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A regional scale Cretaceous transform fault zone at the northern Austroalpine margin: Geology of the western Ammergau Alps, Bavaria

Anna-Katharina Sieberer[1]*, Hugo Ortner[1]
[1)] Department of Geology, University of Innsbruck, Innrain 52f, 6020 Innsbruck, Austria
[*)] Corresponding author, anna-katharina.sieberer@uibk.ac.at, annasieberer@hotmail.com

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Abstract
We reinvestigated parts of the northern Austroalpine margin and provided structural and kinematic field data in order to interpret the kinematic relationship between the Cenoman-Randschuppe (CRS) marginal slice, Falkensteinzug (FSZ), Tannheim- and Karwendel thrust sheets occurring in a narrow strip at the northern front of the northwestern Northern Calcareous Alps (NCA). As a consequence, we propose a revised model for the tectonic evolution of the northern Austroalpine margin. As thrusting propagates from SSE to NNW (Cretaceous orogeny), the Karwendel thrust sheet (including its frontal part, the FSZ) was emplaced onto the Tannheim thrust sheet in the Albian, deduced from (i) upper-footwall deposits, the youngest sediments below the Karwendel thrust (Tannheim- and Losenstein Fms.), and (ii) thrust-sheet-top deposits unconformably overlying the deeply eroded northern Karwendel thrust sheet (Branderfleck Fm.). The future CRS marginal slice was, at that time, part of the foreland of this Early Cretaceous Alpine orogenic wedge. Pervasive overprint by sinistral shear within the CRS marginal slice and northern Tannheim thrust sheet suggests sinistral W-E striking transform faults cutting across this foreland, decoupling CRS marginal slice and FSZ from the main body of the NCA and enabling an independent evolution of the CRS marginal slice from the Early Cretaceous onwards. Subsequent Late Cretaceous and younger shortening leads to successive incorporation of Arosa zone, Rhenodanubian Flysch (RDF) and Helvetic units into the Alpine nappe stack; the Tannheim thrust representing the basal thrust of the NCA. Growth strata within thrust-sheet-top deposits (Branderfleck-Fm.) give evidence for refolding of thrust sheet boundaries. In a typical thin-skinned fold-and-thrust belt, deformation should cease towards the thrust front, whereas within the NCA it increases. An Austroalpine thrust front controlled by E-trending transform faults could cause an increase in deformation towards the most external NCA and explain the absence of the Arosa zone between Allgäu and Vienna. Such faults would most probably also cut out Lower Austroalpine units. Therefore, RDF and CRS marginal slice are juxtaposed; the latter found in the tectonic position of the Arosa zone. The presence of transform faults underlines the strong imprint of the opening of the North Atlantic Ocean on the depositional setting and tectonic evolution of the NCA.

1. Introduction

The Cenoman-Randschuppe (CRS) marginal slice is the northernmost and tectonically deepest unit of the Northern Calcareous Alps fold-and-thrust belt (NCA) (Auer and Eisbacher, 2003; Gaupp and Eynatten, 2004). It is extremely narrow, with a maximum width of 700 m in the area of lake Tegernsee (Tollmann, 1969), and discontinuous, but occurs between Hindelang, Germany in the west to Vienna, Austria in the east, accompanying the NCA over most of its length (Richter, 1939; Müller, 1973). The CRS marginal slice was originally defined as *Randcenoman* by Richter (1937) and redefined by Tollmann (1969) as *Cenoman-Randschuppe*. The CRS marginal slice has a tectonic position equivalent to the Arosa zone further west (Richter, 1959; Trümpy, 1960), the latter representing the suture of the southern branch of the Penninic Ocean. Rocks of the CRS marginal slice appear highly deformed (Müller, 1973; Schnabel, 1979) and outcrop conditions are usually poor. The only exception is the western Ammergau Alps, where a complete section of Early to Late Cretaceous (Aptian to Turonian) rocks is exposed (Lukas and Weidich, 1987; Weidich, 1990) in the Schleifmühlgraben, termed Hölle by Fraas (1892).

In this study, parts of the northern Austroalpine margin have been reinvestigated and a revised model for the tectonic evolution of the area is proposed. Mapping of the study area was carried out at a scale of 1:10.000 and focused on (i) providing structural and kinematic data in

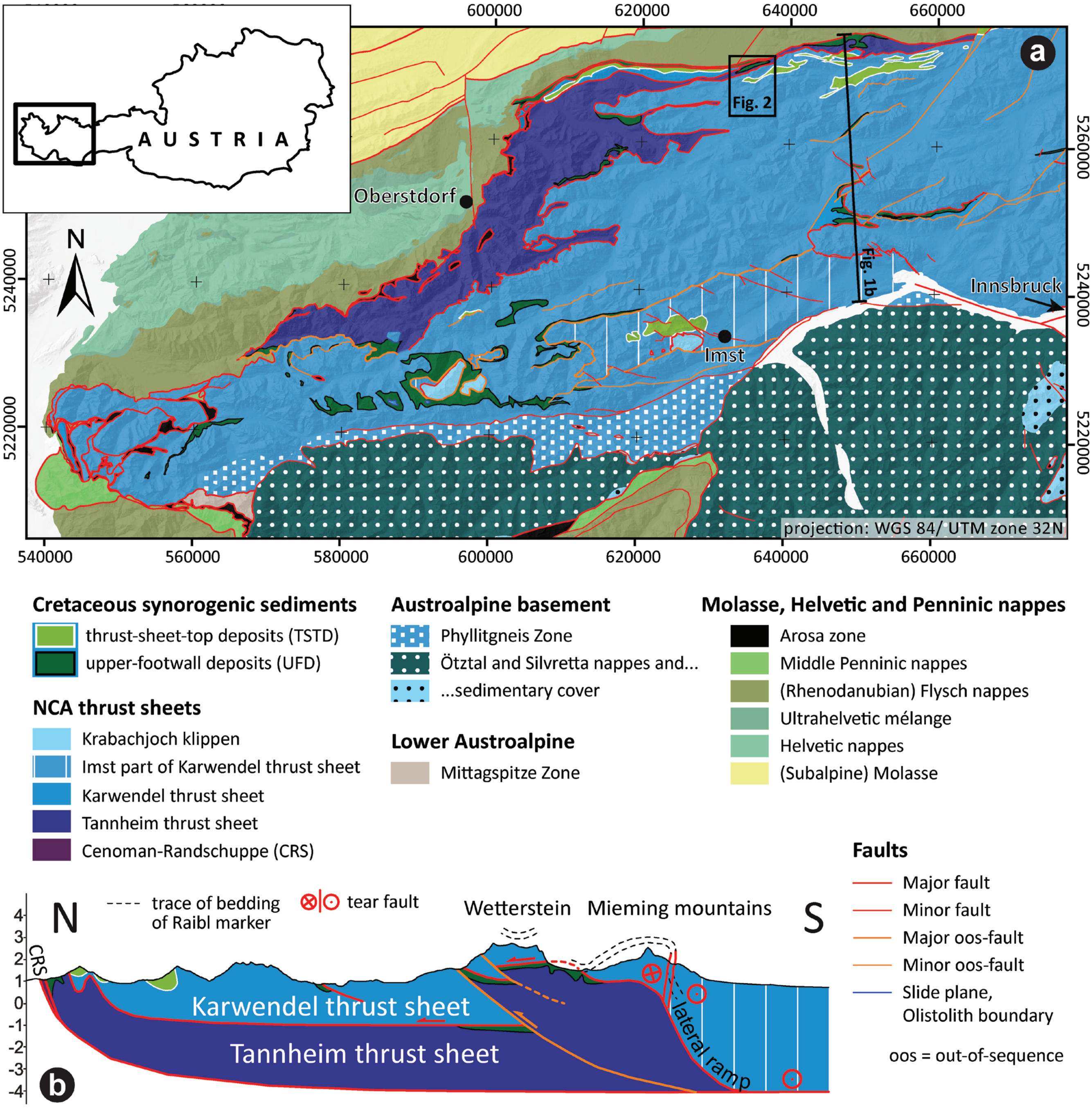

Figure 1: (a) Tectonic map of the westernmost Northern Calcareous Alps (NCA) with subdivision of tectonic units following Ortner (2016) and Ortner and Kilian (2022) and synorogenic sediments following Ortner (2003) and Ortner and Gaupp (2007). Note the differentiation in faults and out-of-sequence (oos) faults, the latter either dissect or are active in the hinterland of existing faults. The inset indicates the location of Figure 1a within western Austria and southwestern Germany. The indicated trace refers to the conceptual N-S cross-sections across the NCA east of the study area shown in Figure 1b. The black square indicates the location of the study area shown in Figure 2. (b) Cross-section of the Northern Calcareous Alps following the tectonic subdivision of Ortner (2016) and Ortner and Kilian (2022).

order to interpret the kinematic relationship between CRS marginal slice, Falkensteinzug (FSZ), Tannheim- and Karwendel thrust sheets occurring in a narrow strip at the northern margin of the Ammergau Alps in southwestern Bavaria (Figs 1 and 2) and (ii) the relationship between overlying Cretaceous synorogenic sediments deposited conformably or unconformably above the underlying lithological and tectonic units.

2. Geological setting

The NCA represent the most external, thin-skinned part of the Austroalpine nappe system (Schmid et al., 2004), comprising 3 to 6 km (Eisbacher and Brandner, 1996) of non- to very-low grade metamorphic (Petschik, 1983) Mesozoic sediments. Permian to Triassic shallow to deep marine sediments (Brandner, 1984) accumulated on the SE passive continental margin of Pangea, facing the

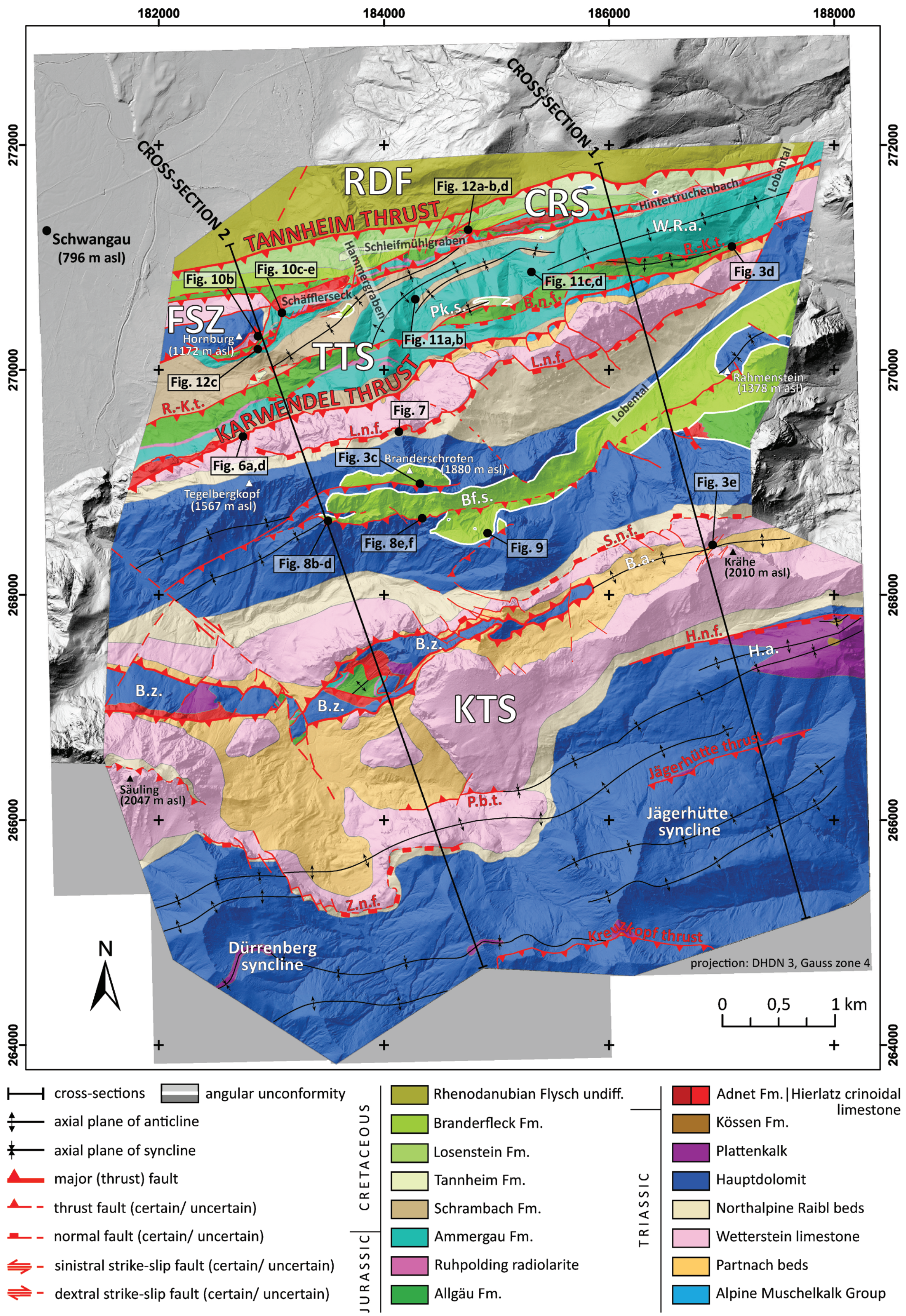

Figure 2: Geological map of the study area. The positions of the cross-sections of Figure 3 are indicated. Abbreviations - CRS - Cenoman-Randschuppe, FSZ - Falkensteinzug, TTS - Tannheim thrust sheet, KTS - Karwendel thrust sheet, W.R.a. - Weißer Risskopf anticline, Pk.s. - Pechkopf syncline, R.-K.t. - Rohrkopf-Klammgraben thrust, B.n.f. - Buchenbichl normal fault, L.n.f - Latschenschrofen normal fault, Bf.s. - Branderfleck syncline, S.n.f. - Schönleitenschrofen normal fault, B.z. - Benna zone, B.a. - Benna anticline, H.n.f. - Hochblasse normal fault, H.a. - Hochblasse anticline, P.b.t. - Pöllat backthrust, Z.n.f. - Zunderkopf normal fault.

Meliata Ocean branch of the Neotethys (Schlager and Schöllnberger, 1974; Lein, 1987). Rifting of the Penninic Ocean during the Early Jurassic led to breakup of Pangea and the separation of the microcontinent Apulia (Froitzheim and Manatschal, 1996; Manatschal, 2004). Close to the rift axis low angle normal faults and half graben basins formed (Eberli, 1987, 1988; Manatschal and Bernoulli, 1999), while in the more internal part of the continent the Late Triassic platform-basin-topography drowned during major subsidence (Krainer and Mostler, 1997). Penninic rifting influences the depositional realms of the NCA and the Lower Austroalpine units (Eberli, 1988; Froitzheim and Manatschal, 1996), leading to Early to Middle Jurassic pelagic syn-rift sedimentation followed by Late Jurassic post-rift sedimentation, the latter located at the northwestern passive continental margin of Apulia (Schmid et al., 2004). Intra-oceanic eastward subduction of the Neotethys from the late Middle Jurassic onwards was followed by obduction of Meliata Ocean ophiolites onto distal parts of the Apulian continental margin and/or an intracontinental (intra-Apulian) subduction zone, defining the onset of the Cretaceous orogeny (Schmid et al., 2004; Stüwe and Schuster, 2010). The NCA (Apulia) were in a lower plate position.

In this study we use the term Cretaceous orogeny for NNW-directed NCA nappe transport mostly without folding of NCA strata. This contrasts with more internal parts of the NCA where Cretaceous nappe transport was NW-directed (Eisbacher and Brandner, 1996; Ortner and Kilian, 2022). The resulting growth of the NCA foreland fold-and-thrust belt occurred from internal (SE) to external (NW) with respect to the Alpine orogen.

During Cretaceous orogeny the external NCA were detached from their basement, transported over several tens of km and stacked in thrust sheets (Eisbacher and Brandner, 1996; Ortner, 2003) which were recently redefined by Ortner (2016) and Ortner and Kilian (2022) in the western NCA. The structurally deepest and most proximal thrust sheet of the western NCA with respect to the stable European continent is the Tannheim thrust sheet (including the Allgäu- and parts of the Lechtal thrust sheet according to the nomenclature of Tollmann, 1976b). The tectonically higher Karwendel thrust sheet (including parts of the Lechtal- and the Inntal thrust sheet according to Tollmann, 1976b) represents the largest thrust sheet of the western NCA, showing displacement along the Karwendel thrust of at least 28 km (Eisbacher et al., 1990). The FSZ and CRS represent the frontal parts of the Karwendel- and Tannheim thrust sheets, respectively (Figs 2 and 3). The Vils slice (Figs 2 and 3) is a local imbrication of the Karwendel thrust sheet. Subduction of the Penninic Ocean (Europe, lower plate) started in the Late Cretaceous (Handy et al., 2010), and led to propagation of the Alpine orogenic front (Apulia, upper plate) from southeast to northwest under a dextral transpressive regime (Faupl and Wagreich, 2000) into the Penninic realm (Ortner, 2001). The NCA were transported piggy-back on top of accreted Penninic units until late Eocene collision (Paleogene orogeny), when Helvetic units were incorporated into the Alpine orogen. During Late Cretaceous to Paleogene shortening the convergence direction changed from top NNW to top NNE and existing thrust sheet boundaries within the NCA were folded. Folding propagated from external (NW) to internal (SE) with respect to the Alpine orogen. In the NCA, Cretaceous to Paleogene shortening is continuous and not separated by Late Cretaceous extension syn- to post-depositional to the Gosau Group, as observed in the Austroalpine basement units (Ducan-Ela phase; Froitzheim et al., 1994; Neubauer et al., 1995; Willingshofer et al., 1999; Fügenschuh et al., 2000) and generally assumed by Schmid et al. (2004). However, Late Cretaceous extension, as suggested by, e.g., Froitzheim et al. (1994) and Froitzheim et al. (2012), has not been described in the western NCA (Ortner and Kilian, 2022 and references therein). Continuous shortening is documented by Cenomanian to Santonian growth strata of the Branderfleck Fm. in the external western NCA (this study) and Coniacian to Paleocene growth strata of the Gosau Group in more internal parts (e.g., Ortner, 2001; Ortner et al., 2016).

Nappe stacking was accompanied by sedimentation. Siliciclastic to partly ophiolitic detritus, shed from temporarily uplifted, exhumed, and eroded nappes situated in the internal part of the Alpine orogenic wedge, can be found in all Cretaceous synorogenic sediments (Pober and Faupl, 1988; Winkler, 1988; Eynatten and Gaupp, 1999; Faupl and Wagreich, 2000). Synorogenic sediments were separated into upper-footwall deposits of the Lech-, Tannheim-, Losenstein-, and Branderfleck Fms. and into thrust-sheet-top deposits of the Branderfleck Fm. and Gosau Group by Ortner and Gaupp (2007). Upper-footwall deposits represent the youngest sediments below a thrust sheet and therefore provide information on the maximum age of thrusting. Thrust-sheet-top deposits represent sedimentation during and after thrust sheet emplacement, show growth strata on deeply eroded nappes, and reveal a minimum age of thrusting. According to the youngest upper-footwall deposits within the study area, stacking of the Karwendel thrust sheet onto the Tannheim thrust sheet reached the Ammergau Alps in the Albian. The Tannheim thrust sheet was emplaced onto the Penninic Arosa zone in the Turonian (Ortner, 2003). Penninic Rhenodanubian Flysch (RDF) and later Helvetic units were successively accreted into the Alpine orogen from the Maastrichtian onwards (Faupl and Wagreich, 2000). Not relevant for the study area but mentioned for completeness is Neogene post-collisional shortening, leading to incorporation of Molasse units into the Alpine nappe stack (Ortner et al., 2015).

3. Sedimentary succession

The sedimentary succession of the western Ammergau Alps reaches from the Middle Triassic Alpine Muschelkalk Group to the Late Cretaceous Branderfleck Fm. (Fig. 4a). Specific tectonic units of the study area contain specific sedimentary successions (Fig. 4a), the latter showing

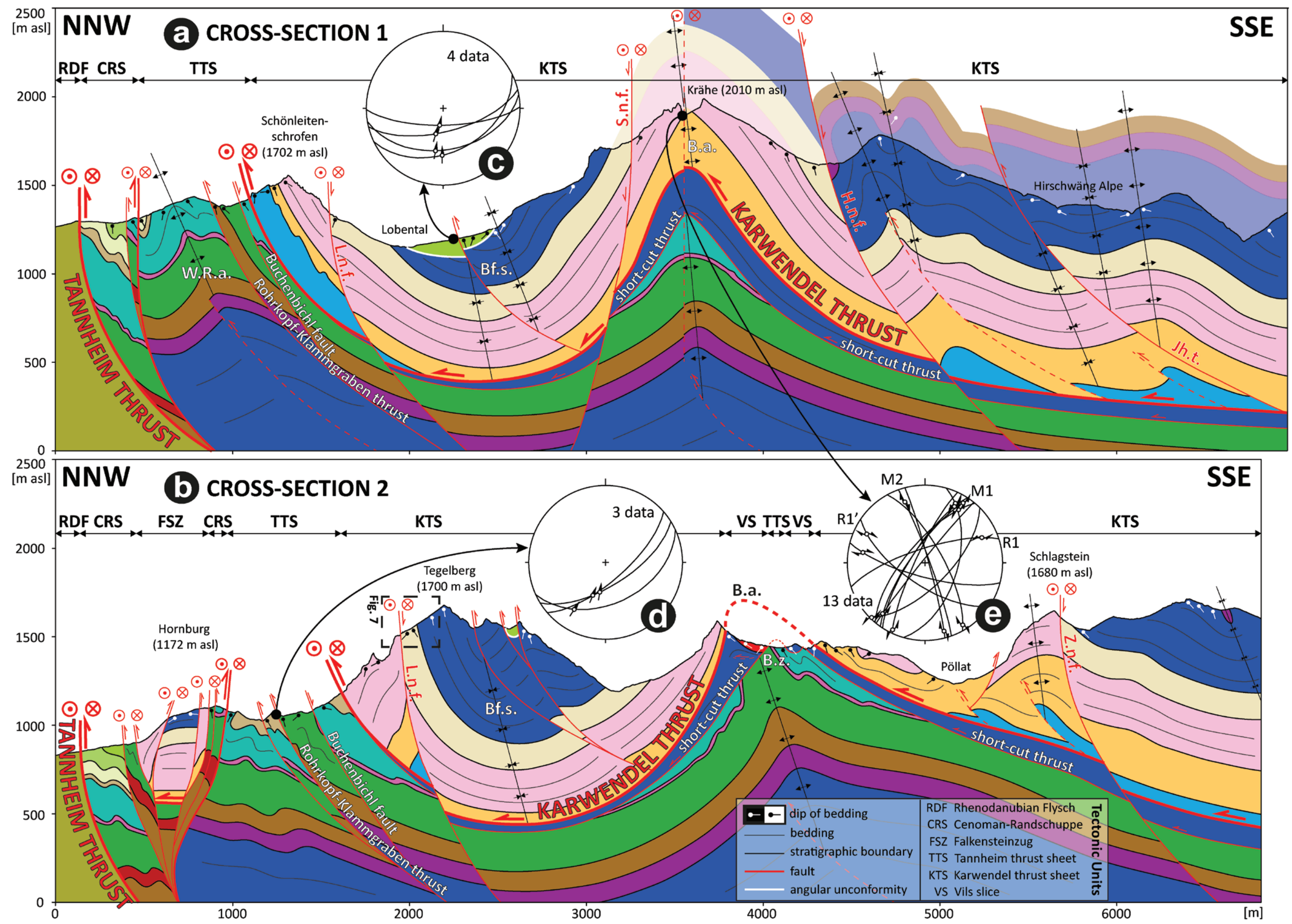

Figure 3: Cross sections of the western Ammergau Alps (see Fig. 2 for locations and legend). Note the gentle overall dip of NCA strata towards E when comparing cross section 1 and 2. (a) Eastern cross-section 1 showing subvertical strata and reverse faults with sinistral strike-slip behaviour in the northern part. (b) Western cross-section 2 showing the subhorizontal dipping succession of the FSZ incorporated in the sinistral transform fault zone with negative flower structure geometry in the northern part. Stereographic projection of fault planes of (c) out-of-syncline thrusts within the Branderfleck syncline showing top N to NNE-directed shortening, (d) the out-of-sequence Rohrkopf-Klammgraben thrust within the Tannheim thrust sheet showing again NNE-directed shortening, and (e) the central part of the study area showing sinistral N(N)E-striking strike-slip faults (label M1) which are dissected by NNW-striking dextral strike-slip faults (label M2). The square of dashed black lines indicates the location of Figure 7. For explanation of abbreviations see Figure 2. Additional abbreviations: VS – Vils slice, Jh.t. – Jägerhütte thrust. All lower hemisphere stereographic projections in this and subsequent figures were produced using the TectonicsFP software (Ortner et al., 2002).

imprint of lateral and vertical facies differentiation (Fig. 4a,b). The Karwendel thrust sheet (including FSZ and Vils slice) contains sediments of the Middle Triassic Alpine Muschelkalk Group up to Middle Jurassic Chiemgau beds, and synorogenic thrust-sheet-top deposits of the Branderfleck Fm. unconformably overlying Triassic (mainly Hauptdolomit) to Jurassic rocks. The sedimentary succession of the Tannheim thrust sheet ranges from the Late Triassic Kössen Fm. to Late Cretaceous upper-footwall deposits of the Branderfleck Fm. The CRS comprises a conformable succession ranging from the Early Jurassic Allgäu Fm., Adnet Fm., and Hierlatz crinoidal limestone to Late Cretaceous upper-footwall deposits of the Branderfleck Fm. The Branderfleck Fm. occurs both as thrust-sheet-top deposit and upper-footwall deposit within the study area (Figs 4a and 5).

The overall depositional realm of the northwestern NCA is dominated by series of deepening and shallowing cycles, accompanied by tectonic subsidence (Brandner, 1984), and controlled by rift and subduction processes (Froitzheim et al., 1996). Permian terrestrial deposits of the Alpine Verrucano, interfingering with the salt-bearing, layered evaporitic sequence of the Haselgebirge (Spötl, 1989; Leitner and Spötl, 2017), represent the basal succession of the NCA, overlying deeply eroded Variscan basement (Lein, 1987). Together with the Early Triassic alternating sequence of dolostone, mudstone and evaporites of the Reichenhall Fm. (Spötl, 1988) the Haselgebirge acts as the basal detachment of the external NCA during the Alpine orogenies (Linzer et al., 1995). The oldest stratigraphic unit outcropping in the study area, directly in the hanging wall of the Karwendel thrust, is sparitic shallow marine (Steinalm Fm.) to cherty pelagic (Reifling Fm.) limestone of the Anisian/ Ladinian Alpine Muschelkalk Group, the latter interfingering with marl and siltstone of the Ladinian Partnach beds and

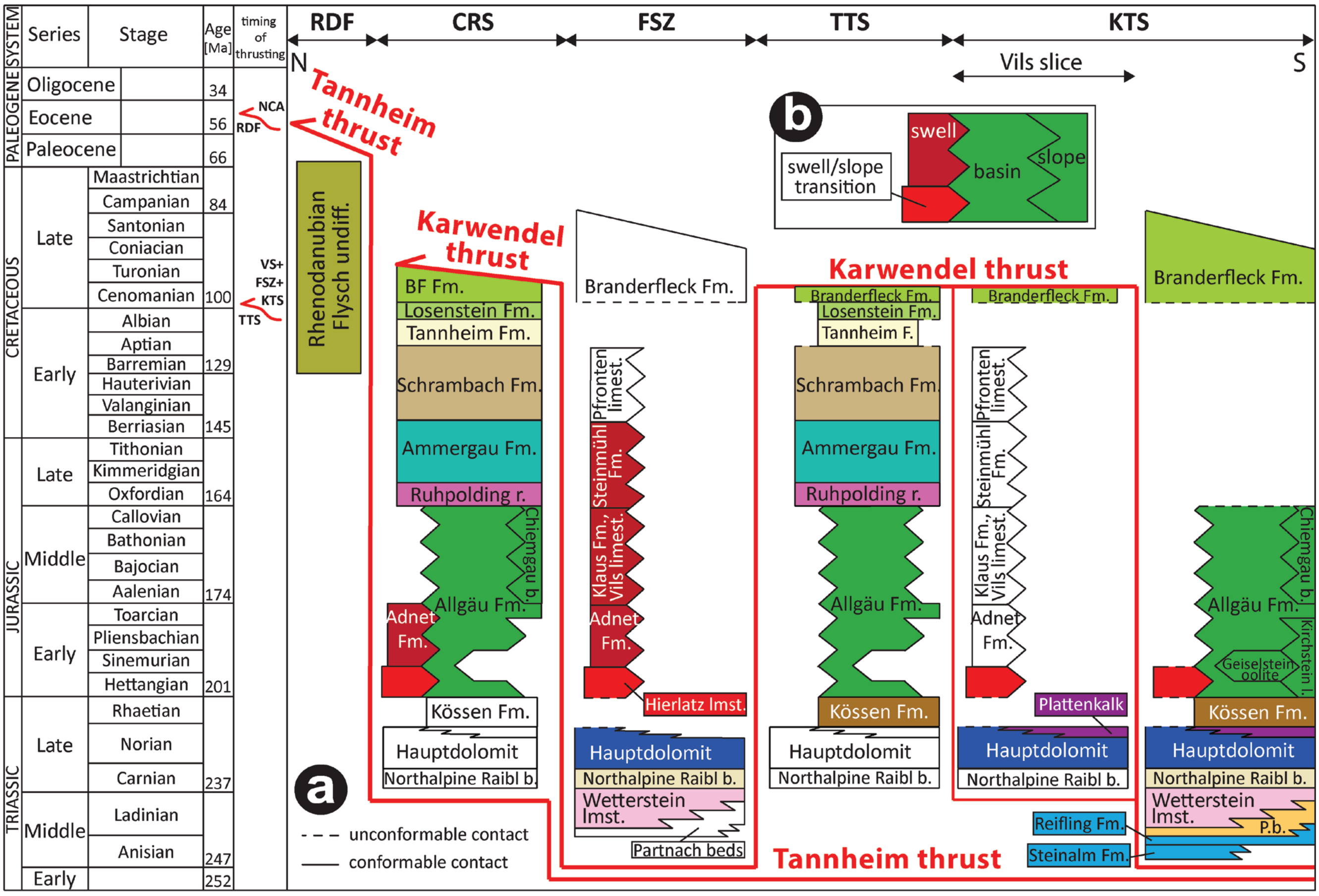

Figure 4: (a) Sedimentary successions, their relation to specific tectonic units (thrust sheets) and timing of thrusting within the study area. Conformable upper-footwall deposits occur within the Cenoman-Randschuppe (CRS) marginal slice and the Tannheim thrust sheet (TTS), whereas unconformable thrust-sheet-top deposits occur within Falkensteinzug (FSZ), Vils slice (VS) and Karwendel thrust sheet (KTS). Coloured units occur within the study area. Modified after Gaupp (1982) and Ortner (2016). (b) Schematic illustration of lateral and vertical facies differentiation (deep swells, slopes, and basins) within the Jurassic, as used in Figure 4a. Abbreviations: RDF - Rhenodanubian Flysch, BF Fm. - Branderfleck Formation, Northalpine Raibl b. - Northalpine Raibl beds, P.b. - Partnach beds.

with massive reef facies carbonate of the Early Carnian Wetterstein carbonate platform (Bechstädt and Mostler, 1976). The extraordinarily thin (up to 250 m) succession of uppermost Wetterstein limestone of the study area, compared to the up to 1700 m thick Wetterstein limestone of the Karwendel Mountains (Sarnthein, 1965, 1966) southeast of the study area, represents the fill of the Partnach basin and is comparable with the Southalpine Carnian Cassian dolomite (Gianolla et al., 2018). The up to 50 m thick succession of mixed carbonatic to siliciclastic sediments of the Carnian Northalpine Raibl beds overlying the Wetterstein carbonate platform contains bedded limestone, shale, dolomite, cellular dolomite and gypsum (Jerz, 1966). The Norian Hauptdolomit, deposited on an extensive tidal flat (Fruth and Scherreiks, 1984), dominates the Karwendel thrust sheet of the study area in terms of surface area, but does not exceed 300 m of thickness. Interfingering with the top of Hauptdolomit, Late Norian to Early Rhaetian Plattenkalk reflects deposition of limestone and marl in a subtidal setting (Czurda and Nicklas, 1970). An alternation of siliciclastic and carbonate sediments defines the Rhaetian Kössen Fm. (Golebiowski, 1991).

Lateral and vertical facies differentiation from the Early Jurassic onwards (Fig. 4b) are related to Penninic rifting and led to deposition of red nodular limestone of the Adnet Fm. on submarine highs (Böhm et al., 1999) and basinal deposits of grey, marly to cherty limestone of the hemipelagic Allgäu Fm. (Jacobshagen, 1965). Locally, the Geiselsteinoolite (Fabricius, 1967) is intercalated into the Allgäu Fm. The transition from swell to slope is represented by the crinoid-rich Hierlatz limestone (Krainer and Mostler, 1997). The Middle Jurassic succession shows a transition from deep swell deposits of red micritic and cephalopod-bearing limestone of the Klaus Fm., crinoid rich Vils limestone of swells and slopes, cherty limestone of the Chiemgau beds, and marly bioturbated limestone of the basinal upper Allgäu Fm. (Jacobshagen, 1965; Krystyn, 1970; Böhm, 1992). The Late Jurassic marks the change to post-rift sedimentation ranging from the red ammonite-bearing Steinmühl limestone on deep swells and slopes to the basinal Ruhpolding radiolarite of Oxfordian age and well-bedded pelagic micritic limestone of the Kimmeridgian to Berriasian Ammergau

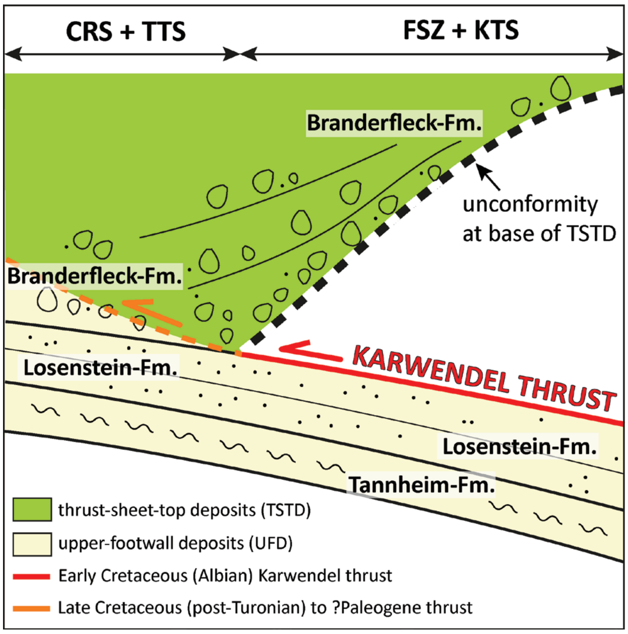

Figure 5: Conceptual sketch of synorogenic deposits at the northern front of the Karwendel thrust sheet, as occurring in the study area. Sediments of the Branderfleck Fm. occur both as thrust-sheet-top deposits (within KTS, FSZ) and upper-footwall deposits (within TTS, CRS). Abbreviations: CRS - Cenoman-Randschuppe, TTS - Tannheim thrust sheet, FSZ - Falkensteinzug, KTS - Karwendel thrust sheet.

Fm. (Flügel, 1967; Diersche, 1980).

As a response to inversion of the Adriatic passive margin and the propagating Alpine orogenic front, pelagic sedimentation was increasingly influenced by siliciclastic detritus. The Berriasian to Aptian Schrambach Fm. developed gradually without lithological change from the underlying Ammergau Fm., but shows a significant increase in marl towards the top (Zacher, 1966; Tollmann, 1976a; Rasser et al., 2003). The Late Aptian to Middle Albian Tannheim Fm. (Zacher, 1966) shows dark-grey to black marl with intercalated layers to lenses of bioturbated mudstone and thin layers of fine grained, light-brown weathered sandstone. Grey claystone and siltstone with intercalated turbiditic sandstone, pebbly mudstone, and conglomerate are characteristic for the Albian Losenstein Fm. (Kollmann, 1968). As the Tannheim-, Losenstein- and Branderfleck Fms. represent a coarsening and shallowing upward sequence (Gaupp, 1983; Wagreich, 2003), the Branderfleck Fm. (Gaupp, 1982) consists of marl, calcareous sandstone, and breccia.

4. Field observations

Here we present the results of the structural investigation within the western Ammergau Alps, concentrating on the tectonic units of Karwendel thrust sheet (including FSZ), Tannheim thrust sheet and CRS marginal slice, described in the following regarding their present-day position from south to north, respectively. Orientations of bedding planes, fault planes with slickensides, fold axes, and foliations were used as macroscopic structural records. Although the study area is affected by brittle deformation, ductile deformation is observed in shear zones within marl and marly limestone from incompetent stratigraphic units (e.g., Partnach beds and Allgäu-, Ammergau-, Schrambach-, and Tannheim Fms.), leading to the formation of scaly (SC-) fabrics (e.g., Vannucchi et al., 2019).

4.1 Karwendel thrust sheet

The WSW-ENE striking Karwendel thrust separates the Tannheim thrust sheet in the footwall from the Karwendel thrust sheet in the hanging wall (Figs 2 and 3). The incompetent, marl-rich layers of the Allgäu-, Ammergau-, Schrambach-, and Tannheim Fms., located in the footwall of the Karwendel thrust, show intensive ductile deformation; SC and SC′-fabrics (Fig. 6a) document thrusting towards the (N)NW to N(NE) (Fig. 6b) implying an activity of the Karwendel thrust both during the Cretaceous orogeny (top NW) and a reactivation during Late Cretaceous to Paleogene shortening (top NNW to N(NE)). Folds in the footwall of the Karwendel thrust within incompetent Jurassic to Cretaceous rocks (Fig. 3a,b) are orientated approximately WSW-ENE (mean fold axis 258/10), implicating a mean shortening direction NNW-SSE (Fig. 6c), also known from the Tannheim Mountains (Kirschner, 1996; Oswald et al., 2019) west of the study area. Rigid Wetterstein limestone in the hanging wall of the Karwendel thrust mostly acts competent and is not affected by shearing. NW-SE striking, dextral strike-slip faults (Ammer faults, Kockel et al., 1931) offset the Karwendel thrust several m to tens of m (Figs 3e and 6d). Strata in the hanging wall of the Karwendel thrust experienced folding during thrust sheet emplacement in the Early Cretaceous. The front of the Karwendel thrust sheet results in a ramp anticline (Figs 3a,b and 7a,b), which is partly preserved in the western study area around Latschenschrofen (Fig. 3b) and cut by oblique, sinistral normal faults, e.g., the steeply S-dipping Latschenschrofen fault (L.n.f. of Figs 2 and 7b,c). Smaller scale rollover anticlines show NNW-SSE directed shortening (Fig. 7d). The northern part of the Karwendel thrust sheet within the study area is folded into the regional scale Branderfleck syncline (Bf.s. of Figs 2 and 3a,b). The core of the southerly adjacent Benna anticline (B.a. of Figs 2 and 3a,b) unveils the tectonic window of the Benna zone (Kockel et al., 1931; B.z. of Figs 2 and 3b) in which the Vils slice and Tannheim thrust sheet are exposed (Figs 2 and 3a,b). The southern part of the Karwendel thrust sheet consists of Late Triassic rocks with open folds (Hochblasse anticline, Jägerhütte syncline) dissected by out-of-sequence thrusts (Jägerhütte thrust, Kreuzkopf thrust) and backthrusts (Pöllat backthrust) (Figs 2 and 3a,b).

4.1.1 Branderfleck syncline

The regional Branderfleck syncline (Figs 2 and 3a,b) reaches from Tegelbergkopf and Branderschrofen (see Fig. 2 for locations) further towards the east in direction of the Kochelsee (Weidich, 1982). In the western to central study area, it exposes Hauptdolomit which is unconformably overlain by synorogenic sediments of the

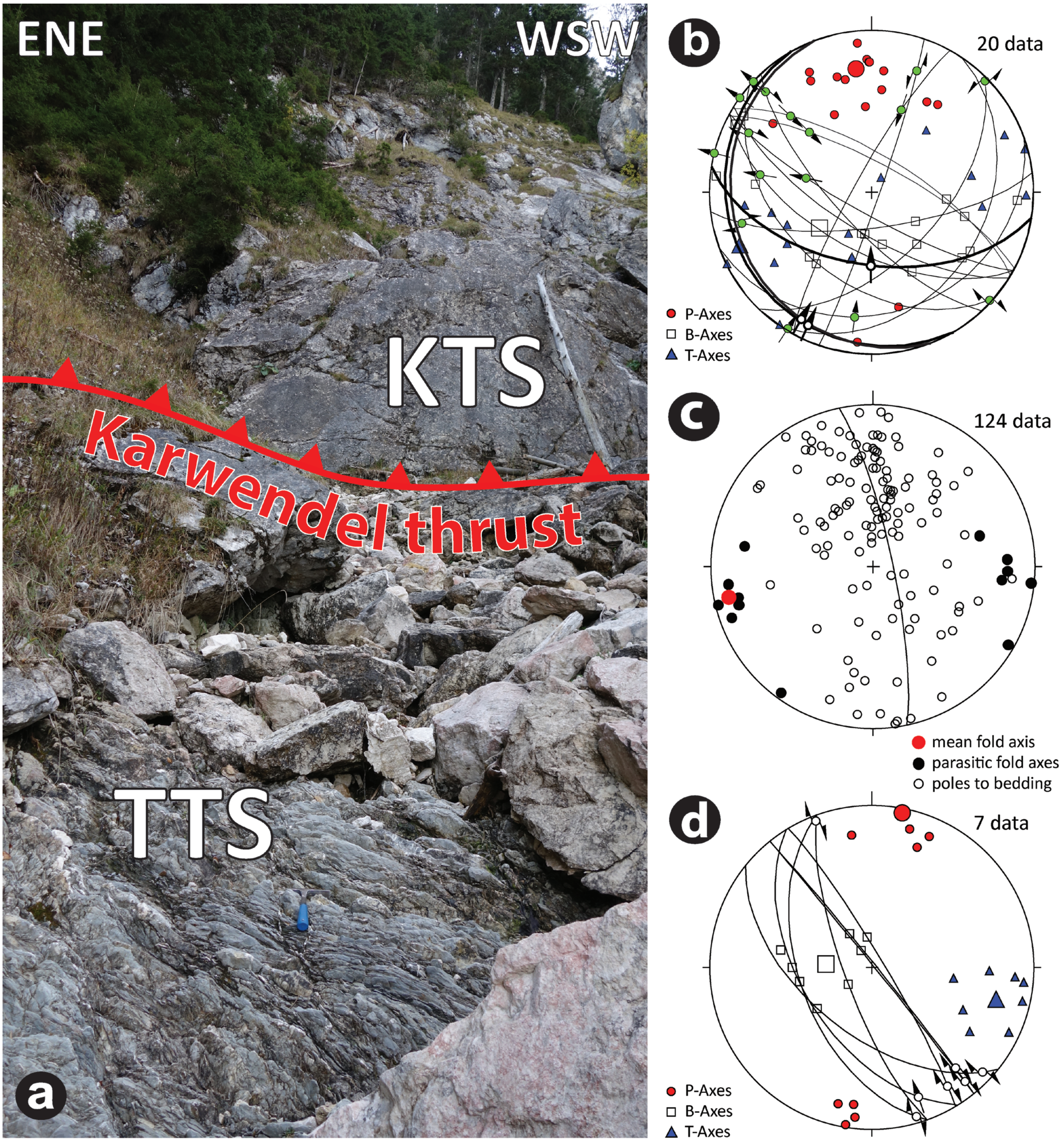

Figure 6: Structural data of the Karwendel thrust (see Fig. 2 for locations) showing (a) competent Wetterstein limestone in the hanging wall and incompetent Schrambach Fm. in the footwall of the Karwendel thrust (red line). Stereographic projections of the Karwendel thrust showing (b) fault planes (bold black lines), SC-fabrics (filled green circles at origin of arrows) and distribution of PT axes (P 353/24) from Jurassic to Cretaceous sediments in the footwall of the Karwendel thrust, implicating NNW-directed kinematics of the major thrust fault in the hanging wall, (c) poles to bedding (open circles), fold axes of parasitic folds (black circles), mean fold axis 258/10 (red circle), and π-circle (great circle) measured within Jurassic to Cretaceous sediments in the footwall of the Karwendel thrust defining the transport direction of the Karwendel thrust in the hanging wall, and (d) fault planes (white) and distribution of PT axes (P 011/03) from late stage dextral strike-slip faults dissecting Wetterstein limestone of the frontal Karwendel thrust sheet and the Karwendel thrust itself.

Branderfleck Fm. In the eastern study area, Hauptdolomit is in unconformable contact to Early Jurassic Hierlatz crinoidal limestone and Allgäu Fm. (for more details see Zacher, 1963), which is, in turn, unconformably overlain by synorogenic sediments of the Branderfleck Fm. (Fig. 2). Doubling of stratigraphic units within the Branderfleck syncline documents the presence of out-of-syncline thrusts (Mitra, 2002), approximately WSW-ENE striking and N to NE vergent (Fig. 3a-c). Incompetent sediments of the Northalpine Raibl- and/ or Partnach beds probably are the décollement of both faults and folds. In the western study area, south(west) of Tegelbergkopf, only one out-of-syncline thrust evolved, in the central study area around Branderschrofen, it splays up into two (Fig. 3b) to three branches, whereas southwest of Rahmenstein (see Fig. 2 for location), in the eastern study area, one branch is noted (Fig. 3a). The kinematics of these out-of-syncline thrust faults show top N to NNE transport directions (Fig. 3c).

Deposition of sediments of the Branderfleck Fm. occurred syn-thrusting in the front of the out-of-syncline thrusts, leading to growth strata within the Branderfleck Fm. Fold growth during sedimentation of the Branderfleck Fm. created growth strata with progressive unconformities (Fig. 8a,b), comparable to synclines flanking the Mediano anticline of the Pyrenees (Poblet et al., 1998). Besides unconformities within sedimentary layers of the Branderfleck Fm., angular unconformities between the Branderfleck Fm. and underlying sedimentary units are observed (Figs 8b and 9). Growth strata of the study area document ongoing contraction after nappe emplacement, comparable to, e.g., Ortner (2001) and Ortner et al. (2016). Local scarp breccias (lower BF in Fig. 8b) with red marl (ss2 in Fig. 8b) on top, fine grained sandstone, and brown marl form one of the investigated growth triangles within the Branderfleck Fm. (Fig. 8b) located SW of Branderschrofen (see Fig. 2 for location). Bedding within the above-mentioned growth-strata syncline SW of Branderschrofen flattens towards its core, showed by inward moving poles to bedding in the stereographic projection (Fig. 8c). The fold axis of the growth syncline plunges gently towards the ENE (083/11) (Fig. 8c), indicating NNW-SSE directed shortening in this particular part of the Branderfleck syncline. Parasitic folds within sediments of the Branderfleck Fm. or Hauptdolomit of the Branderfleck syncline can partly be seen as drag folds related to out-of-syncline thrusts. The northern limb of the growth syncline was backthrusted top SSE onto the southern limb of the syncline (Fig. 8b), documented by slickensides (Fig. 8d), reflecting the overall shortening direction of NNW-SSE within the Karwendel thrust sheet (compare Fig. 6b). Despite local variations of shortening directions within the northern Karwendel thrust sheet, which correspond either to out-of-syncline thrusts or local strike-slip faults, an evidence for an ongoing shortening process throughout the Cretaceous are parallel fold axes of Branderfleck Fm. (Fig. 8e) and Hauptdolomit (Fig. 8f) of the Branderfleck syncline S of Branderschrofen. Within the Branderfleck

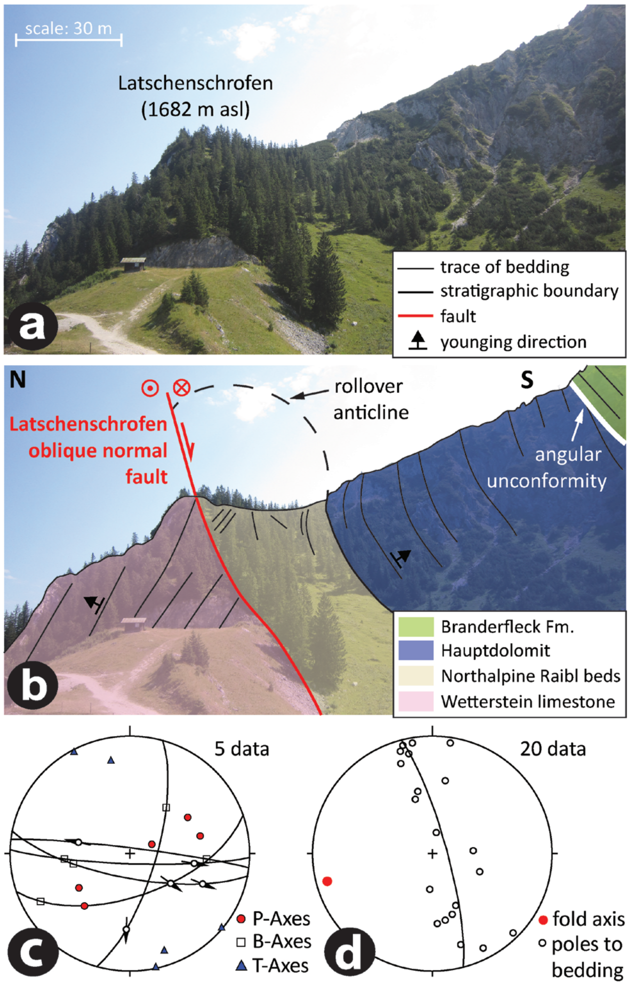

Figure 7: (a) View of the summit of Latschenschrofen and parts of the Branderschrofen north ridge (see Fig. 2 for location) from the W and (b) the accompanying geologic interpretation. Stereographic projections of structures within the frontal part of the Karwendel thrust sheet showing (c) fault planes (white) and distribution of PT axes of the Latschenschrofen normal fault and (d) poles to bedding (open circles), fold axis 255/10 (red circle), and π-circle (great circle) measured within sediments of the Northalpine Raibl beds south of Latschenschrofen.

syncline SSE of Branderschrofen, angular unconformities between Branderfleck Fm. and the underlying sediments (Norian Hauptdolomit to Jurassic cherty limestone in the eastern study area) are common and vary between 15° and 50° (Fig. 9a,b). Directly north of the summit of Branderschrofen, the angular unconformity between Branderfleck Fm. and Hauptdolomit is clearly visible (Fig. 7a,b). However, the dip of bedding changes insignificantly from Hauptdolomit (183/60) to Branderfleck Fm. (154/60) along the north ridge of Branderschrofen.

4.1.2 Falkensteinzug

The most external part of the Karwendel thrust sheet, the FSZ, ends, according to Reum (1962), at Schäfflerseck toward the east (Figs 2 and 3). The FSZ exposes strata from Wetterstein limestone to Hauptdolomit, transgressively overlain by Early Jurassic to (?) Cretaceous red limestone (Fig. 4a). The FSZ of the study area is bordered by

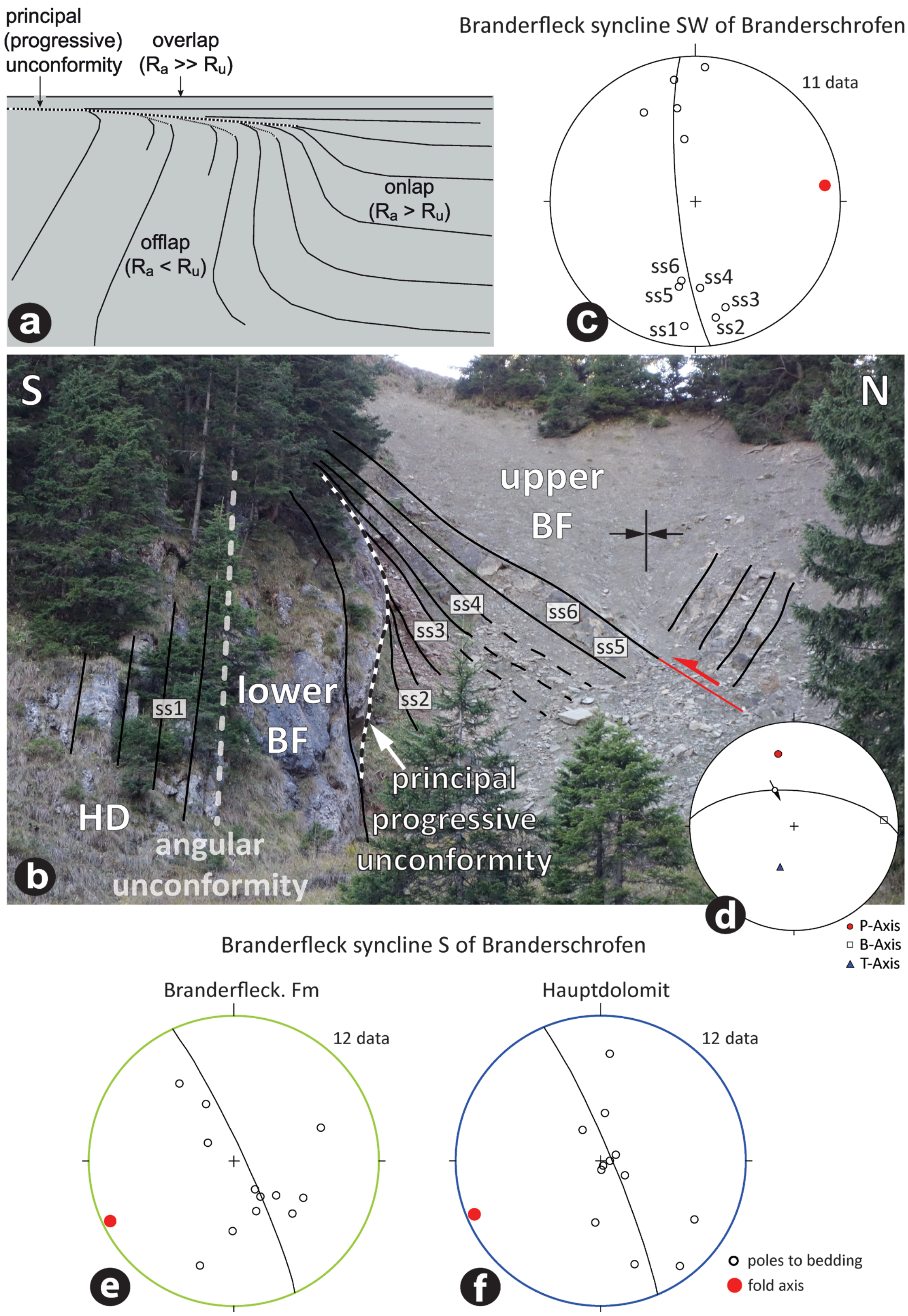

Figure 8: Structural data of the Branderfleck syncline within the northern Karwendel thrust sheet (see Fig. 2 for locations). (a) Schematic model describing the formation of a progressive unconformity (modified from Ortner et al., 2016; Ra = rate of deposition, Ru = rate of vertical structural growth). (b) Growth strata within sediments of the Branderfleck Fm. (lower BF, upper BF) SW of Branderschrofen with an angular unconformity between Hauptdolomit (HD) and BF, and a progressive unconformity within sediments of the BF, documenting deformation while sedimentation. (c) Stereographic projection of the growth strata shown in (b) with poles to bedding (open circles) of HD and BF, fold axis 283/23 (red circle), and π-circle (great circle). Note progressive shallowing of dip indicated by poles to bedding labeled with ss1 to ss6 in progressive younger beds toward the core of the growth syncline. (d) Stereographic projection of the fault plane shown in (b) documenting top SSE-directed backthrusting of the northern limb of the growth-strata onto the southern limb. (e) Stereographic projection of BF and (f) of HD within the same area of the Branderfleck syncline S of Branderschrofen showing poles to bedding (open circles) and fold axis 244/06 (red circle) of BF in (e) and poles to bedding (open circles) and fold axis 247/06 (red circle) of HD in (f).

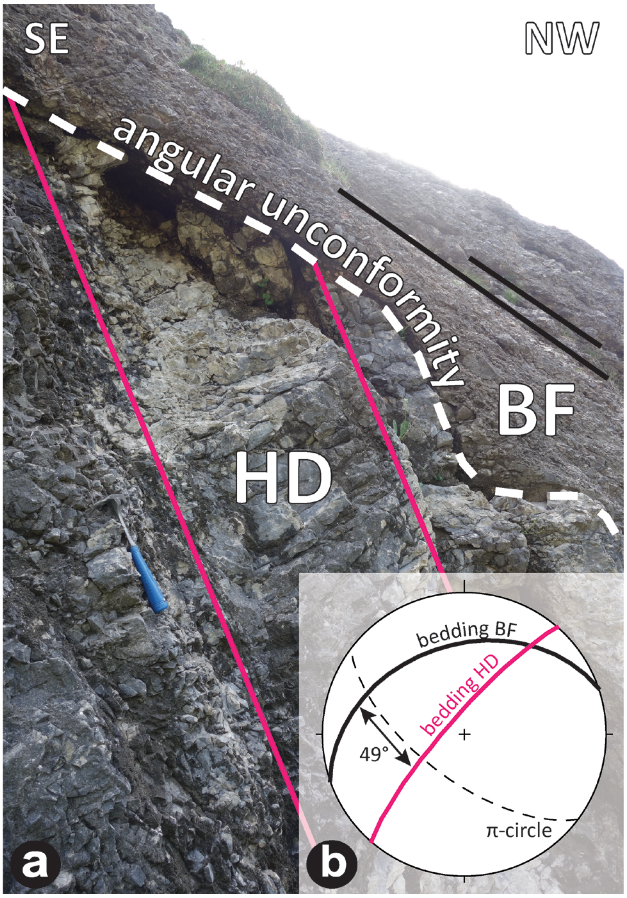

Figure 9: (a) Angular unconformity between steep towards NW-dipping (311/80) Hauptdolomit (HD; pink lines indicate bedding) and gently NNW-dipping (341/37) Branderfleck Fm. (BF; black lines indicate bedding), at the southern limb of the Branderfleck syncline (see Fig. 2 for location). (b) Stereographic projection showing the angular unconformity of 49° between bedding of Hauptdolomit (HD; pink great circle) and bedding of Branderfleck Fm. (BF: black great circle) shown in (a). The angular unconformity shown represents the principal unconformity as shown in the sketch of Figure 8a.

subvertically dipping strike-slip faults to the N, E, and S (Figs 2 and 3b and 10b), and is covered by quaternary deposits west of Hornburg. As Wetterstein limestone occurs to the N and to the SE of Hauptdolomit at Hornburg (Fig. 3b), it is appropriate to suggest a synformal geometry of the FSZ at Hornburg (Custodis and Schmidt-Thomé, 1939; Reum, 1962; Zacher, 1964). In contrast, bedding of Wetterstein limestone and Hauptdolomit does not indicate folding but gently dipping bedding planes towards the WNW (Fig. 10a). Northalpine Raibl beds between Wetterstein limestone and Hauptdolomit are cut out along (S)W-(N)E striking strike-slip faults (Figs 2 and 10b) and are only outcropping east of Hornburg (Fig. 2). Across SW-NE striking transpressive faults at the eastern termination of the FSZ, the Allgäu Fm. of the CRS is buttressed against Wetterstein limestone of the FSZ (Fig. 10b). Red limestone of the Schäfflerseck slice shows faults (Fig. 10c-e) and SC-fabrics (Fig. 10d,e) indicating normal faulting towards the E and NE. The SE-dipping transtensive strike-slip fault (black great circle in Fig. 10d, red dashed line in Fig. 10e) brings sediments of the Ammergau Fm. next to red limestone of the Adnet Fm. and likely represents an overturned (originally NW-dipping, now SE-dipping and steepened) backthrust of FSZ onto CRS.

4.2 Tannheim thrust sheet

In-sequence thrusting of the Karwendel- onto the Tannheim thrust sheet leads to (i) tight to isoclinal folding of the sedimentary succession of the Tannheim thrust sheet and (ii) to out-of-sequence thrusting within the Tannheim thrust sheet (Fig. 3) as shortening cannot longer be taken up by folding. The Tannheim thrust sheet is lithologically dominated by the incompetent Ammergau- and Schrambach Fms. (Figs 2 and 3), which are strongly sheared. Shearing of incompetent lithologies within the Tannheim thrust sheet increases towards the N.

The Weißer Risskopf anticline (W.R.a. of Fig. 2) plunges gently towards the W(SW), implicating N(NW)-S(SE) directed shortening (Fig. 11a,b). The Pechkopf syncline (Pk.s. of Fig. 2), occurring directly in the footwall of the out-of-sequence Rohrkopf-Klammgraben thrust (R.-K.t. of Fig. 2, Fig. 3a,b,d), shows a mean fold axis plunging gently towards the WNW (283/01), implicating N(NE)-S(SW) directed shortening (Fig. 3d). Fold axes of parasitic folds show shortening directions ranging from NNW to N(N)E (Fig. 11c,d). The out-of-sequence Rohrkopf-Klammgraben thrust fault evolves out of the tight, north-verging Klammgraben anticline with the incompetent sediments of the Kössen Fm. in the core, easing the detachment of the southern limb of the anticline and thrusting it onto the northern limb approximately towards the north (Fig. 3d). Ongoing compression led to steepening of the Rohrkopf-Klammgraben thrust, its hanging wall sedimentary succession, and inherited oblique normal faults, i.e., the Buchenbichl normal fault (B.n.f. of Figs 2 and 3a,b). The steeply S-dipping Buchenbichl fault locally cuts out Ruhpolding radiolarite (Figs 2 and 3a,b).

4.3 Cenoman-Randschuppe marginal slice

The CRS marginal slice is exposed north of the Tannheim thrust sheet from the Hornburg in the west towards Lobental in the east. Rocks of the CRS marginal slice are strongly deformed and subvertical bedding, tight folds, and fault-bounded slices are found. North and northwest of Hintertruchenbach (see Fig. 2 for location), Late Triassic Hauptdolomit olistoliths occur within the Early Cretaceous Tannheim Fm. of the CRS (Fig. 2).

The best exposures of the CRS marginal slice within the study area are found at the eastern end of Schleifmühlgraben and in Hammergraben (see Fig. 2 for locations). Sinistral transtensive (Fig. 12a) to transpressive movement along subvertical strike-slip faults dominates the Schleifmühlgraben. Pervasive SC-fabrics and SC′-fabrics within incompetent marl of the Allgäu Fm. (Fig. 12b,d) and the Ammergau Fm. of the Schleifmühlgraben document sinistral movement. W-E boundaries of zones affected by SC-fabrics and SC′-

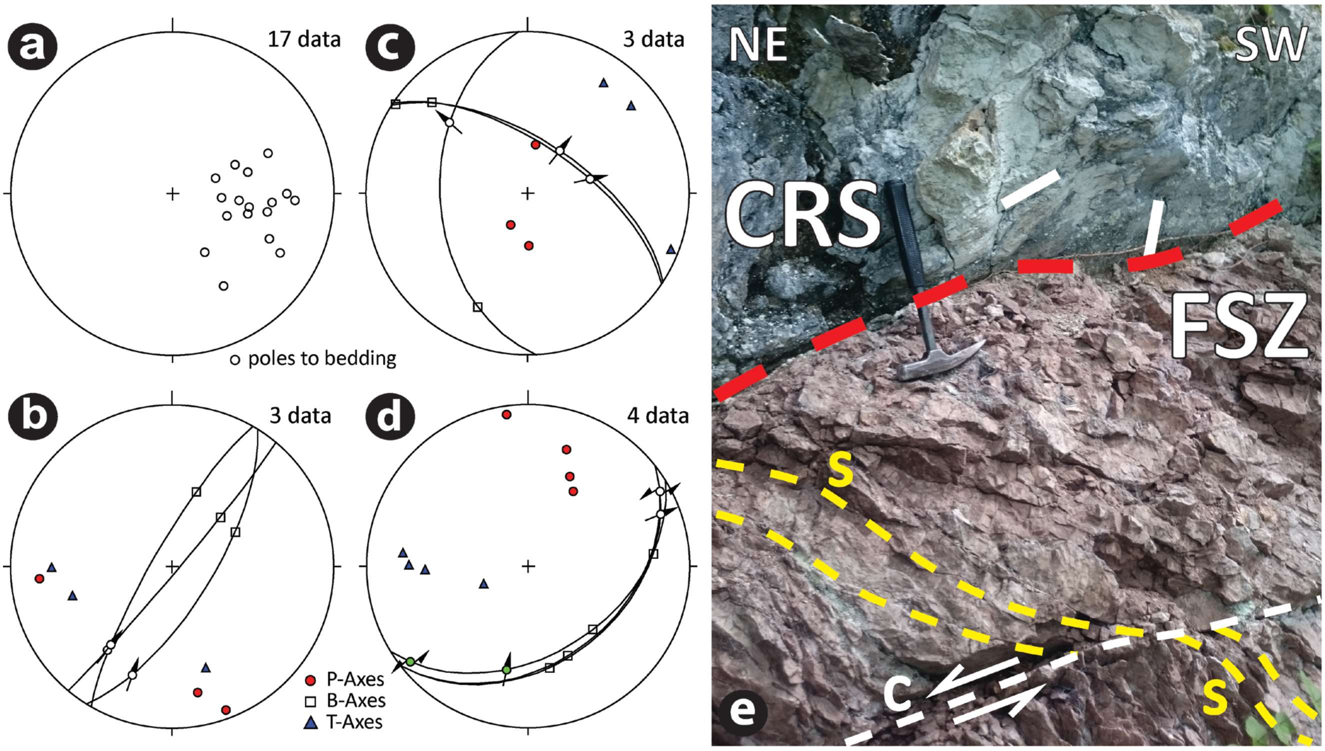

Figure 10: Stereographic projections of structures within the FSZ (see Fig. 2 for locations). (a) Poles to bedding (open circles) of Wetterstein limestone and Hauptdolomit of Falkensteinzug (FSZ). (b) Transpressive movement along subvertical NE-SW striking strike-slip fault planes (white) and distribution of PT axes (P 140/04) SE of Hornburg, buttressing the Allgäu Fm. of the Cenoman-Randschuppe (CRS) marginal slice against Wetterstein limestone of the FSZ. (c) Fault planes (white) and PT axes (P 192/84) of normal faults east of FSZ at Hornburg. (d) Fault planes (white), SC-fabrics (green) and distribution of PT axes (P 015/30) showing sinistral transtensive movement at the southwestern end of Schäfflerseck (FSZ). (e) A sinistral transtensive strike-slip fault (red dashed line) at Schäfflerseck brings Ammergau Fm. (CRS) next to red incompetent limestone of the (?) Adnet Fm. (FSZ), forming sinistral SC-fabrics (S-planes yellow dashed line, C-planes white dashed line) in the latter, which were used to deduce transport directions, shown in (d). White lines emphasise slickenlines within the Ammergau Fm., showing both sinistral strike-slip and normal movement, as shown in (d).

fabrics (bold grey great circles in Fig. 12a,b and bold grey line in Fig. 12d) demonstrate sinistral shear in W-E shear zones in the CRS marginal slice of the study area. Fold axes (FA) were determined from the southern CRS south of Falkensteinzug at Hornburg within Ruhpolding radiolarite (FA 050/43) and within the Ammergau Fm. south of Schäfflerseck (FA 065/45) with a mean fold axis of 058/47 (Fig. 12c). The 47° plunge is steeper than most other fold axes within the CRS marginal slice. This fold axis likely formed from steepening of pre-existing structures due to further shortening.

5. Discussion

Although numerous previous authors dealt with the sedimentological and paleontological aspects of the Ammergau Alps (Boese, 1894; Kockel et al., 1931; Weidich, 1990), structural information is scarce. Based on the observations presented in chapter 4, our study demonstrates that the northern Austroalpine margin was affected by multiple events of thrusting, interrupted by a strike-slip event.

5.1 Structural evolution of the study area in time

The deformational sequence presented here is based on crosscutting relationships, transport directions derived from SC-fabrics and on the comparison of transport directions of the study area with other parts of the NCA. We propose the following structural evolution for the northern Austroalpine margin of the western Ammergau Alps:

- D1: Early Jurassic normal faulting related to rifting of the Penninic Ocean that caused deposition on deep swells and in basins which are developed in the Tannheim- and Karwendel thrust sheets of the study area (Fig. 4a,b).
- D2: Early Cretaceous (Early Albian) shortening resulting in top NNW thrusting and folding (Fig. 6) that emplaced the Karwendel- onto the Tannheim thrust sheet, and folding starting before the end of thrusting (Fig. 13a).
- D3: Early Cretaceous (Late Albian) sinistral strike-slip transform faulting (Figs 3e and 10b,d and 12a,b,d) with negative flower structure geometry at the northernmost margin of the NCA separating CRS marginal slice and FSZ from the main body of the NCA (Figs 3a,b and 13b). Decoupling most probably immediately followed Cretaceous shortening as the FSZ was already emplaced onto the Tannheim thrust sheet. Late Albian activity of transform faulting is inferred from the age of Ehrwaldite basanitic dykes (~100 Ma, Trommsdorff et al., 1990) that intrude E-W sinistral strike-slip faults in the more internal NCA (Ortner and Kilian, 2022). Oblique normal faults related

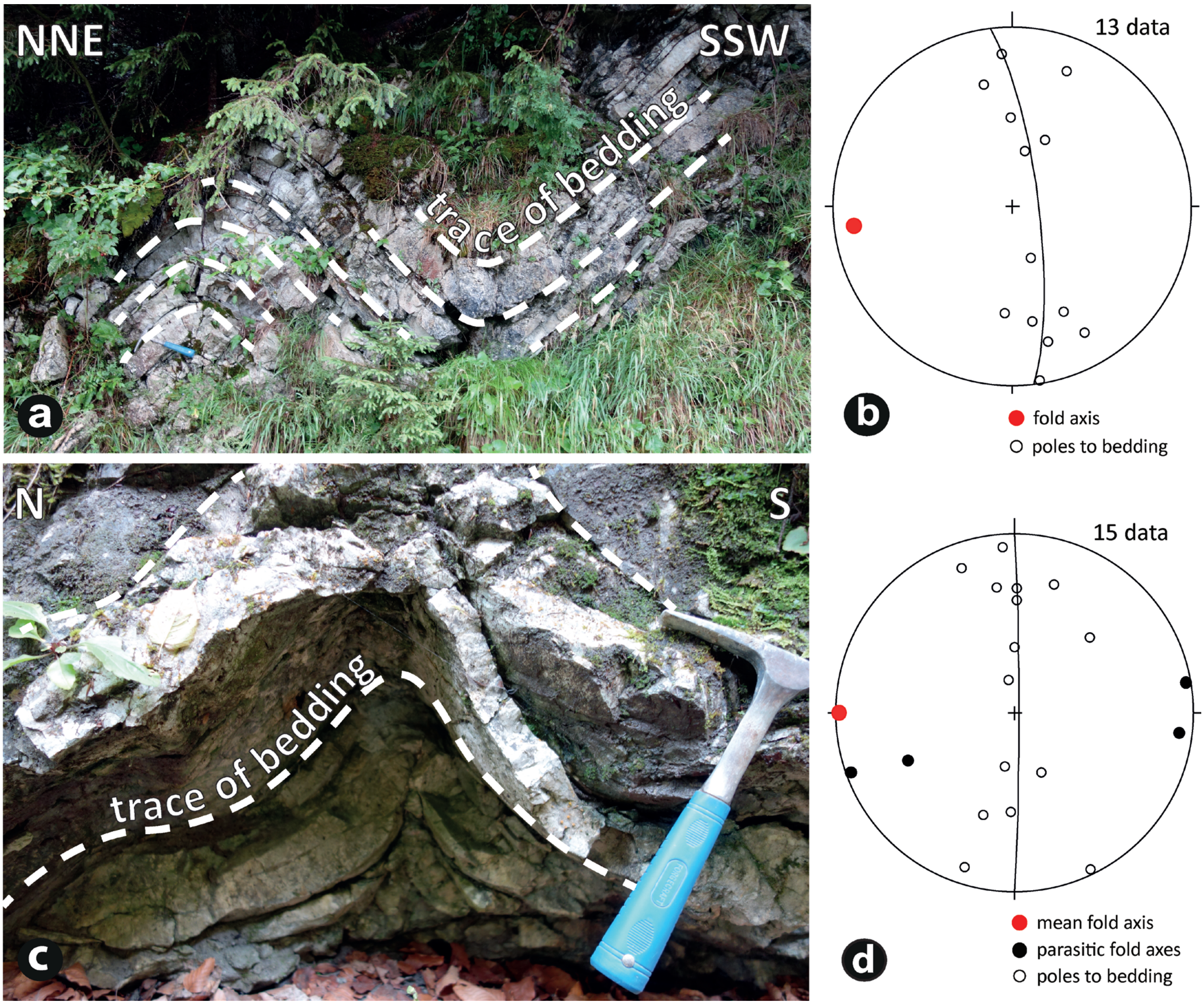

Figure 11: Outcrop-scale folds within the Tannheim thrust sheet (see Fig. 2 for locations). (a) Folds within the Ammergau Fm. NW of Weißer Risskopf and (b) stereographic projection of poles to bedding (open circles), fold axis 263/12 (red circle) and π-circle (great circle) of Weißer Risskopf anticline. (c) Folds within the Ammergau Fm. WNW of Pechkopf and (d) stereographic projection of poles to bedding (open circles), fold axes of parasitic folds (black circles), mean fold axis 270/02 (red circle), and π-circle (great circle) of the Pechkopf syncline.

to this transtensive strike-slip event are preserved throughout the study area and strike E-W. These faults dissect D2 fold structures and have offsets of several meters to tens of meters.

- D4: Late Cretaceous Late Cretaceous to Paleogene shortening resulting in top N(NE) thrusting, folding of the Karwendel thrust with the formation of growth strata in synorogenic sediments of the Branderfleck Fm. (Fig. 8), inversion of the sinistral strike-slip shear zone (Fig. 13c), nappe internal out-of-sequence thrusting, and steepening of existing structures (Figs 3a,b and 13c). Gradual incorporation of Arosa zone, Rhenodanubian Flysch (RDF) and Helvetic units into the Alpine nappe stack due to ongoing shortening; the Tannheim thrust representing the basal thrust of the NCA.
- D5: Neogene compression leads to incorporation of Molasse units into the Alpine nappe stack.

Our study emphasises that Cretaceous synorogenic sediments are crucial for reconstructing the deformational history. During NNW-directed emplacement of the Karwendel- onto the Tannheim thrust sheet during the Cretaceous orogeny, parts of the sedimentary succession of the Karwendel thrust sheet (KTS) in the hanging wall were eroded. At this time, the future CRS marginal slice was still part of the Tannheim thrust sheet (TTS) or, in other words, located in the foreland of the Cretaceous Alpine orogenic wedge (Gaupp, 1983; Sieberer and Ortner, 2018), where the synorogenic sediments were deposited conformably (Fig. 5). Olistoliths derived from the front of the prograding Alpine orogen (i.e., from the KTS) were deposited within the Cretaceous foreland basin north of the orogen (i.e., within the future CRS marginal slice). During ongoing NNW to NNE-directed shortening, the Karwendel thrust and the KTS in its hanging wall

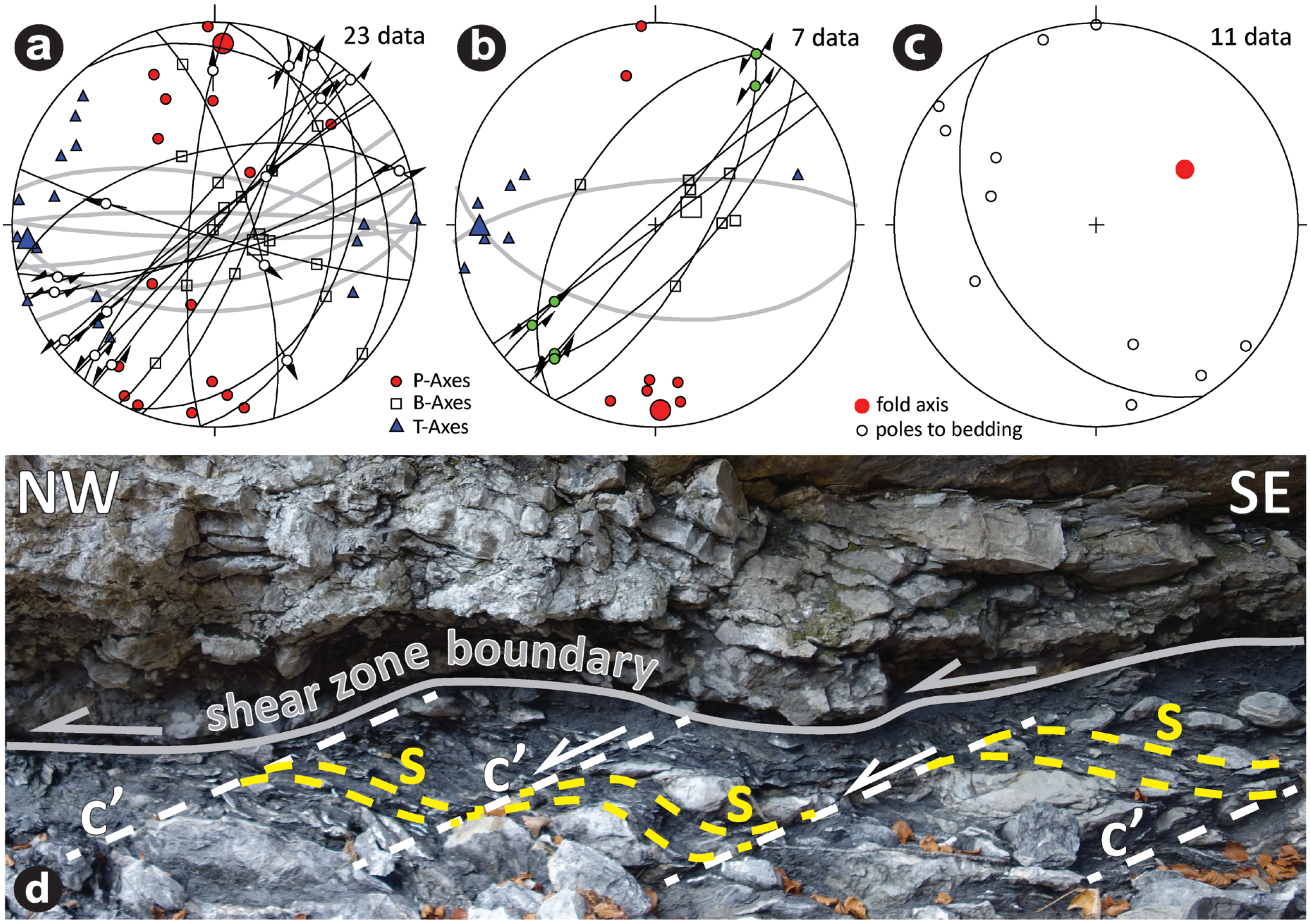

Figure 12: Stereographic projections of structures within the Cenoman-Randschuppe (CRS) marginal slice (see Fig. 2 for locations) showing (a) C’-planes with white open circles at origin of arrows, shear zone boundaries (bold grey great circles), and PT axes (P 003/11) of a sinistral transtensive shear zone within Schleifmühlgraben, (b) C-planes of SC-fabrics (filled green circles at origin of arrows), shear zone boundaries (bold grey great circles), and PT axes showing sinistral movement along NNE-SSW striking C-planes (Riedel faults to the main W-E oriented sinistral shear zone) with an approximately N-S orientated mean compression direction P of 178/09 within Schleifmühlgraben, and (c) poles to bedding (open circles) and fold axis 058/47 (red circle) of a steep fold within the southern CRS marginal slice south of Hornburg. (d) Intensively sheared sediments of the Allgäu Fm. between Schleifmühlgraben and Fällgraben forming sinistral SC’-fabrics (S-planes yellow dashed line, C’-planes white dashed line, shear zone boundary bold grey line) which were used to deduce transport directions.

were folded and thrust-sheet-top deposits of the Late Cretaceous Branderfleck Fm. covered the eroded KTS, creating synsedimentary growth strata.

Moreover, we demonstrate the presence of conformable upper-footwall deposits of the Branderfleck Fm. within the northern TTS (Figs 2 and 5). This means that the northern termination of the KTS is located within the study area and was entirely covered with sediments of the Branderfleck Fm. (Fig. 5). Due to ongoing Late Cretaceous to Paleogene shortening along the Karwendel thrust, sediments of the Branderfleck Fm. occur both as thrust-sheet-top deposits (within KTS and FSZ) and upper-footwall deposits (within TTS and CRS) (Fig. 5).

5.2 Transform fault zone setting at the northern Austroalpine margin

Our results show, that the NCA are not a typical thin-skinned fold-and-thrust belt, when, e.g., compared to the thin-skinned fold-and-thrust belt of the southern Pyrenees (Vergés et al., 2002; López-Mir et al., 2015). For example, structures get wider and smoother towards the southern foreland (Ebro basin) of the Pyrenees, whereas in the Alps, deformation increases towards the northern foreland (Kockel et al., 1931). Therefore, structures localising more deformation at the northern margin of the NCA, in the CRS marginal slice and the FSZ, are needed.

Jurassic normal faults, related to the rifting of the Penninic Ocean, localising folding and thrusting in parts of the NCA (Ortner and Kilian, 2016; Oswald et al., 2019), are one possible explanation for parts of the localisation of deformation at the northern Austroalpine margin. Jurassic normal faults affect, e.g., the depositional setting of the external NCA, the position of the Karwendel thrust, or the formation of the Vils slice. The Vils slice is interpreted as a remnant of an inverted rift-related half-graben shoulder floored by a shortcut-thrust following McClay and Buchanan (1992) and Oswald et al. (2019). Additionally, we suggest a transform setting likely having influenced external parts of the thin-skinned fold-and-thrust belt

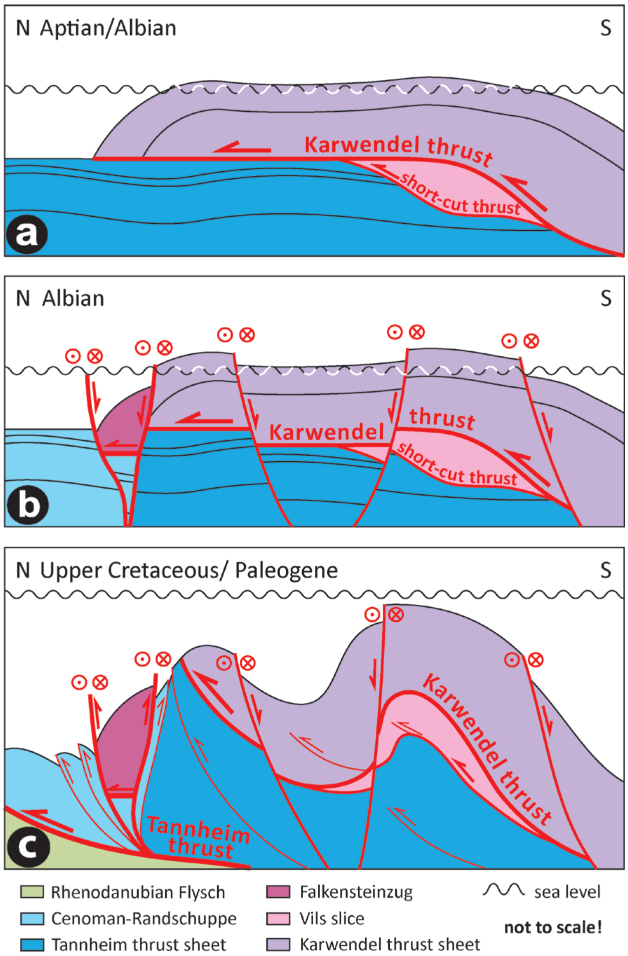

Figure 13: Conceptual model (not to scale!) of the proposed structural evolution of the western Ammergau Alps from the late Early Cretaceous until the Paleogene. (a) Emplacement of Karwendel- onto Tannheim thrust sheet along the Karwendel thrust, and the subsequent detachment of an Early Jurassic halfgraben shoulder (e.g., shortcut-thrust at the base of the Vils slice in the footwall of the Karwendel thrust) during Cretaceous orogeny. Note the ramp anticline at the front of the Karwendel thrust sheet in the hanging wall of the Karwendel thrust at this early stage of deformation. (b) Sinistral transtensive transform faults decoupling the Cenoman-Randschuppe marginal slice and Falkensteinzug from the main body of the Northern Calcareous Alps (NCA) and affect the entire northern part of the NCA. (c) Inversion of the sinistral strike-slip shear zone, folding of thrust sheet boundaries, nappe internal out-of-sequence thrusting and steepening of existing structures during Late Cretaceous to Paleogene shortening.

formation of the NCA. Pervasive overprint by sinistral shear at the northern margin of the NCA, mostly affecting the CRS marginal slice and the northern TTS, is documented in this study. Sinistral shear is not exclusively dominant along a distinct, regional scale sinistral strike-slip fault, but documented by sinistral SC- and SC'-fabrics within Jurassic and Cretaceous sediments (Figs 10d-e and 12a,b,d), suggesting the CRS marginal slice and FSZ being separated from the main body of the NCA along an approximately W-E striking, anastomosing, sinistral transform fault zone (Fig. 13b). The transtensive character of this sinistral transform fault zone results in approximately W(SW)-E(NE) striking normal faults observed in the whole study area, also cross-cutting the Karwendel thrust. The sinistral, oblique normal faults post-date initial detachment folding in the hanging wall of the Karwendel thrust as clearly shown at Latschenschrofen, where the S-dipping Latschenschrofen fault cuts the ramp anticline of the Karwendel thrust (Figs 3b and 7a,b). The Latschenschrofen fault belongs to a set of Albian sinistral transtensive strike-slip faults that show local offsets of meters to tens of meters and are therefore not relevant on the regional scale. The oblique Buchenbichl normal fault (Fig. 3a,b) shows comparable low offsets and pre-dates out-of-sequence thrusting within the Tannheim thrust sheet. This delimits the activity of the sinistral shear zone at the northern Austroalpine margin to after nappe stacking of Karwendel thrust sheet onto Tannheim thrust sheet and before out-of-sequence thrusting within the Tannheim thrust sheet. Sinistral, oblique normal faults were steepened by Late Cretaceous to Paleogene contraction.

The FSZ was previously interpreted as a narrow synform, folded into sediments of the Tannheim thrust sheet, inferred from the steep to subvertical attitude of the northern and southern parts of the FSZ (Reum, 1962; Zacher, 1964). According to Eisbacher et al. (1990), the FSZ repeats the hanging wall cutoff of the Wetterstein limestone and Northalpine Raibl beds. This repetition is either explained by extensional tectonics or by lateral movement via sinistral strike-slip faults, transporting the FSZ into the study area. We suggest the FSZ being involved in a sinistral transtensive strike-slip zone with negative flower structure geometry at the northern Austroalpine margin, which cut off the FSZ from the main body of the Karwendel thrust sheet and transported it into the study area (Fig. 13b,c). Due to inversion during Late Cretaceous to Paleogene shortening, this sinistral transtensive strike-slip zone with negative flower structure geometry developed into a pop-up (positive flower) structure (Fig. 13c). This inversion is supported by (i) observations by, e.g., Kockel and Richter (1924) and Tollmann (1969) of the Tannheim thrust sheet directly south of FSZ (within this study termed CRS marginal slice, see Fig. 2) dipping below the FSZ, (ii) observations within the Schäfflerseck slice, which got backthrusted onto sediments of the Tannheim- and Losenstein Fms. of the CRS to the SE, and onto sediments of the Ammergau Fm. of the CRS to the SW, the latter being overturned and resembling a SE-dipping normal fault at present due to later-stage compression towards the NNE (Fig. 10d,e), and (iii) the presence of CRS- derived olistoliths consisting of Adnet Fm., Allgäu Fm. and Ruhpolding radiolarite occurring within coarse-grained conglomerates of the Branderfleck Fm. within the northern Tannheim thrust sheet. Timing of backthrusting is syn-depositional to the Branderfleck Fm. (Late Cretaceous). Thrusting towards north and (back)thrusting towards south along subvertical dipping faults within a small distance would be another indication for the inversion of a shear-zone within this northern margin of the Ammergau Alps; the backthrust representing the southern border of this shear

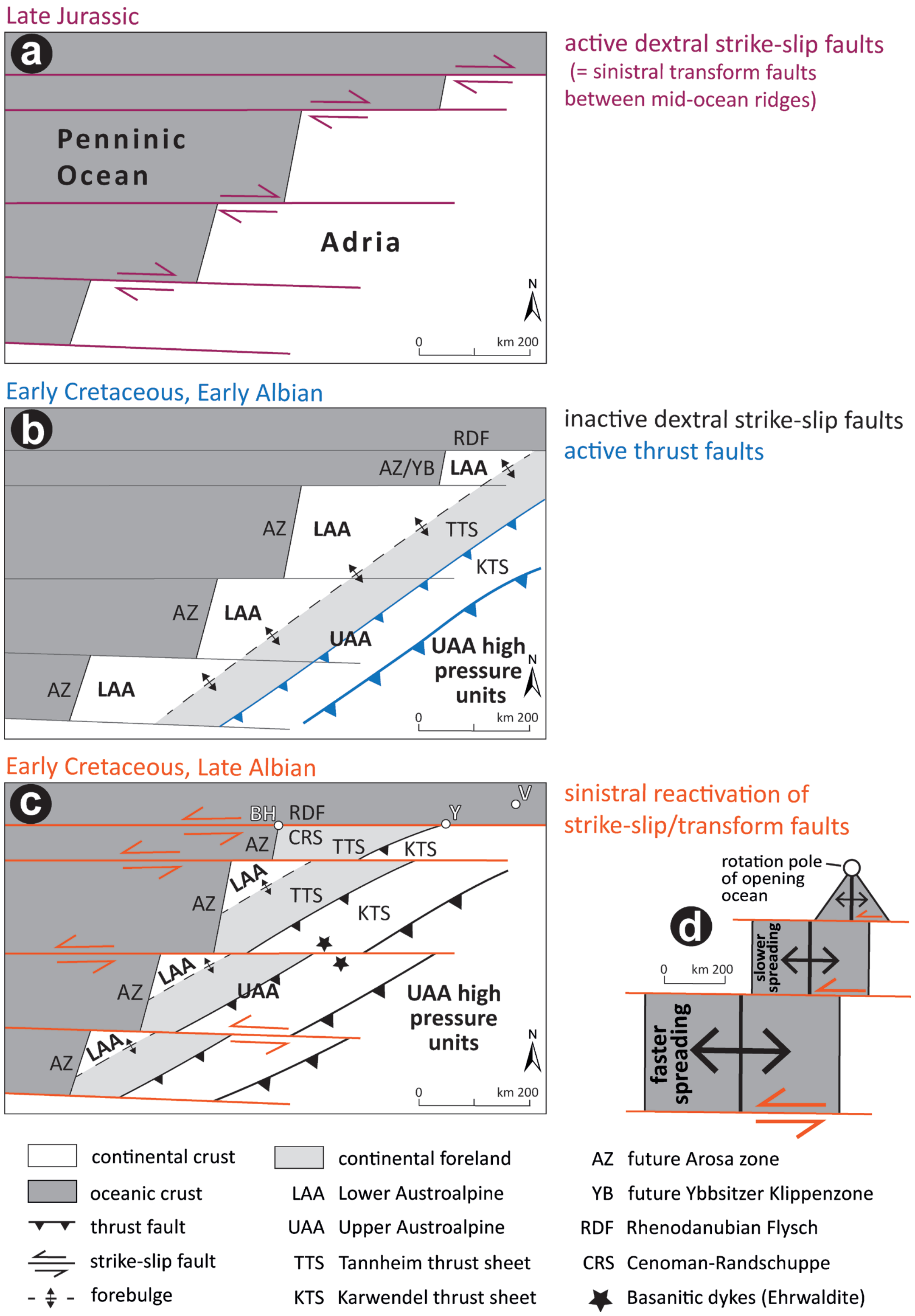

Figure 14: Schematic (not to scale!) paleogeographic sketches of the Adria derived microcontinent Apulia, located between the closing Meliata Ocean in the SE and the closing Penninic Ocean in the NW. Outlines of the continental margin modified from Handy et al. (2010). (a) Late Jurassic strike-slip faults create dextral offsets due to breakup of the continental margins and sinistral offsets between segments of the mid-ocean ridge opening the Penninic Ocean. (b) In Early Albian times, the future Cenoman-Randschuppe (CRS) marginal slice is situated together with the Tannheim thrust sheet in the continental foreland of the advancing Cretaceous Alpine orogen, but in the hinterland of the forebulge of the Cretaceous age foreland basin. (c) During the Late Albian, the CRS marginal slice is located in a sinistral strike-slip setting (reactivation of inherited Jurassic strike-slip and transform faults), where it replaces the future Arosa zone and is juxtaposed to the Rhenodanubian Flysch. The future locations of Bad Hindelang (BH), Ybbsitz (Y) and Vienna (V) are mentioned for demonstration of the regional offset along the approximately W-E striking sinistral transform fault zone. Modified from Weissert and Bernoulli (1985), Trommsdorff et al. (1990), Wagreich and Faupl (1994), Winkler (1996), Handy et al. (2010), Hesse (2011). (d) Schematic (not to scale!) sketch of varying spreading rates (black arrows) along transform faults within the Penninic realm, depending on the proximity towards the rotation pole of the opening ocean. Orange half arrows indicate sinistral strike-slip-(re)activation (in Albian times) of the same transform faults.

zone. The inversion followed and reactivated old strike-slip faults that had formed prior to thrusting. Summing up, pre-existing sinistral transform fault zones localised younger thrusting. Similar inversion structures are known from the eastern Ammergau Alps (Kuhnert, 1965, 1967; cross-section 7 on plate 6 of Tollmann, 1976b), as the northern front of the Karwendel thrust sheet shows overturned strata. Therefore, it is suspected, that due to the oblique movement of the SW-NE striking Karwendel thrust towards the W-E striking transform zone located to the north (Figs 1a and 2), the inversion of the transform fault shear zone affects CRS marginal slice and FSZ and northern Tannheim thrust sheet within the study area of the western Ammergau Alps, but affects the Tannheim thrust sheet and front of the Karwendel thrust sheet further east, within the eastern Ammergau Alps. Another explanation for overturned stratigraphic units and folds at the northern margin of the NCA could be steepening of pre-existing structures due to accretion of RDF, Helvetic nappes and Molasse below the frontal thrust of the NCA, leading to overturning of structures in thrust sheets of the passively transported hanging wall.

Outside the study area, in the western NCA, within the Wetterstein Mountains east of Ehrwald (*Puitentalzone*) and within the Karwendel Mountains, ~100 Ma aged (Trommsdorff et al., 1990) basanitic dykes and sills (*Ehrwaldite*) occur (Richter, 1928; Zacher, 1962; Trommsdorff, 1962; Miller, 1963). The Ehrwaldite originated in the subcontinental mantle, suggesting the absence of oceanic subduction at the time of Ehrwaldite intrusion (Trommsdorff et al., 1990). Within the Puitentalzone, Ehrwaldite dykes and sills intruded into Jurassic to Cretaceous sediments. Ehrwaldite dykes follow shear zones in marl of the Schrambach Fm. and are found following both S- and C-planes of SC-fabrics within an approximately W-E striking sinistral strike-slip zone, as well as in the footwall and the hanging wall of the Karwendel thrust, implying intrusion of Ehrwaldite after main nappe transport (Ortner and Kilian, 2022). The presence of Ehrwaldite within a sinistral strike-slip zone in the central NCA would underline the presence of intracontinental transform faults. In our schematic paleogeographic reconstruction (Fig. 14), we differentiate between two phases of strike-slip faulting, separated by a phase of thrusting: (i) Jurassic transform to strike-slip faults (Fig. 14a) create sinistral offsets between segments of the mid-ocean ridge opening the Penninic Ocean (Weissert and Bernoulli, 1985; Lemoine and Trümpy, 1987; Trümpy, 1988) and dextral offsets due to breakup of the continental margins, respectively, (ii) Early Albian advancing of the Alpine orogen creates a continental foreland basin, and (iii) Late Albian sinistral strike-slip faults reactivate inherited Jurassic faults and offset the Austroalpine nappe stack (Fig. 14c). Rifting and subsequent opening of the Penninic Ocean propagates from SSW to NNE (Schmid et al., 2008; Handy et al., 2010; Le Breton et al., 2021) and results in different spreading rates between transform faults (Fig. 14d). Therefore, we assume sinistral strike-slip not only along the transform fault segments between mid-oceanic ridges but also along the strike-slip faults reaching into the Adriatic continental crust (Fig. 14c,d). The eastward motion of Iberia relative to Europe (Handy et al., 2010; Le Breton et al., 2021) due to rifting and opening of the North Atlantic Ocean (e.g., Stampfli and Borel, 2002; Nirrengarten et al., 2018) could probably have supported Albian reactivation and sinistral shearing along E-trending faults.

In Early Albian times, the future CRS marginal slice is, together with the Tannheim thrust sheet, located in the continental foreland of the advancing Alpine orogen (Fig. 14b). During the Late Albian, the CRS marginal slice is assumed to be located on continental crust directly south of a sinistral transform fault, where it replaces the Arosa zone and is juxtaposed to the Rhenodanubian Flysch (Fig. 14c). As the ophiolite-bearing Arosa zone disappears around Bad Hindelang, Bavaria, Germany in the west and reappears as Ybbsitz- and St.Veit Klippenzones in the area of the Weyrer Bögen, Lower Austria (Schnabel, 1979; Ring et al., 1990; Schnabel, 1992) to the east, regional offset along this approximately W-E striking transform fault zone can be assumed. A transform fault zone tectonic setting also explains the extremely narrow appearance of the CRS marginal slice (Richter et al., 1939; Müller, 1973) and is consistent with the assumption of the RDF being deposited within a W-E striking transform fault zone setting (Fig. 14b,c) (Hesse, 1974, 2011). Moreover, transform faults juxtapose RDF and CRS marginal slice, most probably leading to the cut out of Lower Austroalpine units (Fig. 14b,c). Cretaceous W-E striking sinistral strike-slip faults are also documented offsetting the Austroalpine units of, e.g., Graubünden, Switzerland (i.e., Albula steep zone, Froitzheim et al., 1994) and Styria, Austria (i.e., ductile Gleinalm shear zone, Neubauer et al., 1995).

6. Conclusions

Based on structural field work, we suggest that the Cenoman-Randschuppe marginal slice originated as part of the foreland of the Cretaceous NCA orogenic wedge. In this external part of the Austroalpine, we distinguish following structural events:

1. Emplacement of the Karwendel thrust sheet in the Albian. The future Cenoman-Randschuppe marginal slice was, at that time, still part of the continental foreland of the Cretaceous Austroalpine wedge.
2. Sinistral E-trending transform faults cut across this foreland and the most external part of the orogenic wedge and isolated a narrow strip of rocks belonging to the foreland, representing the Cenoman-Randschuppe marginal slice. The most external part of the Karwendel thrust sheet, the Falkensteinzug, was already superimposed. These transform faults ultimately brought the Rhenodanubian Flysch into close proximity to the Cenoman-Randschuppe marginal slice. The fate of Lower Austroalpine units that should have been present between the Penninic

and Upper Austroalpine units remains unclear, but were most probably cut out by the transform faults.

3. Subsequent Late Cretaceous and younger shortening emplaced the Austroalpine stack onto the Arosa zone and Rhenodanubian Flysch on top of the Tannheim thrust. Refolding of the thrust sheet boundaries is documented by growth strata in the thrust-sheet-top deposits (Branderfleck Fm.).

The existence of E-trending transform faults explains the absence of the Arosa zone, i.e., the suture of the South Penninic ocean containing ophiolites in the area between Hindelang and Vienna, where it reappears in the Ybbsitz and St. Veit Klippenzones. The Arosa zone is thus in the same tectonic position as the Cenoman-Randschuppe marginal slice, the latter replacing the Arosa zone in a transform setting.

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