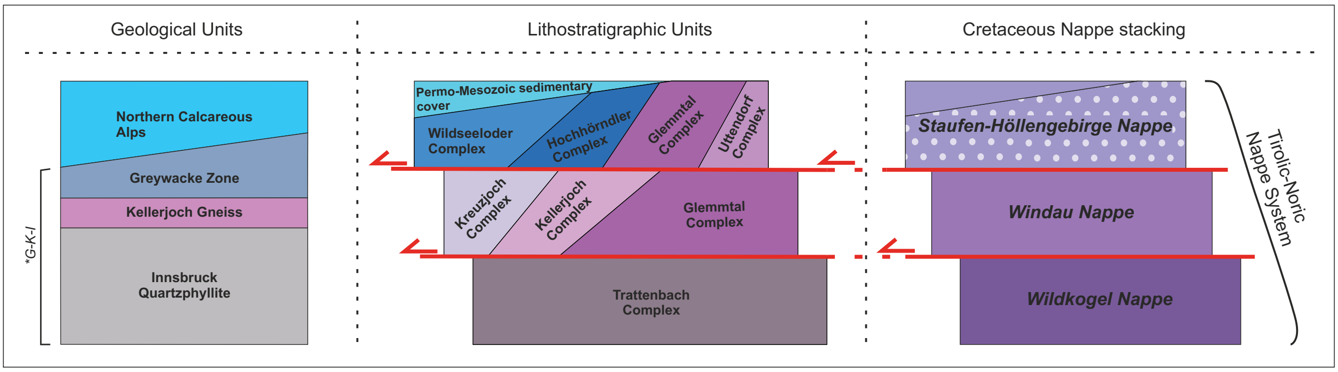

Figure 4: Schematic diagram comparing geological units to lithostratigraphic units and Cretaceous nappe stacking in the basement units below the nappes exposed in the NCA. The figure shows the correlation of the Palaeozoic complexes to the nappes, after Huet et al. (2019) and Paulick et al. (2024). **G-K-I* marks the extent of previously used tectonic units Greywacke Zone, Kellerjoch Gneiss and Innsbruck Quartzphyllite Complex.

North of the Inn valley lie the Tannheim and Karwendel cover nappes, separated by a Cretaceous thrust which was active since Hauterivian (Ortner and Kilian, 2022). Both nappes replace the previously proposed Bajuvaric Allgäu and Lechtal Nappe and the Tirolic Inntal Nappe (Tollmann, 1976b), respectively. The Tannheim and Karwendel Nappe are interpreted as a part of the Bajuvaric Nappe System (Ortner and Kilian, 2022). South of the Inn valley Permo-Mesozoic sediments are present east of Schwaz. The sedimentary contact of the Permian basal breccia and Gröden Formation onto the Variscan basement is still preserved (Pirkl, 1961). This contact can be traced past St. Johann in Tirol further to the east (see Fig. 3) as it lies within one coherent tectonic unit, the SHN (Ortner and Kilian, 2022) of the Tirolic Nappe System (Fig. 3) (Tollmann, 1976b; Mandl, 2000; Schmid et al., 2004). The northern boundary of the SHN has been drawn at the ISZ (Hahn, 1912; 1913a; Tollmann, 1976b; 1985).

2.2.1. Tectonic subdivision after Tollmann (1976b; 1985)

In chapter 5 we will discuss our findings in the light the present-day tectonic subdivisions and will address our concerns on its use in the NCA. Therefore, we give a short excursus in the following on the history and use of tectonic terms.

The currently used tectonic subdivision of nappe systems in the NCA is based on Tollmann (1976b; 1985), who adapted a classification proposed by Hahn (1912; 1913a; 1913b), to divide the NCA into Bajuvaric, Tirolic and Juvavic Units. This was based on the continuity of tectonic contacts and similarity of sedimentary facies. Of high importance was a tectonic lineament that Hahn called "Tirolic Line" (Hahn, 1913a). Tectonic Nappes of the NCA north and underneath this first order fault would be called Bajuvaric, above and south of this fault, reaching to the southern border of the NCA, should be addressed as Tirolic. Juvavic was referred to as nappes of the external shelf, of Hallstatt facies, "thrusted during Cretaceous" onto Tirolic. This concept was further developed and changed by Tollmann (1976b; 1985). The existence of the three units was first explained by the relative position in the nappe stack to each other and major tectonic boundaries between them, and second with observed deformation structures, which were attributed to differing rock behaviours. This was typically attributed to the variations in sedimentary rock types, particularly the distinct Upper Triassic facies (Tollmann, 1985; Mandl, 2000), which consequently influenced nappe configuration.

It has to be distinguished between nappe systems and nappes. The second serve as components of the first. There is no generally admitted definition of a nappe in the NCA and Eastern Alps in general, and the used criteria depend on the different authors. In the early 20th century, Ampferer (1902) was the first to apply the concept of thrusting to the western NCA. Ampferers "Karwendel thrust" then became the basal thrust of his "Inntal Nappe" (Ampferer, 1931), and started the doctrine of describing (parts of) the orogen as volumetric units, as nappes. Tollmann (1973) later defined a single nappe as: *"A nappe/thrust-sheet is a large scale, independent, plate-like thrust- or fold-sheet, with partly kilometres of more or less horizontal transport over another substratum"*. Thus, neither the sedimentary facies, nor thrust timing was decisive for his classification of nappes. Thrust timing however was used in subsequent studies as a criterion for nappes (Kilian and Ortner, 2019; Ortner and Kilian, 2022), or even nappe systems (Mandl et al., 2017).

3. Data and Methods

3.1. Reprocessing of seismic data

The data from the TRANSALP seismic survey (Munich to Treviso) were first processed within an international research project. Original processing is described in detail by Gebrande et al. (2001), Gebrande et al. (2002) and Lüschen et al. (2004). A 40 km long segment from the TRANSALP line, located 20 km north and south of the Inn valley was reprocessed for the present study (Fig. 3). The purpose of reprocessing was targeting potential geothermal reservoirs in approximately 2–4 km depth, as described by Galler et al. (2023), but the results are discussed in a tectonic context here.

The required seismic data for reprocessing were available in parts from various institutions (TU Munich, GFZ Potsdam, Montanuniversität Leoben) and were merged into one dataset as part of this project. The data reprocessing was done on a server and processing platform ProMAX by Geo5 GmbH in Leoben, Austria. Generally, the reprocessing followed a conventional common-midpoint stacking workflow. The different steps of re-processing are described in detail in the supplementary material, also shown in Figure S1. The supplementary material also presents a comparison between the original processing and the new reprocessed data of this study (Fig. S2), and a simplified p-wave velocity model of the reprocessed seismic section for depth conversion (Fig. S3).

3.2. Interpreting reflecting horizons, available drilling data and surface geology

Seismic impedance is defined as the product of the seismic velocity and the density of the rock. Seismic investigations make use of reflection events caused by the seismic impedance contrasts at layer interfaces (Nanda (2016) and references herein).

The reflection seismic profiles and their interpretations are displayed in the vertical axis in two-way travel time (TWT, in milliseconds). Usually, geophysical information from boreholes in the vicinity of the seismic sections are used to validate and complement seismic interpretation. Information from boreholes is available in the depth domain as measured depth or elevation (in meters), and needs to be converted into time domain (in milliseconds), in order to be integrated into a seismic survey. The Kramsach TH1 borehole (Gasser, 2000) with a total depth of 1645 m MD (measured depth) and geophysical borehole measurements up to 1400 m is the only near-site information for the interpretation in addition to the surface outcrops along the TRANSALP seismic section (see Fig. 5a, b and Fig. 3 for location). The geological interpretation of the TRANSALP seismic section therefore remains conceptual and is based on the general knowledge of the structural composition of the western NCA and basement units, as well as surface geology along its trace. Velocity and thickness information from carbonate units (Triassic and Jurassic units) were taken from the Vorderriß 1 (Bachmann et al., 1981) and Hindelang 1 (Lettau, 1995) boreholes, among others, and are largely dependent on the porosity of the carbonate rocks. The location of borehole Vorderriß 1 is shown on Figure 3, borehole Hindelang 1 is located outside the map of Figure 3, further to the west, but still in the western Norther Calcareous Alps. The seismic velocities for the Permo-Mesozoic Units in these boreholes vary between 5500 and 7000 m/s (Fig. 2). The depth conversion of the TRANSALP seismic interpretation was carried out on the conceptually interpreted horizons, which summarized lithostratigraphic units according to their seismic velocities (Fig. S3, Supplement). Due to the sparse data availability the velocity model is based on constant values in the different rock formations. As there is no well information the time-depth dependency could not be further validated.

Furthermore, the final construction of the TRANSALP depth profile (Fig. 5b) was based on surface data along the section trace by Töchterle (2005), and on the GEOFAST sheets Angath (Geologische Bundesanstalt Österreich, 2021c) and Wörgl (Geologische Bundesanstalt Österreich, 2021a). Stratigraphic information used is shown in Figure 2 (and the references in the figure caption herein).

The section KAISER is constructed based on GEOFAST mapsheet Neukirchen am Großvenediger (Geologische Bundesanstalt Österreich, 2021b), new field data, detailed surface mapping and compilations by Ganss (1980), Zerbes and Ott (2000), Ortner (2006), Ortner and Gruber (2013), Huet et al. (2019) and Kunz et al. (2023), as well as interpolation in 3D between the sections KAISER, TRANSALP, and seismic profiles from Angenheister et al. (1972). Stratigraphic information was also included (Fig. 2, and references herein). Construction method used for Permo-Mesozoic cover succession was parallel folding.

4. Results and Interpretation

4.1. Reflections on the TRANSALP seismic line and the resultant interpretation

In this chapter, we highlight the results of the newly processed TRANSALP seismic section and their interpretation in detail. We focus on certain reflectors in the seismic image from Figure 5a in time domain. On Figure 5b, the local stratigraphy (Fig. 2) is used for constructing the entire interpretation in depth domain.

The most striking feature in Figure 5a is a continuous synformal reflection north of the Inn valley (labelled rb). This horizon is interpreted as reflections from Upper Triassic Raibl beds, a sequence of fine clastic sediments, evaporites and carbonates. In a tectonically undisturbed sequence, Raibl beds are intercalated in between carbonate platforms, the Middle Triassic Wetterstein limestone and the Upper Triassic Hauptdolomite. These monotonous carbonate successions, reaching up to over 1500 m in thickness each, are located above (Hauptdolomit) and below (Wetterstein limestone) the rb-horizon, and appear transparent in the seismic image.

The high reflectivity zone marked ts (Fig. 5a) is interpreted to be caused by the high impedance contrasts of Jurassic to Cretaceous pelagic carbonates and synorogenic deposits above the Hauptdolomit platform. These sediments of the high reflectivity zone ts are traceable to the surface in the Thiersee Syncline, which are cut and overthrust by an overturned limb of a frontal anticline, consisting of Triassic carbonates (Töchterle, 2005). This Jurassic-Cretaceous sediment succession of the Thiersee Syncline is traceable down to approximately 2500 m depth (see Fig. 5a, b). The thrust, referred to as Thiersee Thrust (labelled tt), cuts not only younger sediments of the Thiersee Syncline, but also the reflections of the horizon of Raibl beds, and even down into the basement (terminating reflections against the thrust are marked with short black arrows in Figure 5a).

In the hanging wall of the Thiersee Thrust reflections become less distinctive than below. Therefore, the constructed interpretation relies mainly on surface data in this segment (Fig. 5b). The apparent transport on the Thiersee Thrust is in the range of 10 km, measured in the section at the cut off points at top Plattenkalk of the foot wall and in the overturned limb of the hanging wall (marked with 1 and 2 in Fig. 5b).

The label pn marks an area below the rb-horizon and is characterized by an increase in reflectivity in the lateral continuation of the rather transparent Wetterstein limestone. This indicates that below the continuous Raibl beds, a switch in the middle Triassic sediments occurs from carbonate platform sediments to the basinal facies of the Partnach beds (Fig. 2).

The label tr indicates an area of intermediate reflectivity, parallel to the rb-horizon. This is below the thick, transparent Wetterstein limestone and is therefore interpreted as Lower-Middle Triassic siliciclastic, evaporitic and carbonate sediments (Alpine Buntsandstein, Reichenhall-Formation, Alpine Muschelkalk Group). These sediments mark the deepest units of the hanging wall above the main thrust (Lechtal Thrust) between the Tannheim Nappe and the Karwendel Nappe (Ortner and Kilian, 2022), where the detachment horizon in the hanging wall is located in these sediments (Kilian and Ortner, 2019). Below the thrust the reflections are uncertain.

High reflectivity zones labelled am1 and am2 in Figure 5a are interpreted to represent both the autochthonous (Mesozoic) cover of the European Plate below the orogenic wedge. This unit appears north and south of the Inn valley, but the southern part (am2) is located significantly deeper south of the Inn valley. The reflections appear rather horizontal, with little to no dip to the south in this segment. The area between the two levels of autochthonous cover horizons (labelled pu) is constructed as a zone of shortening in the lower plate and therefore shown as an inverted half-graben, resulting in an asymmetric pop-up structure (Fig. 5b). Above the autochthonous Mesozoic we infer the Alpine Basal Thrust, the floor thrust of the Alpine orogenic wedge, topping the reflector am1–am2 from south to the label am1, from where it ramps up towards the foreland basin. It should be mentioned, that the reflections attributed to the autochthonous Mesozoic of the European Plate are almost in contact with the Wetterstein limestone above, at approximately position CDP 600/12.000 m from north. This means that there is no space in between the Karwendel Nappe and the lower European plate at this location, neither for a deeper cover nappe, nor for Austroalpine basement attached to the Permo-Mesozoic cover, nor for Helvetic or Penninic slices. This is in contrast to the previous interpretation of Ortner et al. (2006).

South of the Inn valley, the marker pn-rb shows an area of higher reflectivity, which is generally dipping southwards, and which differs from more transparent units above. These reflectors are interpreted to be caused by fine grained marly and clastic sediments of the Raibl and Partnach beds that are exposed south of the Inn valley. These beds and their substratum are cut by the Brixlegg Thrust (Ortner et al., 2006). The Brixlegg Thrust itself is moderately to shallow dipping southwards, until it becomes horizontal and finally dragged upwards by the younger Tauern Window Northern Boundary Fault (TNBF) (Fig. 5b). The Brixlegg Thrust is intersected by steep south dipping faults. These faults are best visible in the hanging wall of the Brixlegg Thrust, offsetting strong reflections, marked by a blue arrow (Fig. 5a). In map view these faults are inferred as sinistral strike-slip faults (Fig. 3).

Reflection zone labelled kg is connected to the Kellerjoch Orthogneiss, dipping northward as intercalation in quartz phyllites of the Kreuzjoch Complex. The strong reflectivity of the area labelled tb on Figure 5a is assigned to the Trattenbach Complex, which contrasts with the other units of the area by the higher grade rocks (Huet et al., 2019).

In the area labelled STR, prominent reflections are missing. Nevertheless, sets of moderately south dipping reflectors can be recognized (two uppermost white arrows), as well as a change in reflectivity (Figure 5a, yellow and white arrows), below or above the marked zones. These zones are interpreted as multiple branches of the STR Fault System (white arrows mark the uppermost fault branch, yellow arrows mark a deeper fault branch, in our interpretation the middle one of three faults, see Figure 5a, b). These branches separate the basement and its cover into slices, whereas the uppermost consist of the thickest slice with the Brixlegg Thrust as an internal, older structure. Only in the uppermost slice the interpretation of the lithologies is robust, while the deeper slices are lacking strong reflections, and surface outcrops. The only data available is the approximately 1650 m deep well Kramsach TH1 (Gasser, 2000), which reaches Upper Triassic Hauptdolomite at its base. The interpretation still is highly speculative in the drilled slice, including the geometry of nappe boundaries in the Austroalpine basement.

4.2. A cross section from the Alpine Foreland to the Salzach valley across the Kaisergebirge

In order to understand the lateral persistence of major structures seen in the TRANSALP section, we constructed a cross section from the Alpine Foreland to the Salzach valley across the Kaisergebirge, referred to as KAISER section (Fig. 6). In the north of the section the Penninic Rhenodanubian Flysch and Helvetic Units are thrust onto the Foreland Molasse. Although not at surface next to the cross section, up to Eocene deposits from the Helvetic Units crop out approximately 3 km west of the section (Ganss, 1980). The lowermost Austroalpine unit is the Tannheim Nappe (following Ortner and Kilian, 2022), that is detached in the Carnian Raibl beds

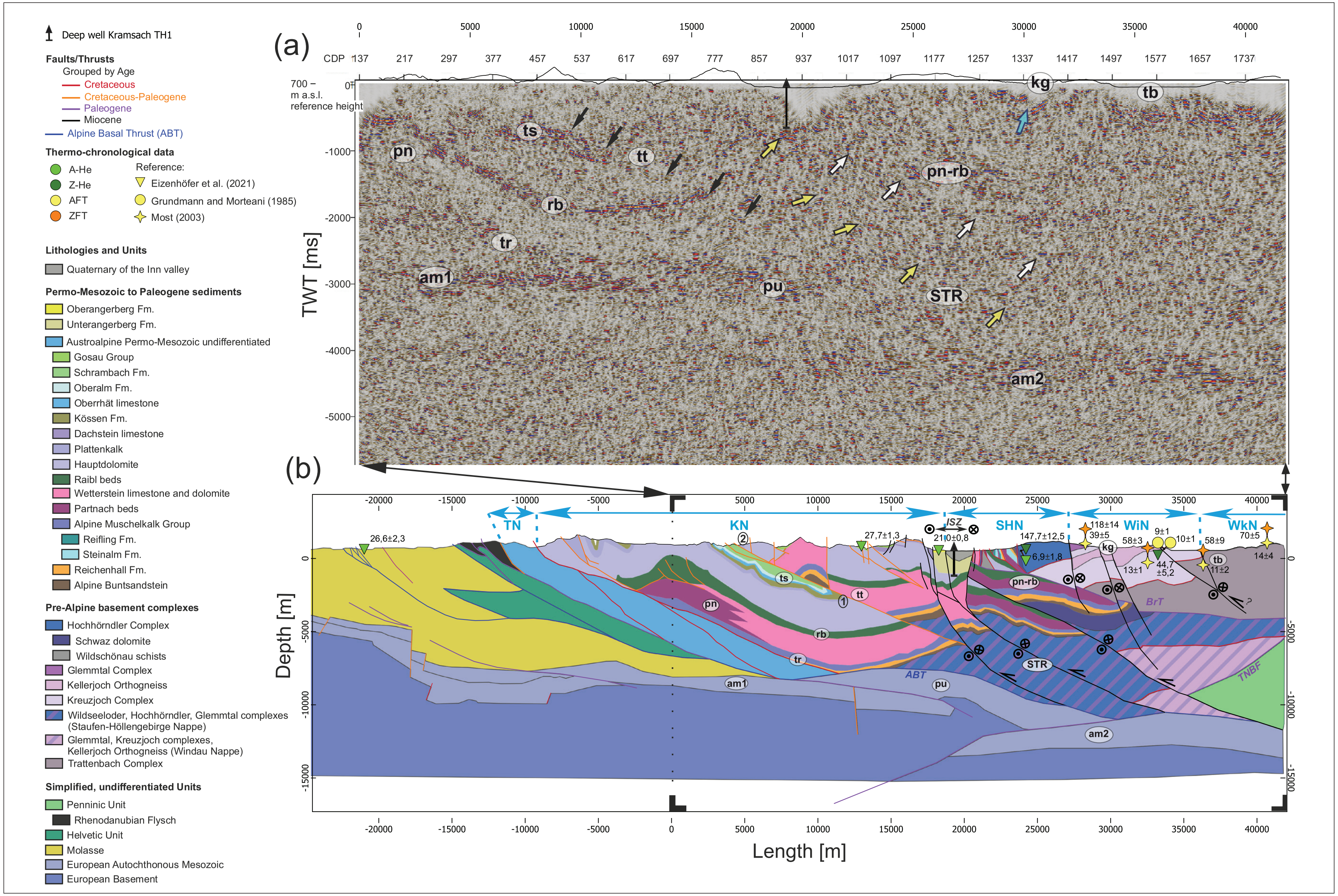

Figure 5: (a) Reprocessed TRANSALP seismic line in time domain (two-way travel time, TWT in milliseconds) north and south of the Inn valley. Arrows mark the bending or termination of reflectors against assumed faults (black arrows: Thiersee Thrust, yellow and white arrows: Subtauern Ramp, blue arrow: steep strike-slip fault). Circled labels are described in section 4.1. am1 and am2: Autochthonous Mesozoic, kg: Kellerjoch Orthogneiss, pn: Partnach beds; pn-rb: Partnach and Raibl beds, pu: pop-up structure, rb: Raibl beds, STR: Subtauern Ramp, tb: Trattenbach Complex, tr: Lower-Middle Triassic sediments, ts: Upper Triassic-Cretaceous sediments of the Thiersee syncline, tt: Thiersee Thrust. **(b)** New interpretation of the TRANSALP seismic section in depth domain. The thin frame with thick edges indicates the reprocessed segment shown in (a). The northern segment is based on the original seismic data (Lüschen et al., 2006) and follows the interpretations of Ortner et al. (2006, 2015). Circled labels 1 and 2 mark the footwall and hanging wall cut off of the Thiersee Thrust. ABT: Alpine Basal Thrust, BrT: Brixlegg Thrust, ISZ: Inntal Shear Zone, KN: Karwendel Nappe, SHN: Staufen-Höllengebirge Nappe, TN: Tannheim Nappe, TNBF: Tauern Window Northern Boundary Fault, WiN: Windau Nappe, WkN: Wildkogel Nappe. Fault structures correlated with the ISZ and STR are labelled with kinematic information. Well Kramsach TH1 is projected 640m from east. The section trace of the TRANSALP seismic line is shown in Figure 3.

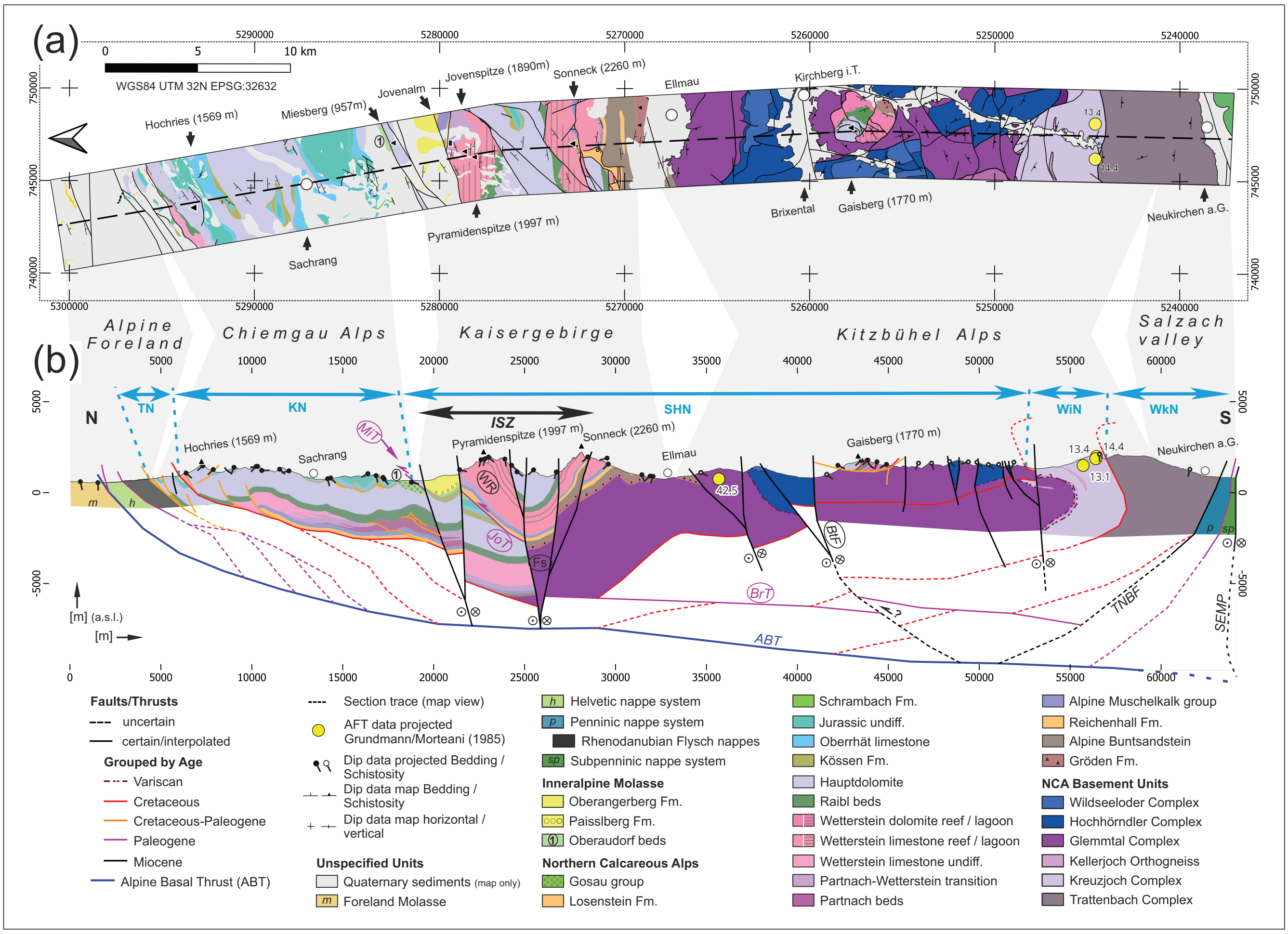

Figure 6: (a) Map and trace of cross section from the Alpine Foreland through the Kaisergebirge to the Salzach valley. **(b)** Cross section from the Alpine Foreland through the Kaisergebirge to the Salzach valley with AFT-data from Grundmann and Morteani (1985) projected into the section. The section trace is shown in Figure 3 and in (a). TN: Tannheim Nappe, KN: Karwendel Nappe, SHN: Staufen-Höllengebirge Nappe, WiN: Windau Nappe, WkN: Wildkogel Nappe, ISZ: Inntal Shear Zone, ABT: Alpine Basal Thrust, BtF: Brixental Fault, BrT: Brixlegg Thrust, JoT: Joven Thrust, MiT: Miesberg Thrust, SEMP: Salzachtal-Ennstal-Mariazell-Puchberg fault, TNBF: Tauern Window Northern Boundary Fault, WR: Wetterstein limestone reef facies, Fs: Positive flower structure, (1) marks the appearance of Oberaudorf beds underneath the MiT. Circled labels are explained in detail in 4.2. Geometry of Kaisergebirge after Ortner and Gruber (2013). ABT constructed by interpolation between seismic data from Lüschen et al. (2006) and Angenheister et al. (1972), BrT interpolated from models of Ortner et al. (2006).

and reaches up to the Albian Losenstein Formation. The overlying Karwendel nappe shows a continuous succession from Permo-Triassic to Jurassic sediments, which extend partly to the Cretaceous Schrambach Formation or is unconformably overlain by Gosau Group deposits or Inneralpine Molasse. It is assumed that within this nappe the middle Triassic changes from Wetterstein facies in the north (north of Mt. Hochries, Fig. 6) to the basinal facies of Partnach Formation. In the area between Kufstein and Kössen, Upper Triassic Hauptdolomit overthrusts Upper Eocene Oberaudorf beds (Tollmann, 1976a) (MiT and label 1 in Fig. 6b). We term this fault the Miesberg Thrust, because it crops out directly north of the mountain named Miesberg east of the section, which is build by Hauptdolomite of the hanging wall. This thrust is also cut by the ISZ. The northern boundary of the SHN was drawn at the Miesberg Thrust and the ISZ, respectively.

The main structure of the Kaisergebirge range in the SHN is caused by strike-slip faulting along the ISZ (Ortner and Sachsenhofer, 1996; Ortner et al., 2006), which consists of several branches and forms a positive flower structure (see map in Fig. 3 and label Fs in Fig. 6). The Oligocene Oberangerberg Formation is cut by the ISZ, which also offsets all older faults and thrusts in map and section view. The uppermost tectonic unit north of the ISZ is part of the Karwendel Nappe and south of the ISZ at the surface lies the SHN. The central part of the Kaisergebirge flower structure shows a doubling of Lower to Upper Triassic sediments, including a massive succession of Wetterstein limestone in reef facies (WR in Fig. 6b). Below the Jovenalm (Fig. 6) however, the Wetterstein reef transitions northward into the Partnach Formation. The fault which causes the duplication and the occurrence of Reichenhall Formation at surface, is thought to be a lateral equivalent of the Eben Thrust, west of Kramsach (Fig. 3). This follows an interpretation by Ortner and Gruber (2013), and fits the estimation of total offset along the ISZ of approximately 40 km (Ortner et al., 2006). The Eben Thrust is an out-of-sequence thrust, which brings the Haselgebirge-Reichenhall succession on top of the Gosau Group and to the surface (Gruber et al., 2022; Kooten et al., 2024). The detachment horizon in the Kaisergebirge for this out-of-sequence thrust is also in Haselgebirge and Reichenhall-Formation. We term this thrust the Joven Thrust, as it does not reach the surface but is directly underneath the Jovenalm and Jovenspitze (Fig. 6). The geometry of the footwall is inferred from sections of Ortner and Gruber (2013) and Kooten et al. (2024). BrT marks the continuation of the Brixlegg Thrust from the TRANSALP section to the east and was constructed following the considerations of Ortner et al. (2006). In this section the Brixlegg Thrust lies more or less horizontal, parallel to the Alpine Basal Thrust, and is cut by the younger ISZ and the Tauern Window bounding TNBF, as well as the subvertical, steeply southward dipping Brixental Fault (BtF). The BtF is also a newly defined fault structure, named after the valley Brixental, where it is covered underneath Quaternary sediments, striking parallel to the valley (Fig. 3 and 6). This fault is needed for explaining the offset of the Hochhörndler and Wildseeloder complexes against the Glemmtal complex (Fig. 6). Furthermore, the western continuation of the BtF is delimiting the SHN to the south against the tectonically lower Windau Nappe (Fig. 3). The southernmost appearance of Permo-Mesozoic sediments is located at Gaisberg (Figs. 3 and 6). The Permian to Triassic sediments rest unconformably upon the basement. According to Ortner and Reiter (1999), this contact is caused by Late Cretaceous normal faulting with top to the southeast kinematics, which displaces Early Cretaceous metamorphic isogrades.

The basement units south of the Kaisergebirge show the appearance of several Variscan complexes. However, the continuation to depth of the Variscan complexes is not well-constrained, as they were overprinted by (Eo-) alpine deformation, and are arranged in a nappe stack of Cretaceous age, evidenced by Eoalpine Ar-Ar ages (100 Ma) (Huet et al., 2018). The basement of the uppermost SHN consists of the Glemmtal, Wildseeloder and Hochhörndler Complex, whereas the Windau Nappe in footwall position also is comprised of Glemmtal Complex, Kellerjoch Orthogneiss and Kreuzjoch Complex (Fig. 4). The Cretaceous nappe stack is arranged in a ramp geometry on the Brixlegg Thrust, which is inferred from the geometry of the same thrust in the TRANSALP section, and postdates Cretaceous thrusting. The thrust between SHN and Windau Nappe, as well as the thrust between Windau Nappe and Wildkogel Nappe at their surface intersection in the southern part of the cross section, are both steepened to overturned and represent the northern limb of a km-scale, recumbent, north facing anticline. The newly proposed BtF shows significant offset in map view (Figs. 3 and 6a), and is interpreted primarily as a sinistral strike-slip fault, but might as well have a vertical component.

5. Discussion

5.1. Interpretation of the tectonic history of the two cross sections

In the following we discuss the lateral (dis-) continuity of structures mentioned in the TRANSALP and KAISER sections and reconstruct the history of deformation of the Permo-Mesozoic cover nappes and their crystalline basement nappes in the study area.

5.1.1. Cretaceous thrusting (in-sequence)

Nappe stacking in the western NCA started in the Hauterivian by emplacement of the Lower Triassic Reichenhall Formation of the Karwendel Nappe onto the Lower Cretaceous Schrambach Formation of the Tannheim Nappe (Kilian and Ortner, 2019; Ortner and Kilian, 2022). This is documented in the Karwendel range (Fig. 3), north of Innsbruck, where subsequent folding and out-of-sequence thrusting brought the internal, older part of the here mentioned Lechtal Thrust to the surface (Kilian and Ortner, 2019). The Karwendel Nappe progressively overrode younger sediments up to the Albian Losenstein Formation in the most external NCA (see Fig. 6), caused by northwest- to north-northwest-directed movement (Auer and Eisbacher, 2003; Eisbacher and Brandner, 1996; Ortner, 2003b; Ortner and Kilian, 2022). The décollement of the external part was located in Permian to Triassic evaporites. In the most internal, southern part, the crystalline basement is still attached to the Permo-Mesozoic cover. At surface the sedimentary contact to the basement of the Phyllitgneis Zone (PGZ) is visible at surface at the most western appearance of the nappe (Fig. 1). The Lechtal Thrust, separating the Karwendel Nappe from the Tannheim Nappe, is visible in our interpretation of the TRANSALP, and in the KAISER section (Figs. 5b and 6b). In the TRANSALP, the Lechtal Thrust is moderately south dipping and, truncated by the Alpine Basal Thrust. In the KAISER section this thrust is assumed to be flatter, as along the whole Chiemgau Alps (Fig. 6) folded Hauptdolomit is exposed at the surface, with flat lying, east-west striking fold axis. The Thiersee Thrust, seen in the TRANSALP section (tt of Fig. 5), is a lateral continuation of the Achental Thrust. The Achental Thrust was also activated in the Cretaceous prior to deposition of Gosau Group (Ortner, 2003a; Gruber et al., 2022; Kooten et al., 2024). Pre-Gosau activity of the Thiersee Thrust is proposed by Töchterle (2005), whereas there is also some north-ward thrusting post-dating Gosau sedimentation (Ortner, 2003a; Töchterle, 2005; Gruber et al., 2022). The youngest sediments below the Thiersee Thrust observed at the surface along the TRANSALP section are marls of the Schrambach Formation. In the eastern Thiersee Syncline the youngest sediments reach up to Albian times (Hagn, 1982). The displacement of the Achental Thrust is assumed to be in the order of 4–5 km (Auer and Eisbacher, 2003; Gruber et al., 2022). However, the displacement of the Thiersee Thrust measured on the seismic interpretation between Plattenkalk in the overturned limb of the hanging wall and the Plattenkalk on top of the massive Hauptdolomite in the footwall, is in the range of 10 km (1 and 2 in Fig. 5b). Given the limited offset of Gosau-Group sediments in the hanging and footwall of the eastern Thiersee Thrust (Risch, 1985), and the extent of Cretaceous sediments at depth underneath the thrust in the seismic section, the dominant phase of thrusting along this fault appears to be of pre-Gosau activity. The Thiersee Thrust itself cuts across the entire Permo-Mesozoic succession and is then cut off at depth by the younger fault-system made up by the ISZ and the STR. In the KAISER section the Thiersee Thrust is not seen, due to its lateral termination, probably in the eastern most Thiersee syncline near Inn valley.

In our study area, Cretaceous thick-skinned nappe displacement affected the basement nappes exposed south of the Inn valley. The Cretaceous thrusts segmented Variscan basement into the SHN, Windau Nappe and Wildkogel Nappe, starting with the tectonically highest (Huet et al., 2019; Hollinetz et al., 2022). These nappes of the Tirolic-Noric Nappe System are partly resting on top of the Königsleiten Nappe, which is part of the Silvretta-Seckau Nappe System (Huet et al., 2019). We interpret that the Cretaceous thrusts are then cut and displaced by the Brixlegg Thrust, as these Cretaceous structures are terminating against the Brixlegg Thrust in the seismic section (Fig. 5). The transgression of Permo-Mesozoic sediments onto different complexes in the two sections is caused by the pre-existing deformation of the Variscan complexes. The exposure at surface of deeper Cretaceous basement nappes in the west, is mostly due to younger, Oligocene-Miocene processes (see below).

5.1.2. Paleogene out-of-sequence thrusting

In Paleogene the nappe stack of thin-skinned Permo-Mesozoic cover nappes as well as thick-skinned basement nappes were cut by major thrusts in an out-of-sequence fashion. The most prominent out-of-sequence thrust in this study is the Brixlegg Thrust, first detected on the TRANSALP by Ortner et al. (2006). We follow the interpretation of Paleogene thrusting, which lead to continent-continent collision and exhumation in Eocene (Handy et al., 2010). In the well Vordersee 1, east of Salzburg (70 km east of section KAISER), Paleogene sediments were drilled underneath the SHN (Geutebrück et al., 1984)(also see cross sections of Hejl et al. (1988) and Pestal et al. (2005)). This can be seen as a lateral equivalent of the Brixlegg Thrust, as the thrust drilled at Vordersee 1 is the floor thrust of the same tectonic unit, and confirms a Paleogene age. In the TRANSALP section the Brixlegg Thrust cuts older thrusts of Cretaceous age (Fig. 5), and must therefore be younger. The Brixlegg Thrust cannot be seen as a nappe boundary in the sense of Cretaceous in-sequence thrusting. We speculate, that the Brixlegg Thrust could have been active in the Eocene. The AFT ages of 39±5 Ma next to the TRANSALP south of the Inn valley (Most, 2003), and around 42 Ma south of St. Johann i.T. (Fig. 3) (Grundmann and Morteani, 1985) might correlate to this event.

For an estimation of the amount of thrusting along the Brixlegg Thrust, it is valid to use the north-south striking TRANSALP cross section, as we can assume north-northeast – south-southwest compression for the time of activity of the Brixlegg Thrust in Paleocene-Eocene (Eisbacher and Brandner, 1996; Ortner, 2003b). Using cut-off points of the base of Schwaz Dolomite in the TRANSALP section, we get approximately 9–10 km of displacement along the fault. The amount of displacement may be larger, as the Schwaz Dolomite in the hanging wall is today in a subvertical position due to Paleogene folding and overprinting of pre-existing folds (Ortner and Reiter (1999) and their deformation phase D4). Another Paleogene thrust is The Joven Thrust (Fig. 6). Apart from postdating Gosau sedimentation and predating ISZ activity, the exact timing is unclear, as well as the amount of thrusting.

5.1.3. Post-Eocene out-of-sequence thrusting and normal faulting

Persistent convergence between Adria and Europe after the Late Eocene is evidenced by the thrusting of Triassic carbonate platform sediments on top of shallow marine clastic deposits of the Priabonian Oberaudorf-beds across the Miesberg Thrust in the area between Kufstein and Kössen (Fig. 6; see 4.2). However, in the Inn valley to the west, between Innsbruck and Kufstein, sedimentation of the Inneralpine Molasse only started in Late Eocene – Early Oligocene (Ortner and Stingl, 2001), also evidenced by the onset of Unterangerberg Formation as first clastic Molasse succession in the TRANSALP section (Fig. 5). Ortner et al. (2006) interpreted the Inneralpine Molasse as wedge-top sediments (following DeCelles and Giles, 1996), implying that the NCA at this time must have been part of the Alpine Foreland system. The ISZ was probably predetermined by a major Upper Oligocene normal fault that formed in response to bending strain in the flexing European plate during subsidence of the foreland basin (Ortner et al., 2006). Downthrow of the southern block caused topography and channelized clastic sediments from the internal Alps to the Chiemgau fan at the southern margin of the foreland basin (Brügel et al., 2000; Ortner and Stingl, 2001). This downthrow of the southern block is visible in both cross sections on the northernmost branch of the ISZ.

5.1.4. Post-Oligocene thrusting and strike-slip faulting (lateral extrusion)

The tectonic evolution of the Eastern Alps in Late Oligocene-Miocene is dominated by normal and strike-slip faulting, due to east-directed escape tectonics of crustal wedges of the collapsing thickened Eastern Alpine crust and opening of the Pannonian Basin (Ratschbacher et al., 1991). The most prominent fault structures addressed to this event in the region are the Brenner Normal Fault (Ratschbacher et al., 1991; Fügenschuh et al., 1997; Wolff et al., 2020) and the ISZ (Linzer et al., 2002; Ortner, 2003b; 2006).

AFT data indicate coeval cooling of the low-grade Windau and Wildkogel basement nappes along the Brenner Normal Fault and the TNBF in Middle Miocene (Fügenschuh et al., 1997; Grundmann and Morteani, 1985; Most, 2003)(see also Figs. 3, 5b and 6). This was interpreted as the result of upramping of the floor thrust of the Venediger Duplex (STR on Fig. 5) via the ISZ to the surface (Lammerer and Weger, 1998; Ortner et al., 2006; Eizenhöfer et al., 2023). These faults are also connected to and contemporaneous with the Brenner Normal Fault (Wolff et al., 2020) and its northern continuation, the Silltal Fault (Fügenschuh et al., 1997).

South of the Inn valley tectonically deeper basement nappes are exposed towards the west. Therefore the STR needs to flatten out to the east, merging into the Alpine Basal Thrust (Ortner et al., 2006). Exhumation above the STR disappears in the area of the Kaisergebirge, except for the rim of the Tauern Window. Concurrent with orogen-perpendicular shortening, orogen-parallel extension was delimited by major strike-slip faulting (Ratschbacher et al., 1991; Linzer et al., 2002), resulting in Miocene faulting of Oligocene Inneralpine Molasse sediments by the ISZ. The decreasing amount of basement uplift south of the ISZ and the flattening of the STR is also going along with a steepening of the ISZ from west to east. Despite the rather narrow time window in the AFT ages at the rim of the Tauern Window and along the Brenner Normal Fault /Silltal Fault between 12 and 14 Ma (see Fig. 3), AFT ages are significantly scattered within the basement nappes of the Wildkogel Nappe and Windau Nappe between the TWNBF and the ISZ. However, most of the data do not allow reconstructing differential uplift in this area. Interestingly, the data next to TRANSALP from Most (2003) show clear cooling paths, with little residence times of the separate samples in the partial annealing zone, and rapid cooling at the time reaching closure temperatures in apatite. This means fast cooling for the more southern part of the Austroalpine basement in Miocene, whereas the more northern part of the basement had already rapidly cooled in Late Eocene (Most, 2003) (Figs. 3 and 5b). Independent from thermo-chronological data, sub-vertical to steeply south-dipping faults are proposed south of the Inn valley (Fig. 5b), that intersect the nappe stack (e.g., the Brixental Fault). These faults seem to have significant offset, and might have not been recognized in the field yet to their full extent, due to monotonous lithologies. The geometry of these faults is still to be debated, as they might as well take on vertical uplift from the STR and therefore may have caused a scattering in Miocene cooling ages.

5.2. The observed structures in a tectonic framework

When assigning tectonic units to the above-mentioned structures, we observe that the existing units of SHN and Karwendel Nappe, and therefore Tirolic and Bajuvaric nappe systems respectively, are separated by different thrusts and faults of assumed Paleogene to Miocene age. For the Brixlegg Thrust we propose a (Middle- to Upper-) Eocene age due to AFT data (see 5.1.2) (Figs. 5 and 6). A similar to slightly younger age is proposed for the Miesberg Thrust in section KAISER (Fig. 6), north of the Kaisergebirge, which overrides Upper Eocene Oberaudorf beds. The Miesberg Thrust and the Oligocene-Miocene ISZ have previously been taken as the boundary between the Karwendel Nappe (former Lechtal Nappe) and SHN, and therefore Bajuvaric and Tirolic nappe systems (Hahn, 1913a; 1913b; Tollmann, 1976b). These relatively young fault structures post-date the time of thrusting which was previously thought to be nappe forming, the Eoalpine phase in Cretaceous (Froitzheim et al., 1994; Schmid et al., 2004; Schuster, 2015; Ortner and Kilian, 2022). Besides this, the nappe system classification still in use is based on Tollmann (1976b; 1985) (see introduction). In the following we will refer to the problems of the used subdivision, and why this calls for a revision of the established tectonic units.

5.2.1. The problems in the tectonic subdivision of the NCA after Tollmann (1976b; 1985)

(1) **Facies tectonics**: Although Tollmann was very aware of the fact that tectonic boundaries do not necessarily align with facies transitions, he called the nappe systems of the NCA *"a good example of facies tectonics" (Tollmann, 1976b)*. Despite already Hahn's (1913a) assertion that sedimentary facies provinces do not align with the boundaries of subsequent tectonic units, and the recommendation to avoid confusion between facies and tectonic terms, the influence of sedimentary facies on the definition of tectonic nappe systems persisted. Moreover, nappe systems were used to define different areas of the Tethyan shelf (Haas et al., 1995; Mandl, 2000), and vice versa the deduced facies zonation on the Tethyan shelf was used as an indication of tectonic origin. The Bajuvaric and Tirolic realms were attributed to the Hauptdolomit and Dachstein facies belts (Mandl, 2000), while isolated Dachstein reefs and Hallstatt facies were assigned to the Juvavic realm (Haas et al., 1995). These facies belts are based on the Upper Triassic carbonates in the Hauptdolomit, Dachstein and Hallstatt facies (Tollmann, 1985). The facies zones of Hauptdolomite and Dachstein limestone partly overlap or exhibit a gradual transition from one into the other within the SHN. This is evidenced by the occurrence of Hauptdolomit overlain by Dachstein limestone in the Loferer Steinberge area (Fischer, 1964; Tollmann, 1976b) and in the Sonntaghorn area (Hahn, 1910). Middle Triassic basin or platform carbonates (Partnach Fm. vs Wetterstein Fm) were also used by Tollmann (1976b) to assign areas of unknown tectonic position either to the Tirolic Inntal Nappe or the Bajuvaric Lechtal Nappe. We see a facies transition in Middle Triassic carbonates in the Tirolic SHN and the Bajuvaric Karwendel Nappe (following Ortner and Kilian, 2022).

(2) **Confusion of terminology**: The different evolu-

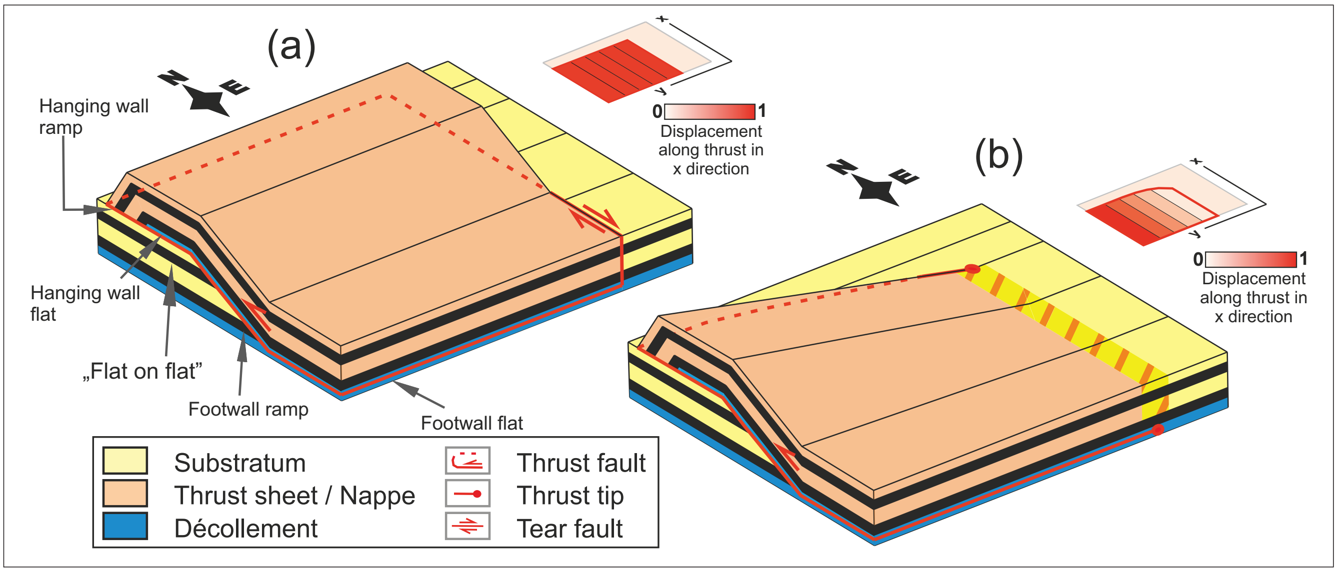

Figure 7: Schematic models of a northward thrusted nappe. Two end-members of nappes / thrust sheets ending in the east, using a fault-bend-fold ramp-anticline model. The small diagrams in the upper right show the difference in the amount of displacement in x-direction (northward). (a): The lateral termination to the east is caused by a tear fault, the displacement along the thrust surface is the same along the thrust. (b): The offset along the thrust decreases to the east and the thrust sheet merges with its substratum where the thrust ends.

tion of the Middle Triassic (Anisian-Ladinian) to the lower Upper Triassic (Carnian) was subsequently employed to divide the zones into sub-facies zones. The sub-facies of the Hauptdolomit facies zone was called "Tyrolean facies" by Tollmann (1985). Besides the use of sub-facies to define tectonic units (see above), it is also problematic concerning the use of names. "Tyrolean" was used for facies, "Tirolic" primarily was used as a tectonic term translated from Hahn's (1912) "tirolisch", then adapted by Tollmann (1976b) referring to his unit of the "Tirolikum". Finally the origin of Tirolic nappes was termed as "Tyrolic" realm (Mandl, 2000), ultimately mixing tectonic and facies terms.

(3) **New findings**: The tectonic subdivision is particularly contentious, given that the Juvavic units do not constitute a coherent tectonic entity, in the sense of a far travelled allochthon from the distal Tethys margin, when viewed in the context of relative autochthonous, salt-related structures (Fernandez et al., 2024). Moreover, Tollmann (1976b) already stated, that the use of the term Juvavic (german "Juvavikum") is due to its historical rooting, as the unit is partly not tectonically distinguishable from the underlaying Tirolic Unit.

(4) **Timing of thrusting**: Because Tollmann (1976b) did not incorporate the timing of thrusting into his definition of nappes, he used thrusts (and more generally faults) of different age as nappe boundaries. Nevertheless, there was a high degree of consistency in subsequent work, with the formation of nappes occurring during the Eoalpine phase, starting in late Early Cretaceous – early Late Cretaceous (Ortner, 2003a; Eisbacher and Brandner, 1996; Tollmann, 1976b; Schmid et al., 2004; Schuster, 2015; Ortner and Kilian, 2022). Similar to the approach of Schmid et al. (2004), limiting nappe formation to the Eoalpine phase, Ortner and Kilian (2022) tied the generation of cover nappes in the NCA to Cretaceous in-sequence thrusting. Out-of-sequence thrusting did then not contribute to nappe formation.

5.3. A possible new definition of nappes and nappe systems

Given the inconsistencies identified in the nomenclature currently used for the classification of nappes and, accordingly, nappe systems, a new definition is proposed.

5.3.1. Nappes defined by geometry

The nappe definition from Tollmann (1973) cited in the introduction already mentions the actual importance of nappe geometry on nappe definition. In more modern and fundamental works on structural geology and tectonics, a nappe or thrust sheet (the two terms are used synonymously here) is simply described by *"a volume of rock bounded below by a thrust fault"* (McClay, 1992), whereas a thrust is described as a low angle fault with predominantly dip-slip movement, where the hanging wall is transported over the footwall (Fossen, 2010). Fossen (2010) also discusses the possibility of taking the thrust distance into account (>5 km). Taking this back to the NCA, we state problems in terminology: (1) A lot of thrusts would not fulfil the criterion of dip slip movement, although they show multiple kilometres of transport onto the footwall. (2) The amount of thrusting is a problematic attribute, which can only serve as a relevant criterion when dealing with perfectly cylindrical, endlessly large nappes, where thrusts do not die out laterally and offset never becomes zero. Obviously, this does not reflect the geometry of thrusts, as Ortner and Kilian (2022)

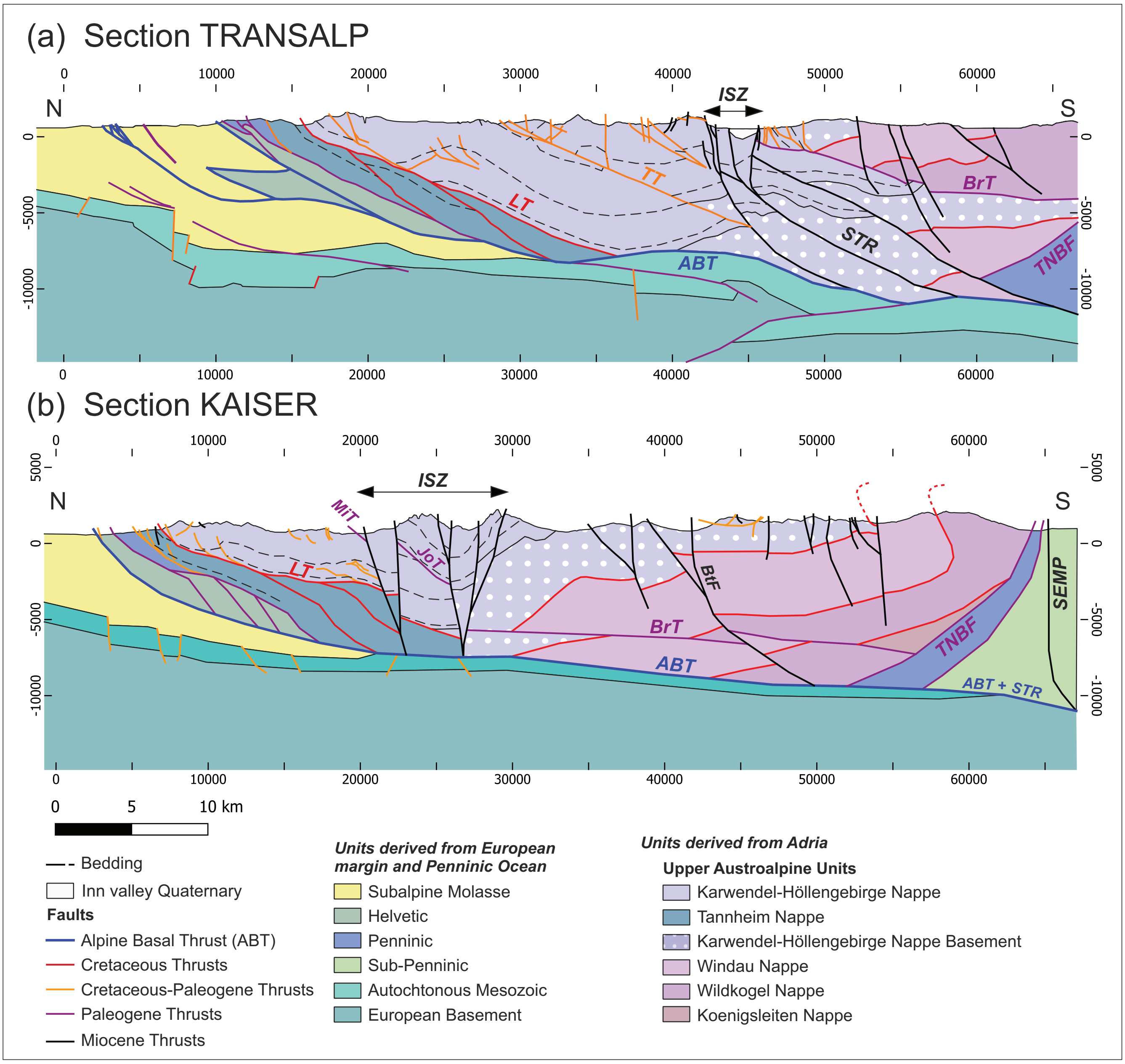

Figure 8: Two cross sections along the TRANSALP seismic profile (a) and from the Alpine Foreland through the Kaisergebirge to the Salzach valley (KAISER, b), showing the tectonic subdivision above the ABT (blue thrust), based on Cretaceous thrusting and a coherent Karwendel-Höllengebirge Nappe. The different colours of thrusts show the different age of activity. ABT: Alpine basal Thrust, BtF: Brixental Fault, BrT: Brixlegg Thrust, ISZ: Inntal Shear Zone, LT: Lechtal Thrust, MiT: Miesberg Thrust, SEMP: Salzachtal-Ennstal-Mariazell-Puchberg Fault, STR: Subtauern ramp, TNBF: Tauern Window Northern Boundary Fault, TT: Thiersee Thrust.

have shown for the western NCA (for example their Obermoos Thrust).

Our suggestion for the definition of nappes therefore is the following:

1. A nappe/thrust sheet is a plate-like structure, which extends on the scale of several kilometres and its horizontal extent is a multiple of its thickness.
2. The nappe is not an infinite structure and can end laterally, either explicitly against a tear fault (Fig. 7a) or where displacement across the thrust ends at the base (Fig. 7b). In such a case the termination is not explicit.
3. The contact of stacked nappes (and/or substratum), (partly) shows a flat-on-flat geometry (Fig. 7a).

The ramp-flat geometry or fault-bend fold model is a geometric model, generally used for nappe emplacement (Boyer and Elliott, 1982; Suppe, 1983; McClay, 1992; Twiss and Moores, 2001). Although its simplicity has its limitations, as nappe internal deformation is neglected (Ramsay, 1992; Hogan and Dunne, 2001), it is suited to describe large scale tectonic structures in thrust fault systems (Twiss and Moores, 2001). The above-mentioned flat-on-flat criterion describes the structure af-

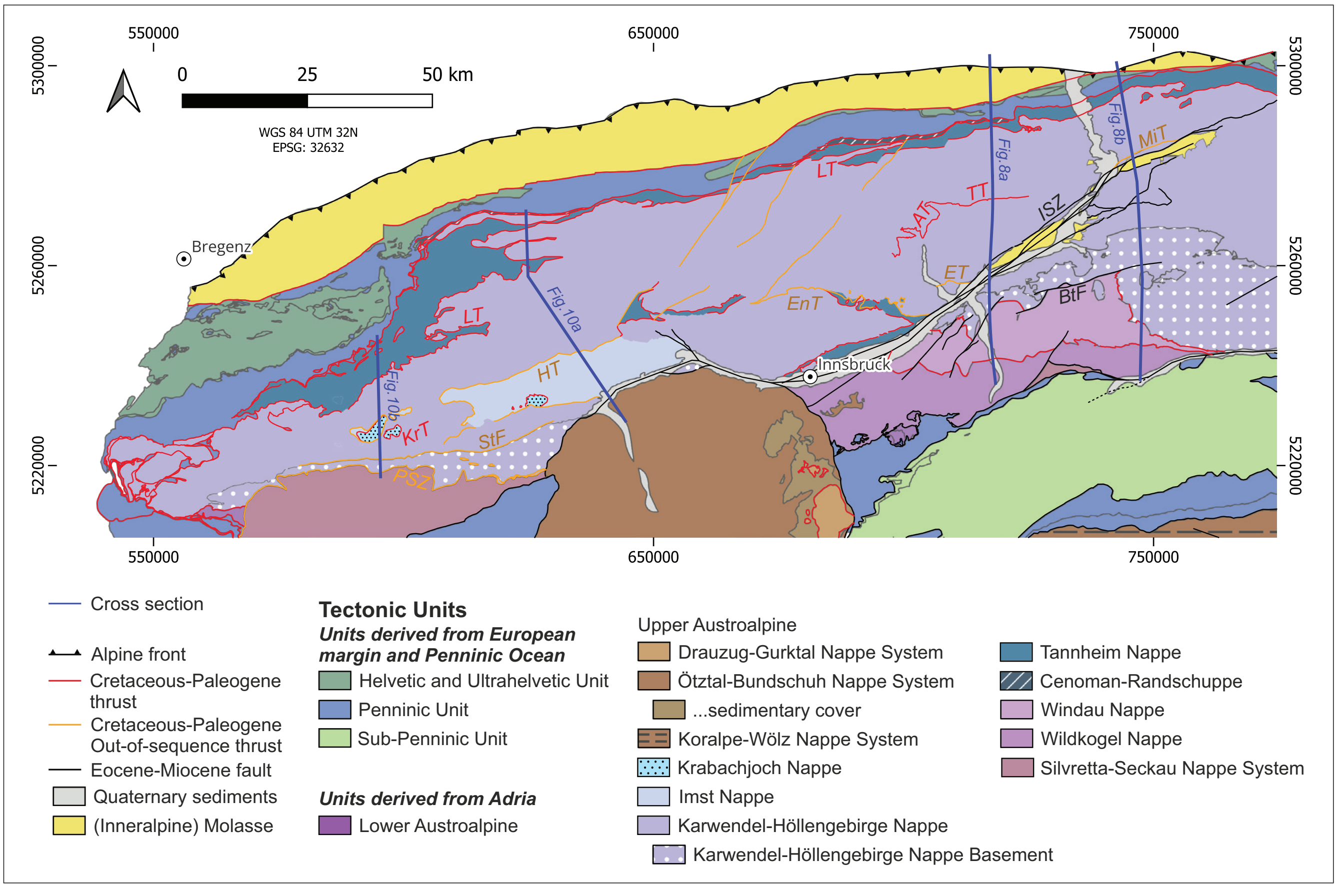

Figure 9: Tectonic subdivision based on the newly defined nomenclature of nappe classification. The blue lines indicate the section traces. Fig. 8a and Fig. 8b mark the sections of TRANSALP and KAISER, Fig.10a and Fig.10b mark schematic cross sections from Figure 10. AT: Achental Thrust, BtF: Brixental Fault, ET: Eben Thrust, EnT: Eng Thrust, HT: Heiterwand Thrust, ISZ: Inntal Shear Zone, KrT: Krabachjoch Thrust, LT: Lechtal Thrust, MiT: Miesberg Thrust, PSZ: Puschlin Shear Zone, StF: Stanzertal Fault, TT: Thiersee Thrust.

ter the hanging wall flat had overridden the footwall ramp. In the flat-on-flat part of the structure, doubling of the succession is observed, as well as large tectonic transport. If the hanging wall had not been entirely transported across the footwall ramp, thickening occurs, but tectonic transport is limited. A ramp is crucial for tectonic thickening – bedding parallel or surface-parallel transport on a décollement does not thicken. It should be noted that the use of the aforementioned classification is more intricate when dealing with polyphase deformation and/or pure basement nappes. It is best applied to cover nappes of foreland thrust belts and the basement partly attached to them. In cases where thrusts cut across rocks that have already undergone significant deformation, the interplay of geometries can potentially cause misleading interpretations. Therefore, the interpretation has to rely on reconstruction of particle paths along the thrusted zone, and not only on the angular relationship between foot and hanging wall. In basement nappes décollements potentially form at the ductile-brittle-transition, ramping up to more shallow depth, eventually linking to a décollement in the cover succession. Consequently, this forms relatively thick nappes (Kley, 1996; Pfiffner, 2017; Muñoz, 2019), that act like thin-skinned nappes (following Hatcher and Hooper, 1992, and their Typ C nappes).

The Brixlegg Thrust (TRANSALP and KAISER sections of Fig. 8) has a hanging wall ramp geometry and does not show a flat-on-flat configuration. This means it does not fulfil the criteria for a nappe bounding thrust. This is also the case for the Thiersee Thrust (Fig. 5) as well as for most of the other mentioned out-of-sequence thrusts, like the Eng Thrust (Kilian and Ortner, 2019) in the Karwendel mountains, the Eben Thrust (Kooten et al., 2024) in the Rofan range, and the Obermoos Thrust (Ortner and Kilian, 2022) in the Zugspitz massif. Also, the Miesberg Thrust and the Joven Thrust (KAISER section on Figs. 6 and 8) show a ramp geometry, which in turn implies that they cannot serve as a nappe boundary either. However the geometric criteria are fulfilled for the Heiterwand Thrust in the Lechtal Alps, which serves as the sole thrust for "Imst part of Karwendel Nappe" of Ortner and Kilian (2022). We suggest to call this independent nappe "Imst Nappe" (Figs. 9 and 10). Its eastern termination is a dextral strike-slip fault, which serves as a tear fault (Fig. 7a) in the sense of Eisbacher and Brandner (1996). The criteria are also fulfilled by the large nappes formed during Cretaceous stacking, the Karwendel Nappe and the Tann-

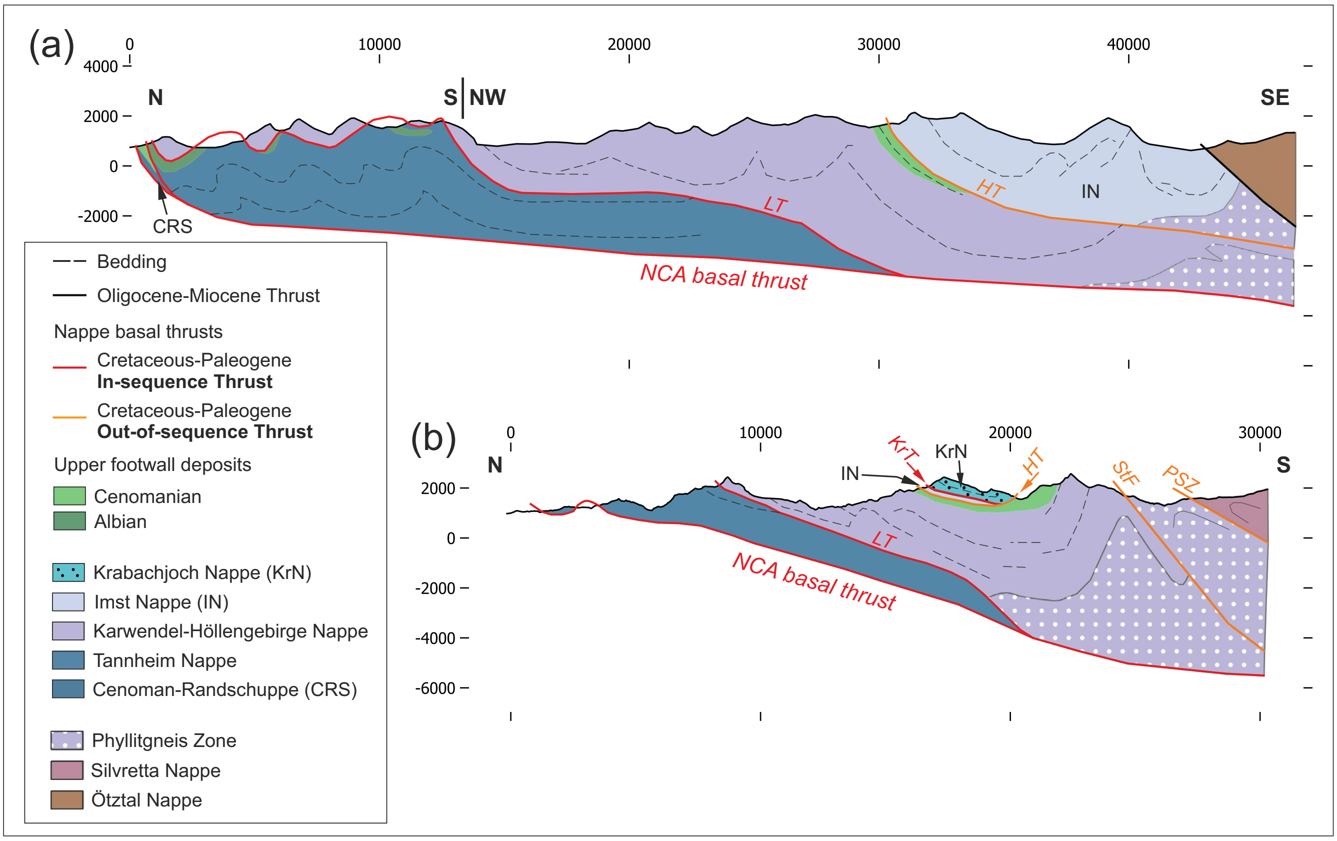

Figure 10: Schematic cross sections across the western part of the NCA, highlighting the geometry of the new defined "Imst Nappe", as well as the Krabachjoch Nappe. **(a)** Cross section from the Ötztal Nappe to the NCA front, redrawn from Eisbacher et al. (1990). **(b)** Cross section from St. Anton in Tirol to the NCA front, adapted from May and Eisbacher (1999). HT: Heiterwand Thrust, KrT: Krabachjoch Thrust, LT: Lechtal Thrust, PSZ: Puschlin Shear Zone, StF: Stanzertal Fault.

heim Nappe (Ortner and Kilian, 2022), as well as for the Krabachjoch Nappe (Ampferer, 1914) (see Figs. 9 and 10). Finally, also the fault-system made up by the ISZ and the STR, individually or collectively analysed, does not serve as a nappe boundary, as it does neither reach a flat-on flat geometry, nor act as a tear fault.

5.3.2. Nappe system classification

Kilian and Ortner (2019) first proposed a Karwendel Nappe, comprised of the former Inntal Nappe and parts of the Lechtal Nappe (Tollmann 1976b). Ortner and Kilian (2022) conclude, that the Karwendel Nappe is in sedimentary contact with the PGZ (or "Venet Complex" after Gruber et al., 2010) of the Silvretta Nappe (Rockenschaub, 1990), and therefore is part of the Bajuvaric Nappe System. The SHN is assigned to the Tirolic Nappe System since Hahn (1913b). As shown in 5.3.1, the aforementioned nappes are not separated by thrusts that fulfil our criteria of nappe boundaries. Therefore, we suggest a continuous nappe, which consists of the Karwendel Nappe and the SHN. The issue with this "super" nappe is, that it is in sedimentary contact with the basement of the former Western Greywacke Zone in the east (Heinisch, 1986) and with the PGZ in the west (after Rockenschaub (1990)), which therefore need to be lateral equivalents of each other's. Following the subdivision of the basement units (see 2.2), the former Innsbruck Quartzphyllite Zone, formerly belonging to the Silvretta-Seckau Nappe System (Schmid et al., 2004), is now to a large extent incorporated in the Wildkogel Nappe and part of the Tirolic-Noric Nappe System. This unit extends to the west underneath the Ötztal Nappe, separated from the latter by the Brenner Normal Fault. This puts the Tirolic-Noric nappes in the footwall of the Ötztal-Bundschuh Nappe System (Schmid et al., 2004), as already schematically shown by Eisbacher et al. (1990) and Stüwe and Schuster (2010) (their Fig. 2).

As mentioned, the PGZ is in sedimentary contact with the succession of the Karwendel Nappe. This succession starts already in Late Carboniferous with the Kristberg beds (Amerom et al., 1982) in the very western part of the NCA. An equivalent of these Carboniferous sediments can be traced to the east into the "Zone of Puschlin" (Rockenschaub, 1990). This, mostly Permo-Mesozoic slivers-bearing zone between the PGZ and the Silvretta Nappe has been seen as shear zone ever since, but with different implications on the large scale tectonic picture (Tollmann, 1963; Kreczy, 1981; Frank, 1983; Spiess, 1987; Rockenschaub, 1990; Nowotny et al., 1993) (termed as "Puschlin Shear Zone" in the following). We interpret the PGZ as basement part of the continuous Karwendel Nappe – and SHN, separated from the Silvretta Nappe. The unique tectonic feature of the eastern PGZ is its Cre-

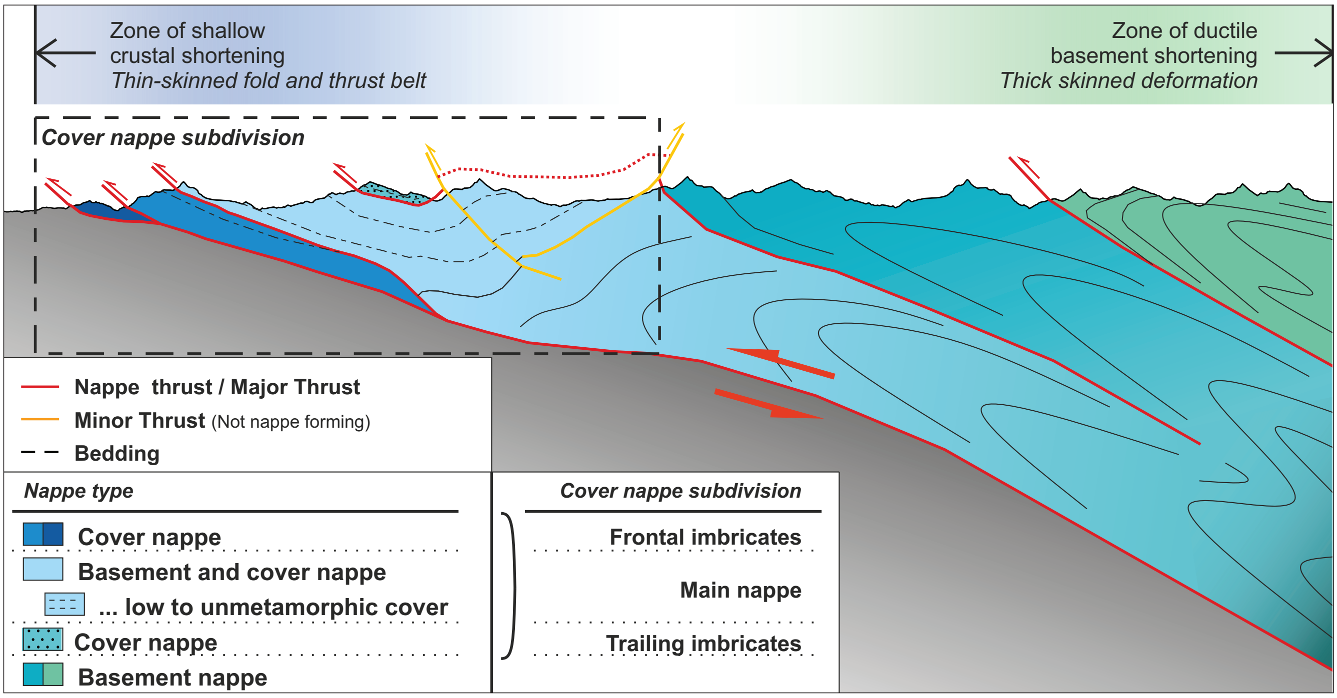

Figure 11: Schematic sketch of an idealised nappe stack, from thin-skinned fold and thrust belt to ductile thick-skinned thrusting. The thin-skinned cover nappe classification is highlighted. Sketch partly based on Twiss and Moores (2001) (p109). The Main nappe with attached basement nappe is drawn as a Type C crystalline nappe, the crystalline nappes in the hanging wall position coloured green are drawn as Type F fold nappes (following Hatcher and Hooper, 1992).

taceous low prograde metamorphic overprint (Amann, 1985), which is in contrast to the weak retrograde Cretaceous overprinting of the Silvretta Nappe south of the Puschlin Shear Zone (Nowotny et al., 1993). However, this Cretaceous overprint is weakened to the western PGZ and affects both PGZ and Silvretta Nappe (Kreczy, 1981; Spiess, 1985). Nevertheless our interpretation does align with Frank (1983), as we see the PGZ as a low grade metamorphic, northern lateral continuation of the Silvretta Nappe. An out-of-sequence thrust (Puschlin Shear Zone, Figs. 9 and 10) separates the Silvretta Nappe from the PGZ. Later on, deformation shifted northward to the base of the Permo-Mesozoic succession along the Stanzertal Fault (Eisbacher and Brandner, 1996). A Paleogene age of this structure was proposed by Eisbacher and Brandner (1996), and is also suggested by slivers of the Arosa Zone at the western tip of the Fault (Ampferer, 1936).

We term this coherent unit of Karwendel Nappe and SHN the "Karwendel-Höllengebirge Nappe" (Fig. 8), which is covering most of the western and middle NCA and its attached basement. It was thrusted northwest-wards onto the synorogenic deposits of the Tannheim Nappe, starting in the Hauterivian, detached in Upper Permian to Middle Triassic Haselgebirge to Reichenhall succession (Kilian and Ortner, 2019). While the formation of large thrust sheets propagated northwest to north-wards in the Late Cretaceous, forming the Tannheim Nappe and the Cenoman-Randschuppe, major out-of-sequence thrusts (Eng Thrust, Eben Thrust, Brixlegg Thrust, etc…) with multiple kilometres offset each, started to intersect the Eoalpine nappe pile. This created nappe like structures all over the western NCA, but not reaching flat-on-flat geometry, in the sense of the above-described criterion.

Additionally, the (Upper) Bajuvaric nappes and Tirolic Nappe System (Tollmann, 1976a; 1976b) are not separated by a thrust which full fills our criterion to floor nappes. The change in facies is only due to sedimentary facies differentiation and not due to tectonic displacement. We therefore propose to abandon the concept of a tectonic subdivision entirely based on Cretaceous (in-sequence) nappe stacking, and decline the usage of the terms "Tirolic", "Bajuvaric" and "Juvavic".

5.3.3. Nappe systems and a possible start to further discussions

As we do see the necessity for grouping tectonic nappes into nappe systems, we want to initiate a discussion in the following paragraph. Similar to the definition of nappes themselves, nappe systems can be grouped by geometry or geometric attributes. A fundamental aspect influencing the deformation behaviour of the nappe depends on whether the nappe is still attached to its basement, or not. The nappe configuration can be classified into three types (Fig. 11): (1): A large Main nappe, that is still attached to basement. (2): Frontal imbricates, nappes that are completely separated from their basement and now lie in the footwall of the Main nappe. (3): Trailing

Tectonic position	Nappe type	Characteristics	Proposed name for the Nappe System	Nappe in the western NCA	Nappe in the central NCA	Nappe in the eastern NCA
upper	Trailing Imbricate	No basement attached above Main Nappe	Krabachjoch-Mürzalpen Nappe System	Krabachjoch Nappe[1]	Dachstein Nappe[6], Totes Gebirge Nappe[6] Warscheneck Nappe[5]	Mürzalpen Nappe[7] Schneeberg Nappe[8] Hengst Nappe[8]
middle	Main Nappe	Basement partly attached	Karwendel-Göller Nappe System	*Imst Nappe*[2], *Karwendel-Höllengebirge Nappe*[3,4]	*Karwendel-Höllengebirge Nappe*[3,4]	Göller Nappe[7]
lower	Frontal Imbricate	No basement attached below Main Nappe	Tannheim-Frankenfels Nappe System	Tannheim Nappe[4], „Cenoman-Randschuppe"[5]	Reichraming Nappe[5], Ternberg Nappe[5], *Langbath Nappe*[6]	Ötscher[7]/Unterberg Nappe[8], Reisalpe Nappe[8], *Lunz-Sulzbach Nappe*[7,8], Frankenfels Nappe[7]

Table 1: Nappes of the NCA, grouped in nappe systems based on their relative position to units having a primary contact to the basement. Such a subdivision would avoid nappe systems defined by sedimentary facies. Nappes based on [1)] May and Eisbacher (1999), [2)] Eisbacher et al. (1990), [3)] This study, [4)] Ortner and Kilian (2022), [5)] Tollmann (1976b), [6)] Fernandez et al. (2024), [7)] Wessely (2006), [8)] Strauss et al. (2023); Names in italic are new terms based on the above mentioned criteria and the geometry of the nappe shown in the cited study.

imbricates, nappes that have no connection to the basement, but overthrust Main nappes, and are therefore in a hanging wall position. The Main nappe is similar to a concept of Tollmann (1973) and his "Stammdecke" (primary nappe), and which he used as a nappe classification based on areal distribution, but not for nappe system definition. Frontal and Trailing imbricates are derived from McClay (1992).

In the western NCA Main nappes are the Karwendel-Höllengebirge Nappe and the Imst Nappe. According to the most western and eastern occurrence of this type of nappes in the cover nappe stack of the NCA, we propose to summarize these nappes as Karwendel-Göller Nappe System (Tab. 1), following the interpretation of Wessely (2006) for the Göller Nappe. Nevertheless, it must be mentioned, that more recent publications interpret the contact between the Göller Nappe and the underlaying basement of the Noric Nappe not as sedimentary, but a tectonic contact (Strauss et al., 2023). Frontal imbricate nappes consist of the Tannheim Nappe and the Cenoman-Randschuppe in our study area. The most eastern part of this nappe system is the Frankenfels Nappe (Wessely, 2006), and we propose the term Tannheim-Frankenfels Nappe System. This nappe system includes all nappes of the former Upper and Lower Bajuvaric Nappe System after Tollmann (1976b), but also nappes from Tirolic Nappe System. For Trailing imbricates type only the Krabachjoch Nappe is representative in our study area. When considering the Göller Nappe as reference nappe, the eastern most trailing imbricate nappe in its hanging wall would be the Mürzalpen Nappe (Wessely, 2006; Strauss et al., 2023), leading to a Krabachjoch-Mürzalpen Nappe System. This nappe system incorporates units of the former Juvavic nappes, as well as from the Tirolic nappes (Tollmann, 1976b). For the central and eastern NCA, this is a first approximation, and we do not make claims for completeness.

6. Conclusion

With the interpretation of the reprocessed 40 km long TRANSALP segment, and another detailed cross section across the Kaisergebirge, we improve our understanding of the subsurface in the lower Inn valley significantly. With the urge to detangle the current inconsistency in nappe definition and to avoid the mixing of tectonic terms and sedimentary realms, we propose a new classification, based on nappe geometry only.

In the wider area along the lower Inn valley, this leads to the elimination of the fault system made up by the ISZ and STR as nappe boundary between the SHN south of the Inn valley and the Karwendel Nappe, north of it. In addition, other thrusts like the Brixlegg Thrust, Miesberg and Joven thrusts are not to be classified as nappe boundaries. These structures overprint a first generation of thrusts related to the Cretaceous nappe stacking as out-of-sequence structures, and do not separate nappes as they do not reach flat-on-flat geometry.

As a consequence, we merge the Karwendel nappe and SHN into the new "Karwendel-Höllengebirge Nappe". Its Permo-Mesozoic sediment succession is in direct contact with its basement. Cretaceous thrusting not only effected the Permo-Mesozoic cover, it also led to the formation of several basement nappes of Palaeozoic low grade metamorphic complexes, in the footwall of the Karwendel-Höllengebirge Nappe. These basement nappes (Windau Nappe and Wildkogel Nappe), together with the Karwendel-Höllengebirge Nappe as well as the other nappes of the NCA are in the footwall position of the Ötztal-Bundschuh Nappe System, and tectonically overlie the Silvretta-Seckau Nappe System in the east, but are as well in a footwall position of the latter in the west, due to an out-of-sequence thrust.

Additional to the Karwendel-Höllengebirge Nappe, we propose a new tectonic subdivision for the western NCA that is based on our classification of nappe bounding basal thrusts. The already established Tannheim Nappe and Cenoman-Randschuppe lie in a footwall position of the aforementioned nappe. Furthermore, the Karwendel-Höllengebirge Nappe is overthrust by the newly defined Imst Nappe and the Krabachjoch Nappe, in the most western NCA.

We also suggest to rediscuss the organization of nappes of the NCA in nappe systems. We propose that nappes can be organized based on primary basement contacts, and their positions relative to the nappes attached with basement. We also propose to abandon the terms Juvavic, Tirolic and Bajuvaric.

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