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Three-dimensional pattern of thrust and allochthonous salt emplacement in the Northern Calcareous Alps, Eastern Alps (Austria)

Oscar Fernandez [a,*], Thomas Leitner [b], Lino Eggerth [a], Diethard Sanders [c], Hugo Ortner [c], Michael Moser [a], Mariusz Fiałkiewicz [d], Luke Hill [a], Bernhard Grasemann [a]

[a] Dept. of Geology, University of Vienna, Josef-Holaubek-Platz 2 (UZA II), 1090, Vienna, Austria
[b] Salinen AG, Altaussee 139, 8992, Altaussee, Austria
[c] Dept. of Geology, University of Innsbruck, Innrain 52, 6020, Innsbruck, Austria
[d] Computational Geology Laboratory, Polish Geological Institute – National Research Institute, Wrocław, Poland

A B S T R A C T

Pre-existing salt structures and thickness variation in the supra-salt stratigraphy exert a strong control on the geometry and evolution of contractional systems. Here we explore a sector of the central Northern Calcareous Alps (Eastern Alps, Austria), and its evolution over a timespan of ~40 Ma, during the Late Jurassic to Early Cretaceous. The nucleation points of structures and their obliquity were conditioned by the presence of pre-existing structures above a highly effective basal evaporitic décollement. The ratio of thickness between the evaporitic detachment and its overlying stratigraphy controlled the evolution of structures, with thicker supra-salt stratigraphy limiting the progression of deformation. Syn-tectonic sedimentation changed the map pattern of salt-to-cover thickness (overburden to salt ratio) during deformation. Increasing sedimentary load above the salt led to the transition from an initial stage of squeezing of salt structures, salt-fed thrusting and salt allochthony, to a stage of low-angle thrusting. Differential shortening across the area led to highly oblique transport directions, up to 90° to each other, and lateral motions within the emplaced units that were accommodated through syn-thrusting extensional faulting.

The structural evolution presented here further provides critical insights into the earliest phases of Alpine orogenesis, in the Late Jurassic to Early Cretaceous, and helps to clarify structural and temporal relationships that had not previously been fully understood.

1. Introduction

Salt *décollements* and their lateral variability exert a major control on thrust systems (e.g., Costa and Vendeville, 2002; Bahroudi and Koyi, 2003; Rowan and Vendeville, 2006; Callot et al., 2007, 2012; Granado et al., 2019, 2021; Célini et al., 2024; Feng et al., 2024; Muñoz et al., 2024; Santolaria et al., 2022, 2024). Furthermore, pre-existing salt-structures in contractional systems lead to the development of oblique structures, which often results in complex three-dimensional folding and thrusting patterns (e.g., Rowan and Vendeville, 2006; Callot et al., 2007, 2012; Dooley et al., 2009, 2015; Muñoz et al., 2013; Legeay et al., 2020; Duffy et al., 2018; Santolaria et al., 2021a, 2021b, 2024). Tectonic shortening of pre-existing salt structures frequently leads to the extrusion of salt onto the surface to form allochthonous bodies that can transport or accumulate variable amounts of supra-salt stratigraphy (Hudec and Jackson, 2006; Rowan, 2017). Besides feeding allochthonous salt bodies, salt structures can also be the nucleation points for thrusts or develop into thrusts themselves (e.g., Rowan and Vendeville, 2006; Dooley et al., 2015; Duffy et al., 2018; Santolaria et al., 2021b).

The combined study of field examples and analogue (sandbox) models has been a key source of insights into the development and architecture of salt-rich contractional systems. In some instances, analogue models can even predict features that are not observed in the real-world examples (cf., thrust salt allochthons in Santolaria et al., 2021a; discussion on 'missing' allochthonous salt in Santolaria et al., 2022). We contend here that the area around the town of Bad Ischl (in the Northern Calcareous Alps, Eastern Alps, Austria; Fig. 1a) provides evidence for the presence of syn-thrusting allochthonous salt, in the proximity of the area that was subject of the study of Santolaria et al. (2022).

Furthermore, the area of the Northern Calcareous Alps (NCA) around the locality of Bad Ischl, presents structures that reveal the intricate relationship between different styles of contractional deformation above a variable thickness salt décollement. These styles include detachment folds, source-fed thrusts, salt allochthons, and low-angle thrusts, all of which have contrasting shortening or emplacement directions. Outcrop observations, borehole and mine gallery data, and a well-constrained syn-tectonic sedimentation record provide a unique view into the

* Corresponding author.
E-mail address: oscar.fernandez.bellon@univie.ac.at (O. Fernandez).

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detailed evolution of a system of oblique salt-related structures.

In this contribution we focus on the structure and evolution of the Lauffen allochthonous salt sheet and of the overthrust Dachstein thrust sheet. The Dachstein thrust sheet is detached along the same Permo-Triassic salt that fed the Lauffen salt sheet. Observations indicate that the Lauffen salt sheet was emplaced onto the Early Cretaceous seafloor, and the Dachstein thrust sheet was emplaced, immediately after, onto the bathymetry defined by the salt sheet. Despite the temporal proximity and that both transport Permo-Triassic salt, both structures were emplaced at nearly normal directions to each other. The geometry of the system is further complicated by oblique folds, detached on the basal Permo-Triassic salt level, that affect the substrate underlying both the Lauffen salt sheet and Dachstein thrust sheet. Syn-tectonic sedimentation in the area provides a record of the sequence of events and makes it possible to unravel an otherwise perplexing structural juxtaposition.

Beyond its remarkable structure, the Lauffen salt sheet is prominent for having been the location of the recovery and documentation of Haloarchaea inferred to be Permian in age (Stan-Lotter et al., 2002, 2003). However, the novel interpretation for the Lauffen salt sheet presented here potentially calls this dating into question.

2. Geological setting

The NCA are the Permo-Mesozoic sedimentary cover of the Austroalpine basement in the Eastern Alps (Schmid et al., 2008) (Fig. 1a). Since the Late Jurassic the NCA have been internally imbricated and thrust northwards, and mostly decoupled from their underlying basement (Fig. 1b) (Faupl and Wagreich, 2000; Fernandez et al., 2024, 2025).

2.1. Stratigraphy

Stratigraphy in the NCA records the rift to passive margin development of the Austroalpine domain, from latest Paleozoic to Middle Jurassic (Fig. 2), and its subsequent inversion. Syn-orogenic deposits related to folding, thrusting and imbrication span mostly from the latest Middle Jurassic to Paleogene times (Fig. 2).

The oldest post-Variscan sediments in the NCA are uppermost Carboniferous to Permian coarse clastics whose deposition records the onset of Tethyan-related rifting in the Austroalpine domain (Mostler, 1972; Mandl, 2000; Leitner and Spötl, 2017). These units fine upwards and are overlain by a succession of Late Permian to Early Triassic age evaporites, clastics, and carbonates that are traditionally grouped into two components (Tollmann, 1976; Schauberger, 1986): a succession of deltaic to shallow marine fine-grained clastics and carbonates (Werfen beds) and an evaporite rich mobile succession of halite and subordinate anhydrite and mudrock (with the informal mining name of Haselgebirge, and referred to here simply as "salt"). At present, the Haselgebirge is constituted by only 50–65% of halite and anhydrite, with lesser amounts of mudstone, fine sandstone, and dolostone (Leitner et al., 2017; Leitner and Mayr, 2017).

Both the Haselgebirge and Werfen beds are highly variable in thickness throughout the NCA due to, both, their syn-rift nature (Leitner and Spötl, 2017; Strauss et al., 2023) and post-depositional salt tectonics (Granado et al., 2019; Strauss et al., 2023; Fernandez et al., 2024). Their original stratigraphic thickness is documented to exceed 500 m (Tollmann, 1976), possibly up to 1000 m (Fernandez et al., 2024). Where both units are present, it is generally assumed that the Werfen beds overlie the Haselgebirge, and it is possible that the Werfen beds deposited in salt-bounded minibasins (Fernandez et al., 2024). It has, however, also been documented that, at least locally, the Haselgebirge continued to deposit coeval with the Werfen beds (Schauberger, 1986).

The Lower Triassic Werfen beds and Haselgebirge are overlain by a succession of Middle to Upper Triassic carbonate rocks (limestones and dolostones, referred to as onwards generically as 'carbonates') which experienced a strong differentiation into shallow water and pelagic domains due to mobilization of the Haselgebirge salt (Fernandez et al., 2024). As pointed out by Fernandez et al. (2024), the NCA developed as a basin where, due to ongoing extension, the rising tops of salt bodies (diapirs and ridges) failed to keep up with carbonate aggradation in the flanking minibasins. As a result, salt diapirs and ridges were areas of deeper bathymetry than the surrounding minibasins (as illustrated in Fig. 2c) and accumulated relatively condensed (few hundreds of meters) slope and pelagic carbonates. Coevally, up to 2–4 km of shallow water carbonates deposited in the surrounding minibasins, that were tens of kilometers wide. The result was a mosaic of areas with thick and thin Triassic stratigraphy above the Haselgebirge salt that also varied in

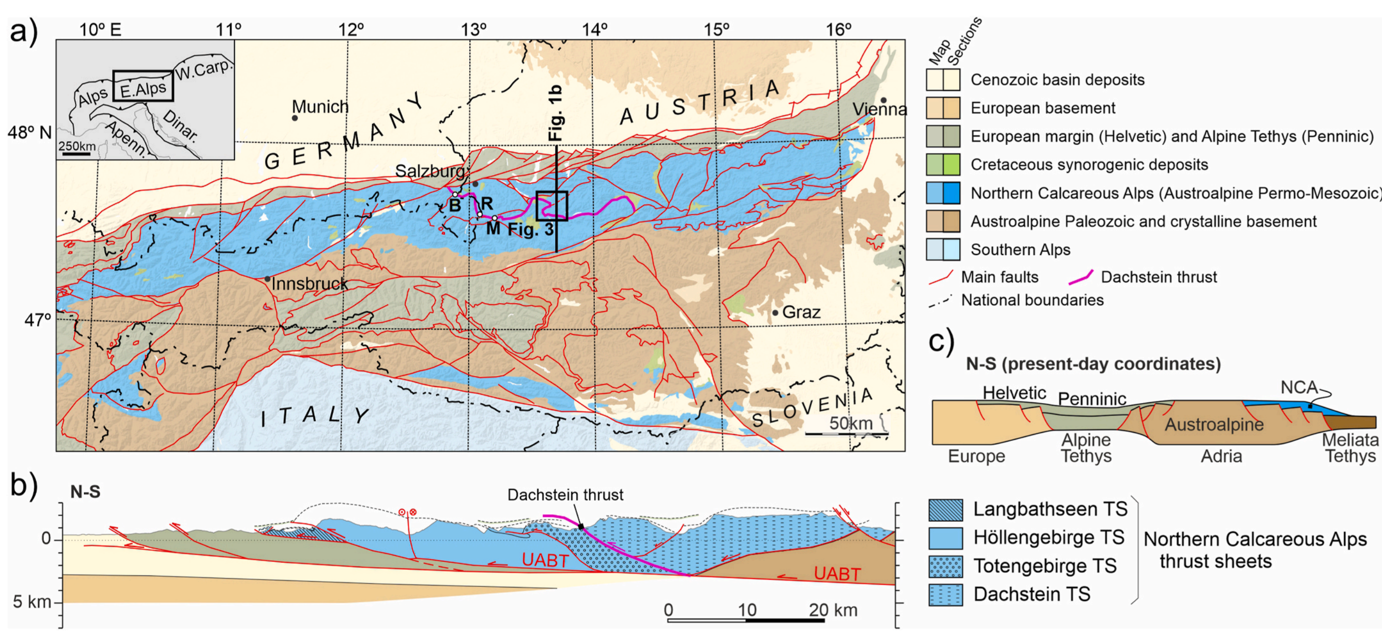

Fig. 1. a) Synthetic geological map of the Eastern Alps. Labels B, R and M refer to the localities of Bad Reichenhall, Rossfeld and Moosegg discussed in the text. In inset: Apenn.: Apennines; Carp.: Carpathians; Dinar.: Dinarides; E.: East; W.: West. b) Simplified regional cross-section of the central Northern Calcareous Alps (NCA) (modified from Schuster et al., 2013). TS: thrust sheet; UABT: Upper Austroalpine Basal Thrust. c) Schematic section showing the relative position of the key paleogeographic domains of the Eastern Alps at latest Middle Jurassic times.

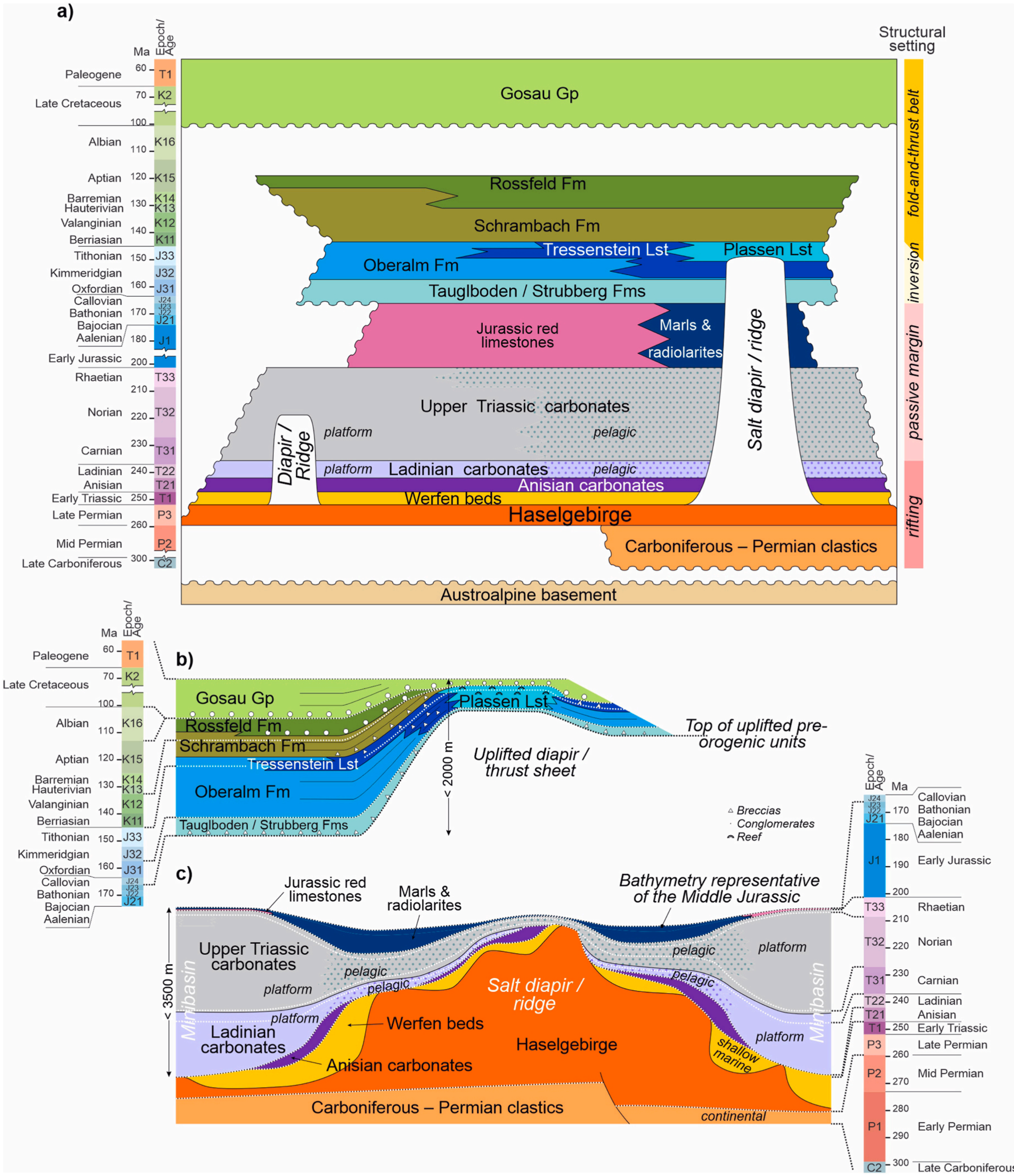

Fig. 2. a) Chronostratigraphic chart of the central Northern Calcareous Alps with stratigraphy simplified from Mandl (2000); Piller et al. (2004). b) Sketch of stratigraphic units in relation to inverted salt structures and thrusts during Jurassic to Cretaceous shortening. c) Sketch of stratigraphic unit arrangement in relation to salt structures during the Permian to Middle Jurassic (after Fernandez et al., 2024). During this period, salt structures in the NCA were characterized by deeper bathymetry than the surrounding minibasins, with thick successions of platform carbonates accumulating in minibasins and condensed pelagic carbonates above inflated salt (Fernandez et al., 2024).

thickness (Fig. 2c). Furthermore, syn-depositional salt tectonics and extension led to some of the Lower to Middle Triassic units to be fragmented and locally absent (Fig. 2c).

At the end of the Triassic, the Austroalpine domain subsided rapidly, and Triassic strata were draped by a relatively thin (few tens of meters) bathyal radiolaritic or pelagic-carbonatic Lower to Middle Jurassic (Mandl, 2000) (Fig. 2).

Inversion of the Austroalpine rifted margin started in the Late Jurassic and lasted to present (Faupl and Wagreich, 2000), although its sedimentary record in the study area reaches only into the Paleogene. Initial inversion during the Late Jurassic led to the squeezing of the main salt structures in the passive margin, leading to uplift of diapir rooves, salt extrusion, folding, and thrusting (Kurz et al., 2023; Fernandez et al., 2025). Carbonate platforms (Plassen Limestone) developed on top of growing structures and were flanked by coarse-grained slope deposits (Tressenstein Limestone) that graded distally into calciturbidites (Oberalm Fm) (Garrison, 1967; Gawlick et al., 2009; Mandl, 2013) and accumulating up to 1200 m in thickness (Fig. 2).

A subsequent stage of deformation during the Early Cretaceous led to further tightening of inverted salt structures and imbrication of regional scale thrust sheets (Faupl and Wagreich, 2000; Mandl, 2000; Ortner and Kilian, 2022). The Lauffen salt sheet and the Dachstein thrust sheet, the main subjects of this contribution, were emplaced during this time. Deformation was synchronous with deposition of marls, shales, sandstones and conglomerates of the Schrambach and Rossfeld Fms (Decker et al., 1987; Faupl and Wagreich, 1992; Krische et al., 2014) (Fig. 2). During this time, the basin recorded the first arrival of clasts of volcanic rocks and serpentinites interpreted to derive from the erosion of obducted Tethyan oceanic rocks (Krische and Gawlick, 2015; Decker et al., 1987).

Thereafter, from Late Cretaceous to Eocene times, the northern portion of the NCA was detached from its basement, along the Permo-Triassic Haselgebirge décollement, and thrust northwards onto the Alpine Tethys and European margins (resulting in the configuration shown in Fig. 1b) (Faupl and Wagreich, 2000). The NCA experienced, internally, further folding, thrusting, and strike-slip faulting, but smaller in magnitude than the Late Jurassic to Early Cretaceous events. The result is that the Late Jurassic to Early Cretaceous structure of the central NCA has been mostly preserved, despite subsequent deformation and far travelled allochthony onto the European margin.

Sedimentary record for the Late Cretaceous to Paleogene evolution of the NCA is provided by the Gosau Gp, a mixed clastic-carbonate unit that in part infilled pre-existing bathymetry, and in part was involved in ongoing deformation (Wagreich and Faupl, 1994; Sanders, 1998; Ortner, 2001; Ortner et al., 2016). The remnants of once thick wedge-top sediments of Oligo-Miocene age are preserved locally in the central NCA (Frisch et al., 2001; Ortner and Stingl, 2001; Ortner et al., 2023). Isolated Oligo-Miocene late orogenic collapse features are also present (e.g., Neubauer, 2016).

2.2. Structural setting

The Lauffen salt sheet is located in the central NCA, along the Traun River, south of the village of Bad Ischl (and roughly 40 km to the ESE of the city of Salzburg, Austria) (Fig. 1a and 3). The central NCA in this area are formed by three main thrust sheets of Permo-Mesozoic strata that were imbricated during the Early Cretaceous (Faupl and Wagreich, 2000; Mandl, 2000; Mandl et al., 2012; Levi, 2023). From structurally lowest to highest these are the Langbathseen, Höllengebirge and the Dachstein thrust sheets (Fernandez et al., 2024) (Fig. 1b). The Höllengebirge thrust sheet is dissected along almost its entire E-W length by a Jurassic-age system of thrusts and folds (the Totengebirge–Trattberg, or TT, contractional system; Fernandez et al., 2025) with the Totengebirge thrust sheet in their hanging wall (Fig. 1b). The Lauffen

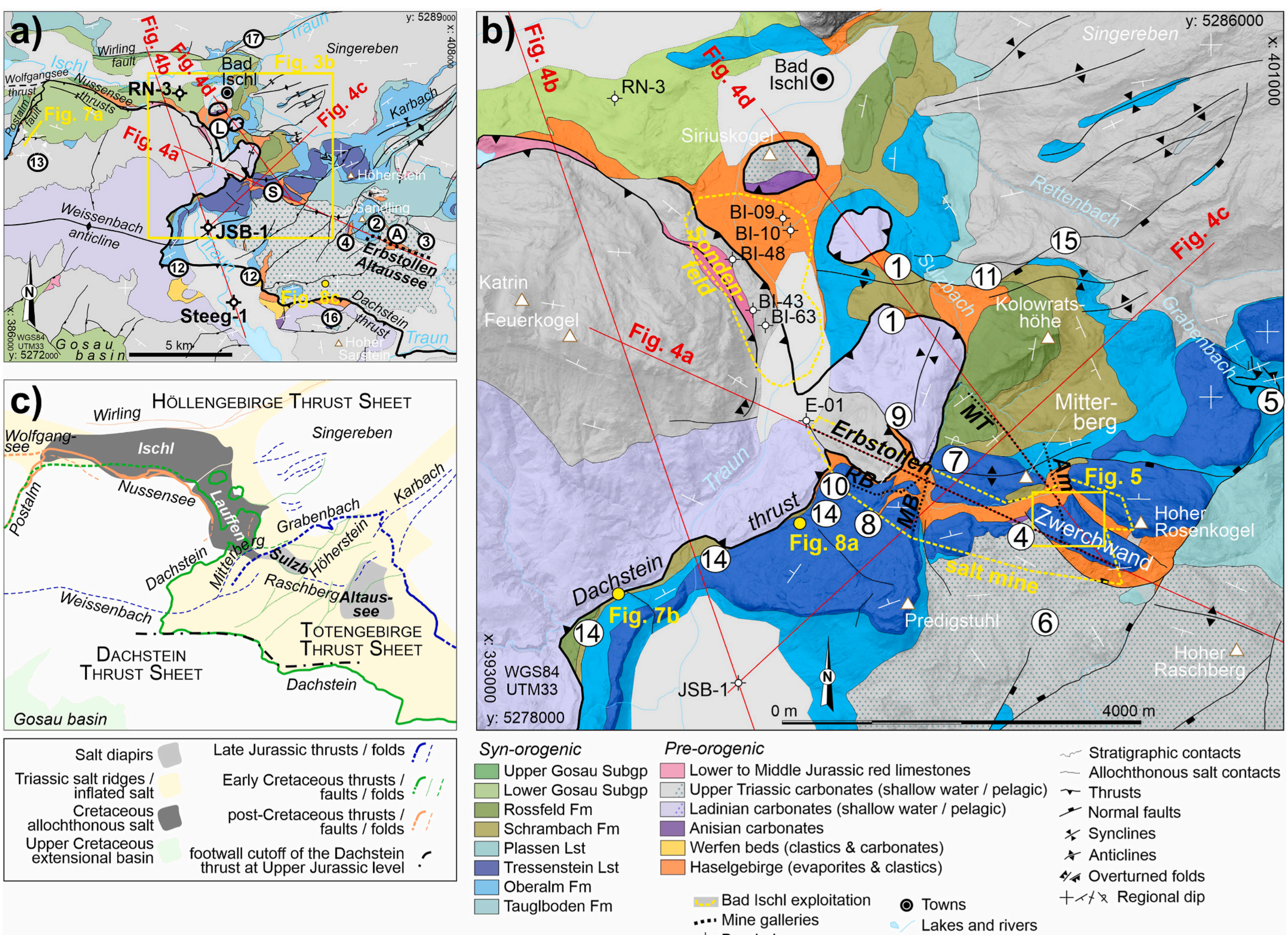

Fig. 3. a) and b) Geological maps of the study area showing the locations of the cross-sections in Fig. 4 and the map in Fig. 5, and the outcrops in Figs. 7 and 8. The circled letters L, S, and A in (a) mark the location of the Lauffen salt sheet, the Sulzbach stock and the Altaussee diapir. The circled numbers indicate features referenced in the main text. Mine gallery name abbreviations; Am: Amalia; MB: Mitterberg; MT: Maria Theresia; RB: Rabenbrunn. This map is based on fieldwork conducted by the authors, previously published 1:50,000 scale geological mapping (Plöchinger, 1982; Schäffer, 1982), local maps (Lehmann, 1926; Wagreich, 1998; Laimer, 2019; Levi, 2023), and an unpublished 1:25,000 scale geological map around the Bad Ischl salt mine (Schadler, 1957). c) Key structural and salt tectonic elements of the map in (a). Sulzb: Sulzbach.

salt sheet is part of the Höllengebirge thrust sheet and lies below the Totengebirge and Dachstein thrust sheets (Fig. 3c). The TT contractional system in this area (the boundary between the Höllengebirge and Totengebirge thrust sheets) is a soft-linked system formed by the Weissenbach anticline, Grabenbach thrust and Karbach folds (Fig. 3c). These structures accommodated Late Jurassic north-to northwest-directed shortening. The Totengebirge and Höllengebirge thrust sheets were thrust over, in the Early Cretaceous, by the Dachstein thrust sheet (Fig. 1b and 3c), which was emplaced in a north to northeast direction (Fernandez et al., 2024). Segments of the TT system (namely the Weissenbach anticline) continued to be active during and after emplacement of the Dachstein thrust sheet (as discussed below; Levi, 2023). Likewise, as the central NCA continued to be thrust passively northwards after the Paleogene, deformation internal to the NCA was accommodated on lesser-order displacement thrusts and strike-slip faults (Linzer et al., 1995; Peresson and Decker, 1997; Levi, 2023). Amongst these are the Wolfgangsee thrust and Nussensee thrusts (Laimer, 2019; Levi, 2023) that cross-cut the leading edge of the Dachstein thrust sheet (Fig. 3a–c) and the re-activated Postalm fault (Fig. 3a–c), which initially acted as a lateral ramp to the Dachstein thrust (Fernandez et al., 2024). Nonetheless, post-Cretaceous deformation in the central NCA had a limited effect on its structure (and on the features discussed herein), as indicated by its regional-scale tabular geometry (Fernandez et al., 2022).

Due to the syn-depositional growth of salt structures, the pre-orogenic thickness of Middle to Upper Triassic units in the NCA thrust sheets varies laterally, from few hundreds of meters to up to 4 km (cf. Fig. 2c). Diapirs and salt ridges were areas of thinner Middle to Upper Triassic stratigraphy (mostly pelagic) and were flanked by areas of thick carbonate platforms (Mandl, 2000,; Strauss et al., 2021; Fernandez et al., 2024) (Fig. 2c). Besides condensed stratigraphy, diapirs and salt ridges are sometimes overlain exclusively by Upper Triassic rocks (with the Middle Triassic being completely absent).

In the study area, the Dachstein thrust sheet (Fig. 3c) is formed mainly by a thick platform minibasin-infill, with only the Gosau basin interpreted to have relatively thin supra-salt stratigraphy (Fernandez et al., 2022). The Höllengeibrge and the Totengebirge thrust sheets (in the footwall of the Dachstein thrust sheet) had inflated salt and thin supra-salt stratigraphy forming a broad area below the Sulzbach and Altaussee, with ridges radiating from it (Fig. 3c).

3. Mining data in the study area

The watershed of the Traun River (Fig. 3a) has been intensively explored for rock salt resources for millennia (Aigner, 1888; Kern and Lammerhuber, 2011; Dicklberger and Nussbaumer, 2017). Within the study area, three accumulations of Haselgebirge evaporites have been subject to large-scale commercial exploitation by the Salinen AG mining company (Fig. 3a–c):

1) a major diapir (the Altaussee diapir; label A in Fig. 3a);
2) a salt stock (the Sulzbach stock; label S in Fig. 3a); and
3) a tabular body of salt that rests directly on Cretaceous sediments (Lauffen salt sheet; label L in Fig. 3a).

Other outcrops of Haselgebirge in the area, namely along the trace of the Dachstein and Nussensee thrusts (Fig. 3a) have not been subject to exploitation and have been documented through field mapping. Only the salt accumulation north of the Nussensse thrusts, in the Ischl River valley, has been drilled by a borehole, the RN-3 borehole (Fig. 3a), not related to salt production. Other boreholes in the area (JSB-1 and Steeg-1; Fig. 3a) have not drilled any salt structures.

The Altaussee diapir and the Sulzbach stock have been mined through galleries and dissolution mining (Altaussee and Bad Ischl salt mines). The Altaussee mine has 10 main exploitation levels (including water drainage drifts) and hundreds of directional boreholes extending, in some instances over 600 m, from these galleries in multiple directions (including horizontally). The subsurface extent of rock salt in this diapir (illustrated in Fig. 4a) is determined from these. The deepest drift, the Altaussee Erbstollen, lies at 740 m a.s.l. (above sea level) and is the only one included in this contribution (Fig. 3a).

The Bad Ischl mine, in turn, has 11 main levels, with tens of directional boreholes. In both mines, exploitation levels are spaced roughly 40 m vertically and salt production is performed through dissolution mining, from caverns located between these levels. The subsurface geometry of the Sulzbach salt stock (illustrated in Fig. 4a) is determined from these. The deepest drift, the Erbstollen, lies at 500 m a.s.l. In this contribution, data from the Rabenbrunn, Mitterberg, Amalia and Maria Theresia galleries (Fig. 3b) is also included. The main objective of the operation of the Bad Ischl salt mine was to produce salt from the Sulzbach salt stock, although some galleries also intersected the Lauffen salt sheet.

The Lauffen salt sheet is mined through dissolution mining with vertical boreholes drilled from the surface in the Bad Ischl borehole field or *Sondenfeld* (Fig. 3c). Boreholes in the *Sondenfeld* locally exceed 600 m of drilled length and frequently reach the base of the salt body (Table 1). Although the Lauffen salt sheet is partly intersected by galleries of the Bad Ischl mine, these have not significantly contributed to its exploitation.

Within all the salt bodies described, the Haselgebirge presents an intricately complex internal structure of lithological banding. In the discussion below, and in the maps and figures, the entire unit is presented as one and referred to as “salt”. However, at present, as much as 50% of the Haselgebirge is non-evaporitic, that represents the less mobile and less soluble residue.

3.1. *Geometry of the Altaussee, Sulzbach and Lauffen salt bodies*

The Altaussee diapir, the Sulzbach salt stock and the Lauffen salt sheet have been previously described from subsurface data (mine galleries and boreholes) and detailed geological mapping (Medwenitsch, 1957; Kohlbeck et al., 1986; Schäffer, 1982; Mandl et al., 2012; Mandl, 2013). The geometry of these salt bodies is constantly updated through standard mining operations by Salinen AG. The currently known cross-sectional geometry of these bodies is shown on Fig. 4a and described below. The boundaries of the rock salt bodies, as mapped by Salinen AG (yellow bold dashed lines in Fig. 4a), are interpolated from gallery and vertical and deviated borehole control points. Deviations between the mapped boundaries and the contacts drawn on Fig. 4a respond to the local re-interpretation of the interpolated boundary of the Haselgebirge unit.

The Altaussee diapir (label A in Fig. 4a) is anvil-shaped, with a tilted stock (dipping to the NW). The stock is roughly 1 km in diameter. The base of the stock is unknown, but it is known to stretch at least as deep as sea level, and up to an elevation of approximately 600 m a.s.l. Above this elevation, the head of the diapir stretches to the SE of the salt stock and is elongate in a roughly NW-SE direction, approximately 2 km × 1 km in plan view. The head of the diapir rises to an elevation of around 1000 m a.s.l. West of the Altaussee diapir, salt was exploited historically in the Michlhallbach valley (Rupp et al., 2011) (Fig. 4a). No details on the structure of the salt body in the Michlhallbach are available, and its connection to the Altaussee diapir shown in Fig. 4a is a tentative proposal.

The Sulzbach salt stock, some 4 km WNW of the Altaussee diapir, and its structure as documented from borehole and gallery constraints is shown in Fig. 4a (label S). The Sulzbach stock has been exploited along its northwestern margin where it is elongate in a NE-SW direction, and roughly 1 × 0.5 km in plan view (Mayrhofer, 1955). The salt stock dips steeply to the SE (Fig. 4d) and reaches down to at least 200 m a.s.l., but its base has not been drilled (Mayrhofer, 1955). The salt stock crops out at surface, at an elevation of around 900 m a.s.l. Outcrop control indicates that the salt stock extends to the southeast, under the hill of the Zwerchwand (east of label 4 in Fig. 3b), but the structure at depth is

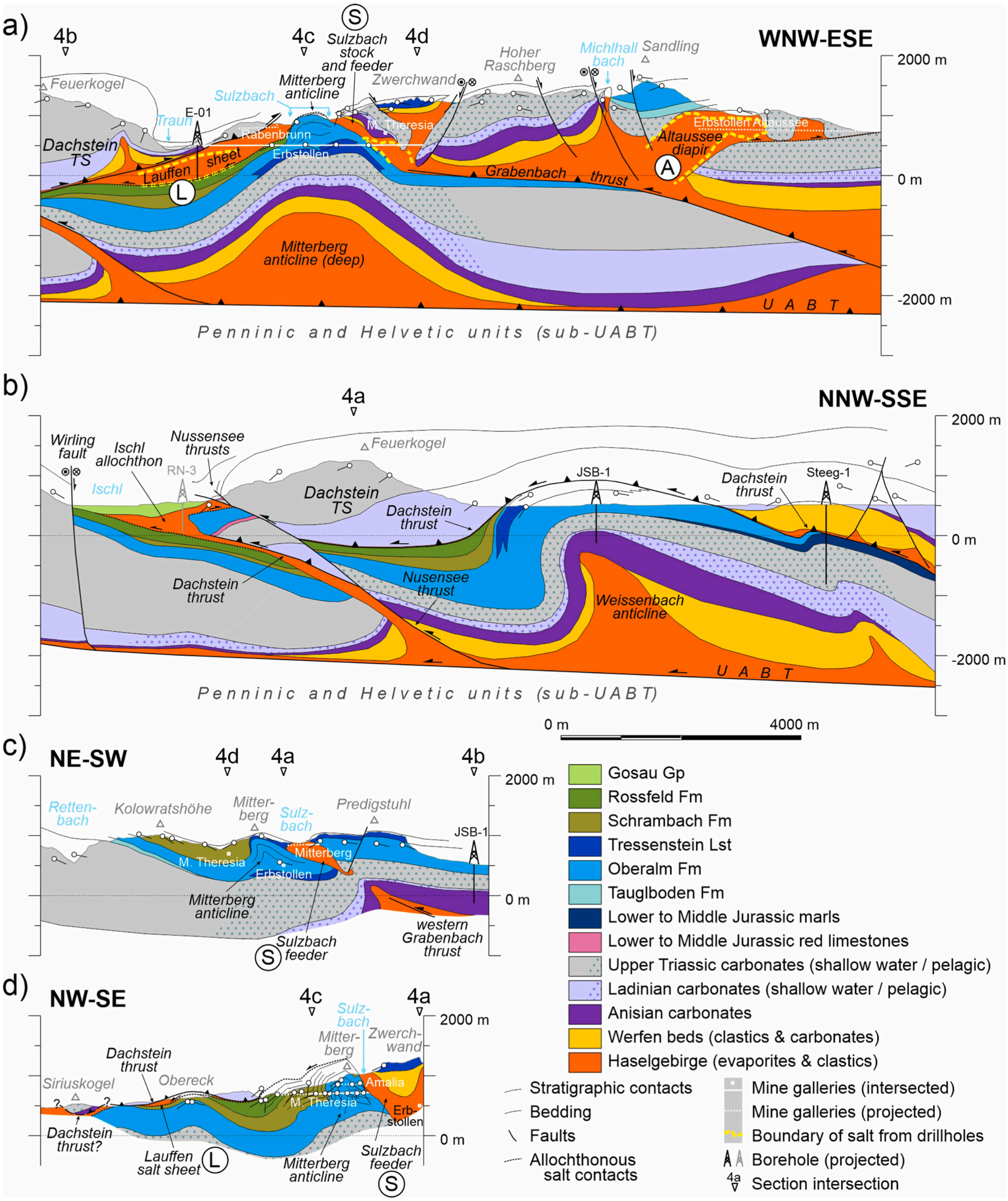

Fig. 4. Oblique cross-sections across the Lauffen salt sheet, the Dachstein thrust sheet, and their surrounding area. TS: thrust sheet; UABT: Upper Austroalpine basal thrust. The labels L, S, and A refer to the Lauffen, Sulzbach and Altaussee salt bodies. Thrusting on the UABT is interpreted to be roughly north-directed (Fernandez et al., 2024). Thrusting on the Dachstein thrust is NE-directed (see text). See Fig. 3 for location.

unconstrained.

The Lauffen salt sheet lies in the Traun River valley (label L in Fig. 4a) and is known from borehole data (Table 1) to be a sheet-like body, some 300–600 m thick, and at least 3 km long in a N-S direction and up to 1 km in an E-W direction. Boreholes from the Bad Ischl *Sondenfeld* indicate that the Lauffen salt sheet is thrust over by the Dachstein thrust sheet in the west (BI-43, BI-48, BI-63; Table 1) and than in turn, it lies on Upper Jurassic or Early Cretaceous rocks (BI-09, BI-10, BI-63; Table 1). The westwards extent of the Lauffen salt sheet, under the Dachstein thrust sheet, is uncertain.

The Lauffen salt sheet extends east of the Traun River valley and is intersected by the Erbstollen and Rabenbrunn galleries of the Bad Ischl salt mine (Fig. 4a). In the Erbstollen gallery, the Lauffen salt sheet is observed to be structurally overlain by the Upper Triassic carbonates of the Dachstein thrust sheet, and to rest above conglomerates and shales of the Rossfeld Fm (Medwenitsch, 1957; Kohlbeck et al., 1986). East of the Traun River valley, Haselgebirge of the Lauffen salt sheet crops out in isolated patches (label 1 in Fig. 3b) and was historically exploited for gypsum (Feichtinger, 2020a, 2020b, 2020c). At these locations, the salt of the Lauffen sheet lies directly above the Schrambach Fm (Fig. 3b).

This geometric relationship of Haselgebirge above Upper Jurassic and Lower Cretaceous rocks has been previously interpreted to originate

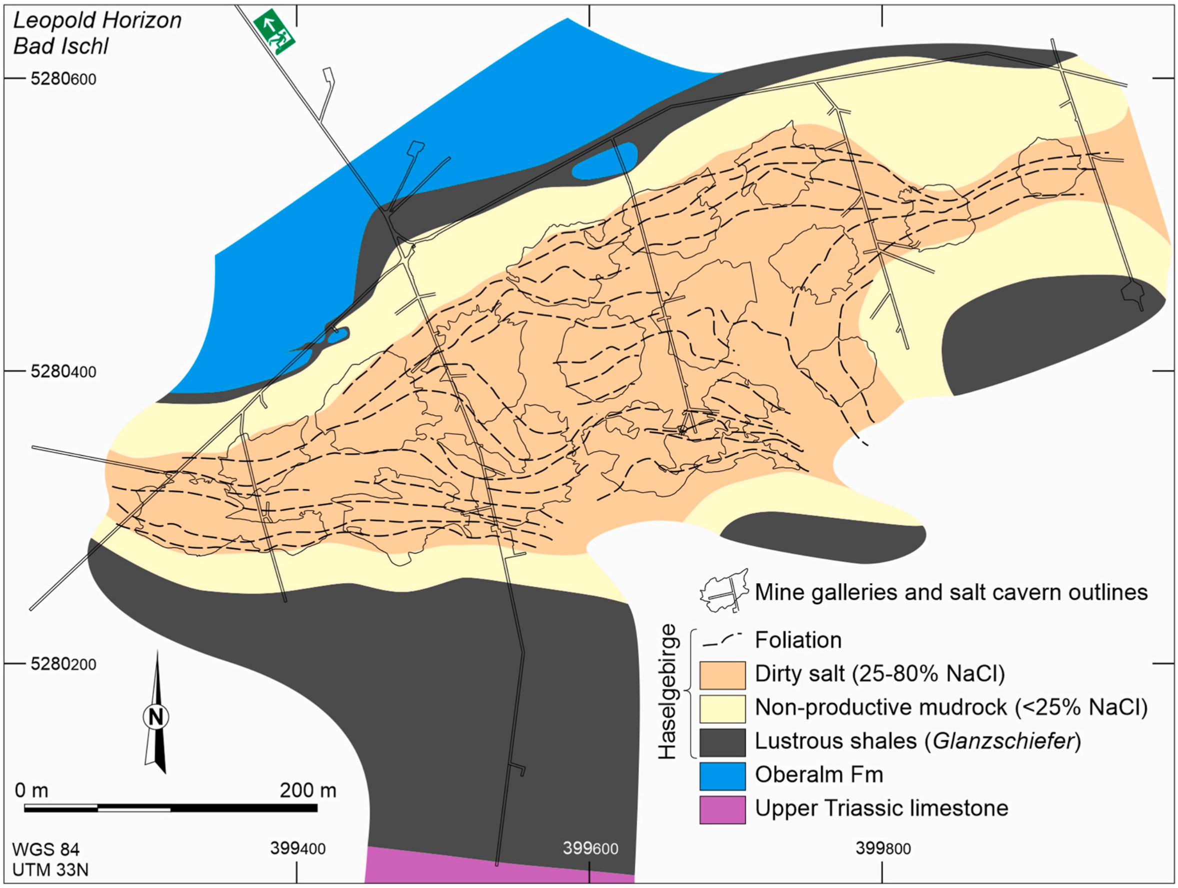

Fig. 5. Map of the Leopold working horizon in the Bad Ischl mine. In black lines is shown the trace of mine galleries of the Leopold level and the outline of dissolution caverns below it. The foliation observed in the salt has been interpolated between caverns. The tops of the caverns are roughly 5 m below the gallery level. See Fig. 3 for location. Simplified from Mayrhofer (1955) and Schauberger (1955).

due to the emplacement of the Haselgebirge salt as a gravitational nappe, over tens of kilometers, and completely decoupled from its original root or source (i.e., as an olistolith) (Mandl, 1982; Tollmann, 1987; Mandl et al., 2012). In the case of Altaussee, authors have previously assumed that the Haselgebirge was emplaced along with its overlying pelagic Triassic sediments (Mandl, 1982; Tollmann, 1987; Mandl et al., 2012). However, as has been discussed by Fernandez et al. (2021, 2024, 2025) and Kurz et al. (2023) and will be shown below, the juxtaposition of Permo-Triassic Haselgebirge salt on the underlying Jurassic to Cretaceous sediments originates due to local allochthonous salt emplacement during the Late Jurassic to Early Cretaecous (with allochthony, in general, being less than 5 km).

4. Structure of the study area

The structure of the study area is characterized by varying structural orientations. To honor its complexity, we have represented the structure of the area with four cross-sections (Fig. 4), that are supported by field structural mapping, data collected within mine galleries, and boreholes. The cross-sections in Fig. 4 and the text below are a description of the structures in the study area based on observations and interpretations contributed by the authors.

One cross-section runs along the Erbstollen of the Bad Ischl salt mine (Fig. 4a) and shows the relationship between the Lauffen salt sheet and the Sulzbach stock with the Dachstein thrust sheet. This section further shows the relationship between the Lauffen and Sulzbach salt bodies and the Altaussee diapir. A second cross-section (Fig. 4b) runs through deep boreholes Steeg-1 and JSB-1 and provides a section of the western margin of the Dachstein thrust sheet and of the allochthonous salt in the Ischl River valley. These two main sections are complemented by shorter sections, one along the JSB-1 borehole and the Mitterberg gallery (Bad Ischl salt mine) (Fig. 4c), and one along the Maria Theresia gallery of the same salt mine (Fig. 4d).

The main objective behind the cross-sections and the discussion below is to explore the relationship between the Cretaceous-emplaced Lauffen allochthonous salt sheet and Dachstein thrust sheet. These two structures interact with, or relate to, multiple other elements that are also contained in the map in Fig. 3c and the cross-sections in Fig. 4. The timing and evolution of the different structures has been interpreted from their relationship with syn-tectonic strata and mutual cross-cutting relationships. Structures in the area present prolonged periods of tectonic activity and can be best explored based on the time of peak tectonic activity. The sequence of cessation in tectonic activity is used to organize the following description of the structures in the study area, and their interpreted evolution.

4.1. The Altaussee diapir

Mine data of the Altaussee mine indicates that the stock of the Altaussee diapir is surrounded by pelagic Upper Triassic limestones, other than to its west, where its boundary has not been encountered. The southeastern half of its head rests on the same Upper Triassic limestones (Fig. 4a; cf. profile by M. Mayr in Lobitzer, 2023). The head of the diapir partly crops out at surface and is covered by either Upper Triassic pelagic carbonates or Upper Jurassic syn-tectonic sediments (label 2, Fig. 3a). Along the east, the head of the diapir and the pelagic Triassic limestones that cover it are thrusted onto the Upper Jurassic Tauglboden Fm (label 3 in Fig. 3a; Medwenitsch, 1957; Mandl et al., 2012).

Table 1
List of boreholes used in this study, depths to the key horizons intersected, and description of the Haselgebirge facies (where applicable).

Borehole name	Location (WGS84 UTM33, in m)							
	X (Easting)	Y (Northing)	Z (Elevation a.s.l.)	Bottom Depth (m a. s.l.)	Total Depth (m)	Tops (depth - unit)	Haselgebirge facies	Notes
BI-09 (Bad Ischl-09)	396415	5283699	475	−21	496	0 - Quaternary 5 - leached Haselgebirge 277 - unleached Haselgebirge 490.15 - Rossfeld Fm 491.9 - Oberalm Fm	Grey rock salt, anhydrite (secondarily red and green claystone)	Drilled by Salinen AG
BI-10 (Bad Ischl-10)	396501	5283565	477	−28	504.9	0 - Quaternary 32 - leached Haselgebirge 146 - Ansian (Gutenstein Fm) 212 - leached Haselgebirge 272 - unleached Haselgebirge 496.5 - Oberalm Fm	Grey rock salt, anhydrite (secondarily red and green claystone)	Drilled by Salinen AG
BI-43 (Bad Ischl-43)	396070	582607	523	−131	654.2	0 - Quaternary 19 - Dachstein Lst 139 - Dachstein Dol 348.7 - unleached Haselgebirge	Red and grey rock salt, anhydrite	Drilled by Salinen AG
BI-48 (Bad Ischl-48)	395842	5283227	537	143	393.6	0 - Norian (Dachstein Lst) 176 - Ladinian (Wetterstein Dol) 270.5 - Anisian (Gutenstein Fm) 307 - leached Haselgebirge 329 - Oberalm Fm 386.95 - leached Haselgebirge 393.6 - unleached Haselgebirge	Grey rock salt, anhydrite (secondarily red and green claystone)	Drilled by Salinen AG
BI-63 (Bad Ischl-63)	396188	5282434	499	−42	541	0 - Quaternary 12.4 – Dachstein Lst 40 – Wetterstein Dol 45 – Dachstein Lst 110 – Dachstein Dol 293 - leached Haselgebirge 328 - unleached Haselgebirge 527 - Rossfeld Fm	Missing description due to incomplete core recovery	Drilled by Salinen AG
E-01 (Erbstollen-01)	396677	5281447	499	−62	560.6	0 - Quaternary 41 - Anisian (Gutenstein Fm) 121 - leached Haselgebirge 248 - unleached Haselgebirge 557 - Rossfeld Fm	Red rock salt, anhydrite and versicolored claystone	Drilled by Salinen AG
RN-3 (Rabennest-3)	394541.0905	5285034.18	540	−64	603.6	0 - Quaternary 23 - leached Haselgebirge 153.4 - unleached Haselgebirge	Green claystone	Drilled by Salinen AG
Steeg-1	397168	5274891	515	−815	1330	0 - Quaternary 137 - Werfen beds 457 - Haselgebirge 483 - (Fault) Undefined limestone 490 - (Fault) Upper Jurassic marls 650 - pelagic U. Triassic (Zlambach Fm) 708 - pelagic U. Triassic (Pötschen Fm)	N/A	from Mandl et al. (2012)

(continued on next page)

Table 1 (*continued*)

Borehole name	Location (WGS84 UTM33, in m)					Tops (depth - unit)	Haselgebirge facies	Notes
	X (Easting)	Y (Northing)	Z (Elevation a.s.l.)	Bottom Depth (m a. s.l.)	Total Depth (m)			
						765 - pelagic U. Triassic (Zlambach Fm)		
JSB-1 (Jodschwefelbad-1)	395920	5278526	520	−137	657	0 - Quaternary 64 -Tressenstein Lst 150 - pelagic U. Triassic (Zlambach Fm) 252 - pelagic U. Triassic (Hallstatt Lst) 318 - pelagic U. Triassic (Pötschen Fm) 373 - U. Triassic (Carnian clastics) 413 - pelagic M. Triassic (Reifling Fm) 434 - Anisian (Steinalm Fm) 440 - Anisian (Gutenstein Fm)	N/A	from Mandl et al. (2012)

The Altaussee diapir is interpreted to have initiated growth in Triassic times. It is interpreted that diapirism led to the differences in supra-salt stratigraphy around this diapir: whereas the Middle Triassic is absent directly above it, the complete supra-salt stratigraphy is present to the west (above label 4 in Fig. 3a and label 4 in Fig. 3b) (cf., Fig. 4a; Schäffer, 1982; Mandl et al., 2012; Fernandez et al., 2024, 2025). Based on this relationship, and the lack of westward closure of the Altaussee stock, it is interpreted here that the Altaussee diapir extends westwards under the Hoher Raschberg mountain (label 5 in Fig. 3b; Fig. 4a).

The position of the head of the Altaussee diapir on Upper Triassic carbonates and the Tauglboden Fm is interpreted to result from thrusting during Late Jurassic contraction (Fernandez et al., 2025). This same contraction event is interpreted to have led to the inflation of the head of the diapir, raising its top to shallow bathymetries and allowing for the development of a Plassen Lst reef on its top (the reef of Mt Sandling in Fig. 3a and 4a; Fernandez et al., 2025).

No evidence has been found for further deformation of the Altaussee diapir after the Late Jurassic other than extension along the NE-SW trending Höherstein fault system, that will be described below.

4.2. The Trattberg–Totengebirge contractional system

The presence of a somewhat cryptic, but key, structure is implied by the geometric relationships encountered in the Bad Ischl Erbstollen gallery (Fig. 4a). Under the Lauffen salt sheet (i.e., to its southeast), the Erbstollen is drilled through an antiform in the Upper Jurassic, below which the Upper Triassic is interpreted to lie. Southeast of this antiform, the Erbstollen crosses the SE-dipping Sulzbach salt stock. In its hanging wall (to the southeast), the Erbstollen encounters Upper Triassic rocks that can be followed up to surface and are capped by a shallower unit of Upper Jurassic rocks. The arrangement of the Triassic-Jurassic successions on both sides of the Sulzbach salt stock indicates the presence of a structural repetition. This repetition is interpreted to occur on the Grabenbach thrust of Fernandez et al. (2025). These authors documented this thrust in outcrop further to east (label 5 in Fig. 3b), where two southeast-dipping low-angle thrust transport vertically-dipping beds of the Oberalm Fm. The thrusts and folds are truncated and capped by nearly flat-lying Tressenstein Lst. The Tressenstein Lst at this location is dated to be latest Jurassic, and coeval with the Plassen Lst reef that crowns the Altaussee diapir (Gawlick et al., 2007). The Grabenbach thrust, where documented by Fernandez et al. (2025), dips down to the south/southeast and carries in its hanging wall the same block of Upper Triassic as that in the hanging wall of the Sulzbach salt stock (label 6 in Fig. 3b).

The syn-tectonic character of the Oberalm Fm and Tressenstein Lst lead to the partial obscuring of the Grabenbach thrust in outcrop, but both the observation in the Erbstollen and in outcrop are consistent with a structure of kilometer-scale displacement. Fernandez et al. (2025) proposed that the Grabenbach thrust relays with the Weissenbach anticline, to the west, and to a set of isoclinal folds in the Karbach area, to the east (Fig. 3c). This set of structures was grouped by Fernandez et al. (2025) into a longer, roughly WSW-ENE trending system of contractional structures called the TT (Trattberg-Totengebirge) contractional system. Shortening along this system has been estimated by Fernandez et al. (2025) to be of around 5 km in the study area.

In the hanging wall of the Grabenbach thrust, between the Altaussee diapir and Sulzbach salt stock, Triassic limestones are folded into the Raschberg anticline This anticline trends roughly E-W between the Sulzbach stock and the Altaussee diapir and bends to a NE-SW direction along the northern flank of the Altaussee diapir (Fig. 3c). To the west, the anticline is not present in the area of the Sulzbach stock, and only a gently dipping panel of Triassic rocks is observed (label 6, Fig. 3b). The Raschberg anticline has been interpreted to be coeval with thrusting on the Grabenbach thrust, and thus terminating growth in the latest Jurassic (Fernandez et al., 2025).

The nature of the relay between the Grabenbach thrust and the Weissenbach anticline is obscured by syn-tectonic sediments. Here we interpret the Grabenbach thrust to die out westwards into a north-vergent salt-cored anticline (Fig. 4c) that merges into the Weissenbach anticline (Fig. 3c). Thickening of Upper Jurassic sediments in the northern limb of the Weissenbach anticline, has been interpreted to indicate Late Jurassic growth of this anticline (Fig. 4b; Fernandez et al., 2025). Nonetheless, the Upper Jurassic Tressenstein Lst, that seals deformation on the Grabenbach thrust, is also strongly tilted (as much as 50°) in the forelimb of the Weissenbach anticline (labels 14 in Fig. 3b). Folding of the Weissenbach anticline also involves the Dachstein thrust sheet (Fig. 4b), which was emplaced in the Early Cretaceous, implying deformation on this structure continued into the Cretaceous (Levi, 2023).

Due to the lack of exposure, it is not certain if post-Jurassic folding of the Weissenbach anticline also implies post-Jurassic shortening on the western segment of Grabenbach thrust. However, the base of the

Jurassic Oberalm Fm is observed to be shallower in the hanging wall of the western Grabenbach thrust while its thickness is relatively constant across the thrust (other than for structural thickening in the Mitterberg anticline) (Fig. 4c). Furthermore, Lower Cretaceous, which is hundreds of meters thick in the footwall of the Grabenbach thrust, is not observed in its hanging wall (Fig. 4c), possibly implying post-Jurassic shortening on the westernmost Grabenbach thrust (coeval with late folding of the Weissenbach anticline).

4.3. The Mitterberg anticline

The Mitterberg anticline is a WSW-ENE trending anticline that runs north of the Sulzbach salt stock (label 7, Fig. 3b). It is intersected by the Erbstollen, Amalia and Maria Theresia galleries of the Bad Ischl mine (Fig. 3b, 4a and 4c, 4d). At surface, and in the Amalia and Maria Theresia galleries, the Mitterberg anticline has a box fold geometry in the Upper Jurassic beds (Fig. 4d; Medwenitsch, 1957). The box-fold geometry of the Mitterberg anticline, with vertical limbs (best represented in Fig. 4d), accounts for its peculiar aspect on the differently oriented cross-sections (e.g., Fig. 4a, cf. Fig. 5 of Medwenitsch, 1957). Triassic units are not present in the core of the anticline in either the Maria Theresia or the Erbstollen galleries, which is interpreted to indicate that the fold is detached from the underlying Upper Triassic (Fig. 4d). The Erbstollen gallery encounters relatively gentle dips that are interpreted to indicate that it intersects the base of the box fold (Fig. 4a). Nonetheless, the broad antiformal geometry of the lowermost Jurassic beds as well as the dip of the Jurassic and Cretaceous to the west below the Lauffen sheet (as controlled by boreholes, Fig. 4a) implies that the deeper Upper Triassic units are also antiformally folded into what we have called the deep Mitterberg anticline. The strike of this deeper fold is not well constrained. The Mitterberg anticline at surface sits along strike of the Grabenbach thrust and on the northern flank of the Weissenbach anticline (Fig. 3c). We interpret that the deeper Mitterberg anticline has potentially a similar trend and it possibly merges into the Weissenbach anticline to the west (Fig. 3c).

The Schrambach and Rossfeld Fms taper stratigraphically and onlap onto the northern limb of the Mitterberg anticline (label 7 in Fig.s. 3b and 4d; and projected onto Fig. 4a, east of label L). This geometry is interpreted to indicate that the Mitterberg anticline grew synchronously with the deposition of these two Lower Cretaceous units. Furthermore, the same beds of Tressenstein Lst that seal deformation on the Grabenbach thrust in the east are folded by the Mitterberg anticline. It is possible that (post-Jurassic) shortening in the Mitterberg anticline was related to shortening on the western segment of the Grabenbach thrust. The mechanism for the transfer of shortening from the Grabenbach thrust into the Mitterberg anticline is however uncertain, because both structures are interpreted to be partly oblique to each other (Fig. 3c).

4.4. The Sulzbach feeder and the Lauffen salt sheet

The Sulzbach salt stock (label S in Fig. 3a) trends parallel to the Mitterberg anticline, along its southern flank. Observations in multiple galleries of the Bad Ischl mine indicate that the Oberalm Fm in the southern flank of the Mitterberg anticline truncates against the Sulzbach salt stock (Fig. 4c and d). In the Erbstollen gallery, it is observed that the Haselgebirge of the Sulzbach stock partly lies above the (lower) Oberalm Fm (Fig. 4a). The Erbstollen gallery intersects the entire salt stock and encounters Upper Triassic dolomites on its opposite wall (Fig. 4a). These rocks are interpreted to correlate with the Upper Triassic that crops out at surface (Fig. 4a).

The internal structure of the salt (Haselgebirge) stock is known from a map of the Leopold working horizon (roughly 680 m a.s.l.) (Fig. 5; Mayrhofer, 1955). The salt stock shows a concentric pattern of lithologic distribution, with the highest halite content in its center. The salt stock is flanked on all sides by foliated mudrock with evaporite content decreasing outwards. The outermost layer of mudrock are black lustrous shales (*Glanzschiefer* in miner parlance: strongly sheared mudrock with reflective scaly fabric). The origin of the concentric pattern is uncertain, but could possibly have resulted from sheath-like folding of the Haselgebirge into the salt stock. The presence of evaporite-poor black lustrous shales in the transition from salt bodies into the surrounding, originally overlying, younger rocks is also observed in other salt bodies in this area (e.g., Medwenitsch, 1958; Schorn and Neubauer, 2014; Leitner and Spötl, 2017) but their origin has not been formally addressed.

The Sulzbach salt stock is locally overlain directly by Upper Jurassic Tressenstein Fm (with only Werfen beds in between). This configuration implies that this salt body had no Middle or Upper Triassic sediments above it, at least during the Late Jurassic. By analogy with the Altaussee diapir, it is possible that the Sulzbach stock was originally a diapir during the Triassic. It is possible that it was completely exposed at the seafloor (or under a cap of Werfen clastics) during much of the Triassic, or that its potentially thin roof was eroded during Jurassic shortening and uplift. Shortening of the Sulzbach stock during the Late Jurassic can explain the position of Haselgebirge above the lower Oberalm Fm observed in the Erbstollen (Fig. 4a). Exposure of the top of the salt stock at the seafloor during this time can also explain the truncation relationship of the Oberalm Fm beds observed in shallower galleries of the Bad Ischl mine (as described above). Furthermore, shortening of the salt stock and seafloor exposure during the Late Jurassic help explain the presence of thin tongues of Haselgebirge evaporites that appear sandwiched between Tressenstein Lst at the western end of the salt stock (label 8 in Fig. 3b). These salt tongues, interpreted as minor allochthonous salt extrusions, are located immediately south of the Lauffen salt sheet.

N-S to NNW-SSE directed shortening of the Sulzbach salt stock is interpreted to be the origin of the oblong map shape of the stock (Mayrhofer, 1955). Other than the Late Jurassic shortening described above, the position of the salt stock between the Weissenbach anticline and the western Grabenbach thrust (Fig. 4c) likely led to shortening continuing into the Early Cretaceous. The precise geometry at depth of the Sulzbach stock towards the west is unconstrained and has been represented on Fig. 4c–be tentatively decoupled from the Grabenbach thrust – Weissenbach anticline. A hard link (potentially welded or sheared) cannot be ruled out.

The Lauffen allochthonous salt sheet is located immediately northwest of the Sulzbach salt stock and in outcrop continuity with it (label 9, Fig. 3b). The Lauffen salt sheet is intersected by the Erbstollen gallery of the Bad Ischl mine (Fig. 4a and 6a). At the location of the Erbstollen, it is a relatively tabular body of Haselgebirge that is sandwiched between the Rossfeld Fm, below, and the Dachstein thrust sheet, above. The youngest sediments below the Lauffen salt sheet have been dated in the Erbstollen gallery to be Late Valanginian to Hauterivian (135–130Ma) (Krische and Gawlick, 2015).

In the Erbstollen gallery, the Haselgebirge presents a mylonitic shear fabric with extremely consistent top-to-the-west or top-to-the-northwest shear indicators (S-C fabric, strain shadows, axial-plane cleavage; Fig. 6). This orientation is consistent with a source of the salt sheet in the Sulzbach salt stock. In conjunction with the outcrop continuity between the Sulzbach stock and the Lauffen sheet, and the presence of minor Late Jurassic allochthons in the immediate vicinity (label 8, Fig. 3b), we interpret that the Sulzbach salt stock is the feeder of the Lauffen salt sheet, a relationship that had escaped previous definition.

The Lauffen salt sheet extends to the north and northwest beyond the Erbstollen. It is drilled through by borehole E−01 outside the Erbstollen (Fig. 3b), where it underlies Middle Triassic carbonates of the Dachstein thrust sheet (Fig. 4a and 6a). Further north, along the Traun River valley, the Lauffen sheet has been drilled through by boreholes of the Bad Ischl *Sondenfeld*. In the *Sondenfeld*, the salt sheet lies directly under either Quaternary glacial sediments (less than 50 m thick) (boreholes BI-09, BI-10; Table 1, Fig. 3b) or is thrust over by shallow-water Triassic carbonates of the Dachstein thrust sheet (boreholes BI-43, BI-48, BI-63; Table 1, Fig. 3b). Contrary to the Erbstollen, however, the Haselgebirge

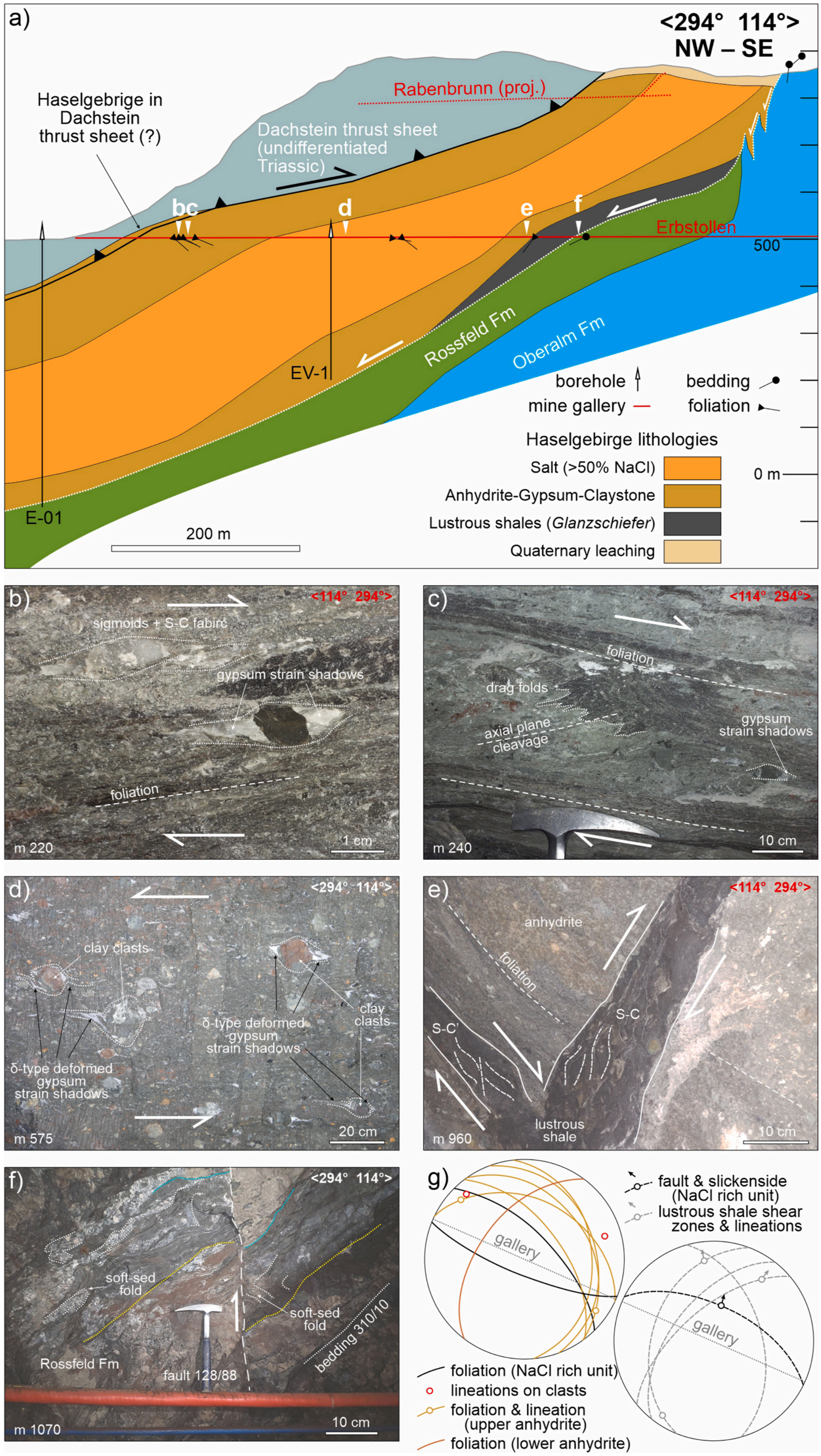

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Fig. 6. a) Section of the Erbstollen gallery in the Bad Ischl mine. The locations of subfigures b-f are shown. b-d) Shear sense indicators in Haselgebirge with mylonitic fabric. e) Lustrous shale shear zones within anhydrite-rich Haselgebirge. The shear zone dipping to the NW cross-cuts the SE-dipping shear zone. f) Detail of the Rossfeld Fm roughly 5 m below the basal contact of the Lauffen salt sheet. g) Plots of foliation, shear sense indicators, faults and shear zones in the Haselgebirge of the Erbstollen.

Fig. 7. a) Panorama of the northern edge of the Dachstein thrust sheet showing the angular unconformity at the base of the Gosau Gp and a syn-to post-Gosau thrust. The Gosau Gp beds dip roughly with the slope and steepen up southwards against the thrust. Beds of the underlying Dachstein Lst dip steeply and locally present minor-scale folding. See Fig. 3c for approximate location. b) Outcrop of the Dachstein thrust sheet placing Middle Triassic dolomite on the Lower Cretaceous Schrambach Fm. The Anisian carbonates and Haselgebirge are absent in the hanging wall of the Dachstein thrust. Faults synthetic to the Dachstein thrust offset the Scharmbach in the footwall and modify the geometry of the Dachstein thrust itself. A stereoplot of faults (with no visible striations) in the footwall and in the hanging wall of the Dachstein thrust is included. See Fig. 3b for location (WGS84 UTM33N x:394645 y:5279565).

of the *Sondenfeld* rests not only on the Rossfeld Fm but also locally on the Schrambach Fm (label 1, Fig. 3b; Fig. 4d), on the Upper Jurassic Oberalm Fm (boreholes BI-10, BI-48; Table 1), and on the Tressenstein Lst (label 10, Fig. 3b). All these units are older than the Rossfeld Fm, onto which the Lauffen sheet was emplaced in the Erbstollen closer to its feeder (Fig. 6a). This configuration (with the Lauffen sheet emplaced on older units further away from its feeder) is interpreted here to result from the emplacement of the salt allochthon onto a previously folded substrate, on which Cretaceous sediments were originally not deposited or were eroded. A pre-allochthony anticline is observed at location 1 in Fig. 3b (Fig. 4d). The absence on this structure of the Rossfeld Fm above the Schrambach Fm and below the Haselgebirge is interpreted to result from its tapering out due to Early Cretaceous growth, equivalent to the tapering of the Rossfeld onto the Mitterberg anticline (above label 7 in Figs. 3b and 4d). Tapering of the Rossfeld Fm below the allochthonous Haselgebirge of the Lauffen sheet is also observed next to label 11 in Fig. 3b, where the Rossfeld Fm thins rapidly away from the Sulzbach feeder.

4.5. Allochthon(s) of the Ischl and the Traun River valleys

North of the *Sondenfeld*, Haselgebirge outcrops have been documented under the Nussensee thrusts, along the Ischl and Traun River valleys (Fig. 3a; Schäffer, 1982; Laimer, 2019). The Haselgebirge at these locations directly underlies the Late Cretaceous Gosau Gp. Its base, however, has not been drilled, as borehole RN-3 (Table 1, Fig. 3a and 4b) fell short. In analogy to the Haselgebirge in the *Sondenfeld*, we interpret that the Haselgebirge in the footwall of the Nussensee thrusts is potentially also part of an allochthonous salt sheet. However, poor outcrop conditions make it difficult to assess the precise relationship between the Gosau Gp and Haselgebirge in this area. In Fig. 4b, the Haselgebirge of the Ischl valley is represented tentatively as being an allochthonous mass, emplaced on the Rossfeld Fm and underlying the Gosau Gp sediments (Fig. 4b). It is further proposed that the Ischl valley Haselgebirge potentially had a different feeder than the Sulzbach; a feeder that was overridden by the Dachstein thrust sheet (Fig. 4b). Although data is limited, differences in composition of the Haselgebirge could be indicative of the different sources. Whereas in the Ischl valley, borehole RN-3 (Table 1) encountered clay-dominated Haselgebirge, the Haselgebirge in the boreholes of the *Sondenfeld* and the Bad Ischl salt mine is dominated by rock salt (grey rock salt in boreholes BI-09, -10, −43, −48; red rock salt with variegated clay in borehole E−01 and mine galleries) (Table 1; Mayrhofer, 1955).

The extent of the salt in the Ischl valley has not been determined by direct methods. However, geophysical exploration in the area indicates the potential presence of a wide and relatively tabular body spanning along the entire Ischl valley (as shown in Fig. 3c) (Arndt and Mayr, 2003). This body could potentially be larger than the Lauffen salt sheet, although its dimension remains to be fully confirmed.

4.6. The Dachstein thrust sheet and the Nussensee thrusts

The Dachstein thrust sheet is the unit with the largest displacement in the study area, having been transported under 10 km in a northeastward direction (Fernandez et al., 2024). The Dachstein thrust ramps up across the Triassic and Upper Jurassic in the south of the study area, north of the Steeg-1 borehole (labels 12 in Figs. 3a and 4b) (Levi, 2023). Along its leading edge, the Rossfeld Fm and the Lauffen allochthonous salt are the youngest elements under the Dachstein thrust sheet (Figs. 3 and 4a, b, d). In turn, the leading edge of the Dachstein thrust sheet is onlapped and unconformably covered by Upper Cretaceous Gosau Gp sediments (label 13 in Figs. 3a and 7a), generally accepted to indicate an Early Cretaceous age for the main emplacement of this thrust sheet (Mandl et al., 2012; Levi, 2023; Fernandez et al., 2024).

The hanging wall of the Dachstein thrust sheet tapers significantly along the western segment of the section in Fig. 4a. There, the Upper Triassic thins from around 2 km to only a few hundreds of meters thickness (Fernandez et al., 2024) and is locally folded into an overturned anticline (Fig. 3b). Both have been interpreted to indicate that this part of the Dachstein thrust sheet originally lay above inflated Haselgebirge (as will be discussed below). Some of this Haselgebirge was potentially transported with this thrust sheet, and is represented interpretatively in the tight salt cored fold in Fig. 4a. However, no Haselgebirge has been encountered above the Dachstein thrust at this location nor for kilometers to the south (Figs. 3b and 7b) (Schäffer, 1982) and it is

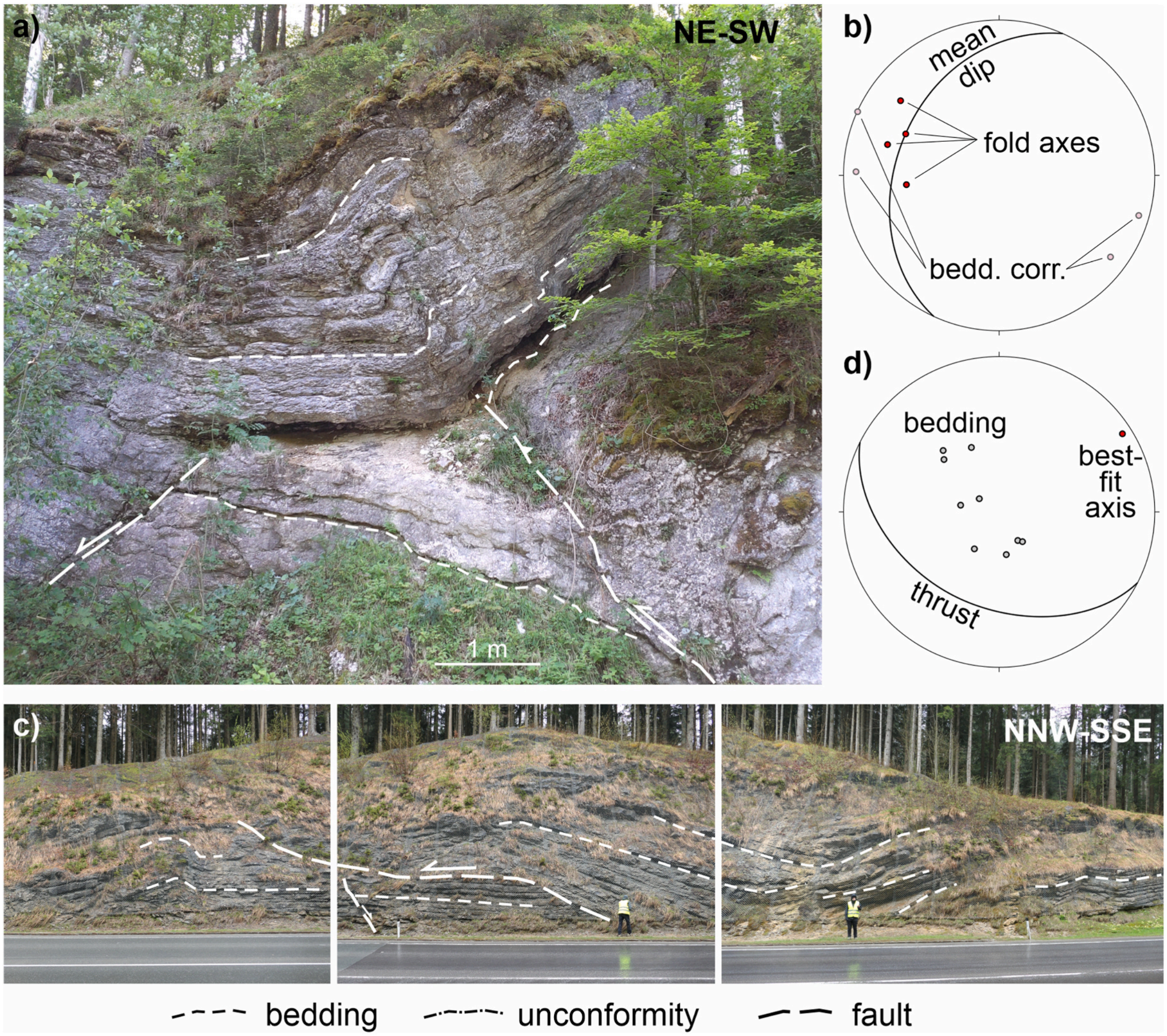

Fig. 8. a) Minor northeast-vergent thrust-related fold in the Tressenstein Lst in the immediate footwall of the Dachstein thrust. See Fig. 3b for location (WGS84 UTM33N x:396625 y:5280375). b) Stereoplot of fold axes measurements in (a) and surrounding area, along with the mean bedding dip away from the fold structures. Bedding corrected fold axes (bedd. corr.) trend WNW-ESE. Plunge of the fold axes is interpreted to originate from post-fold tilting. c) Outcrop of folded and faulted Upper Triassic pelagic limestones in the footwall of the Dachstein thrust. See Fig. 3a for location (WGS84 UTM33N x: 401685 y:5275845). d) Stereoplot of data from the outcrop in (c) indicating structures trend NE-SW to NW-SSE.

therefore considered to be mostly absent in the hanging wall of this thrust.

Similarly to the Lauffen salt sheet, the Dachstein thrust sheet is interpreted to have emplaced over a previously folded footwall. Evidence for this is the fact that the Dachstein thrust cuts up and down stratigraphy along its trace. For instance, in map view it cuts up and down through the Lower Cretaceous across the Traun River valley (labels 13 in Fig. 3a) and cuts down stratigraphy to the north, directly overlying the Oberalm Fm north of label 1 (Fig. 3b).

Folding of the footwall of the Dachstein thrust sheet, however, continued after its emplacement, giving rise to folding of the Dachstein thrust across the Weissenbach anticline (Fig. 4b; Fernandez et al., 2022; Levi, 2023). Folding north of the Sulzbach salt stock along WSW-ENE trending folds (along the western prolongation of the Singereben folds) also generated smaller wavelength folds in the northeastern edge of the Dachstein thrust sheet (Fig. 3b and 4d).

Likewise, metric-scale structures are observed locally in the immediate footwall of the Dachstein thrust (Fig. 7b and 8a,c) and are interpreted to relate to the emplacement of the Dachstein thrust sheet.

Deformation of the Dachstein thrust sheet also involved folding and out-of-sequence thrusting synchronous or posterior to the Lower Gosau Subgp (Nussensee thrusts in Fig. 3a–c, 4b; thrust in Fig. 7a). The Nussensee thrusts are thrusts with reduced displacement (<1 km) that cut across the northern edge of the Dachstein thrust sheet (Laimer, 2019; Levi, 2023). The Nussensee thrusts are located at the eastern end of the Wolfgangsee thrust (Fig. 3a–c), a post-Gosau (Oligo-Miocene) age thrust (Peresson and Decker, 1997) and could potentially represent its eastern prolongation.

Finally, deformation of the Dachstein thrust sheet is also recorded to the south, but in the form of transtensional development of the Gosau basin (Fig. 3c; Wagreich and Decker, 2001; Fernandez et al., 2022).

4.7. The Höherstein extensional faults

Extension is observed east of the Lauffen salt sheet, in a system of NE-SW trending normal faults called here the Höherstein system (Fig. 3c). The Höherstein system cuts across the Oberalm Fm and Tressenstein Lst, indicating its post-Jurassic age. It is likely that this fault system developed in response to post-Jurassic north-directed shortening on the Weissenbach and Mitterberg anticlines. Although the exact timing of the Höherstein system has not been determined, extensional faults with similar trend (label 15, Fig. 3b) post-date the Lower Cretaceous and potentially indicate synchronicity with post-emplacement deformation of the Dachstein thrust sheet. A possible link with extension in the Gosau basin will be discussed below.

5. Structural evolution

As described above, the time of activity of individual structures or sets of structures has been interpreted based on the tectono-sedimentary relationships and on superposition relationships. Fig. 9 schematically shows the evolution of key structures in the area (the Grabenbach thrust, the Mitterberg anticline, the Dachstein thrust and the Sulzbach-Lauffen system) on the cross-section of Fig. 4a. Initial deformation in the area is recorded by northward thrusting of the Raschberg units (the units that at present form the hanging wall of the Sulzbach stock) on the Grabenbach thrust (Fig. 9f–e). Coevally, the deep Mitterberg anticline started to grow, interpreted here as an accentuation of a pre-existing body of inflated salt. Folding of the Mitterberg and potentially other similar structures detached along the Haselgebirge.

Ongoing shortening accentuated the Mitterberg anticline (Fig. 9d) and eventually squeezed the Sulzbach stock leading to extrusion of the Lauffen salt sheet into a flank of the Mitterberg anticline (Fig. 9c). Folding continued to amplify, subsiding the Lauffen salt sheet in the flank of the Mitterberg anticline and therefore possibly protecting it from being tectonically eroded or deforming in the footwall of the Dachstein thrust (Fig. 9b). Continued shortening led to the development of the shallow Mitterberg anticline and further tightening of the Dachstein thrust sheet (Fig. 9a).

Fig. 10 displays the map evolution corresponding to the restoration

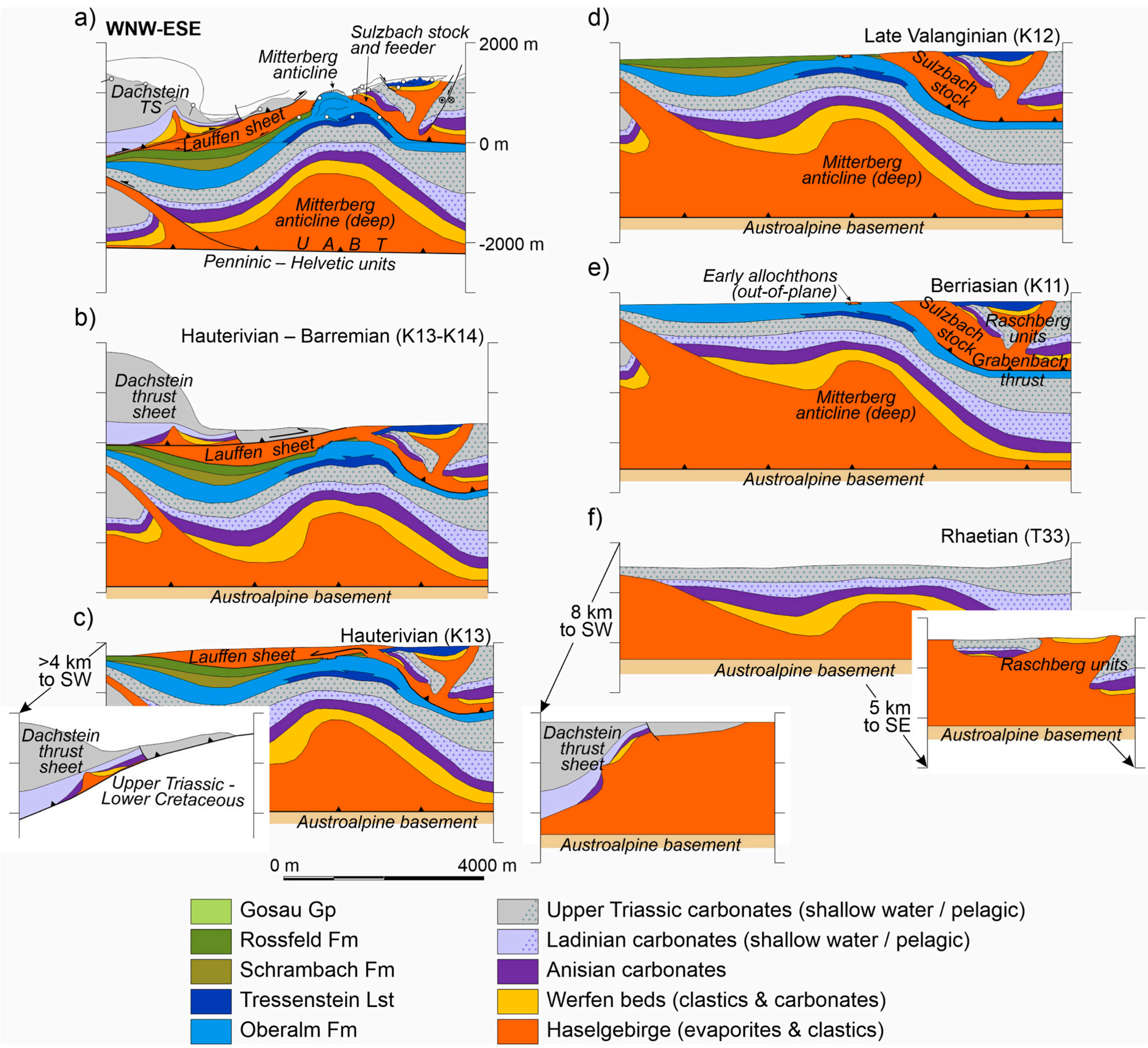

Fig. 9. Schematic restoration of the western portion of the section in Fig. 4a, showing the temporal evolution of three key structures in the study area: the Grabenbach thrust, the Sulzbach stock and associated Lauffen allochthonous salt sheet, and the Dachstein thrust. All structures depicted have transport directions oblique to the section plane, and therefore out-of-plane motion is expected for all structures although it has not been represented for simplicity (other than the out-of-plan transport of the Dachstein thrust sheet and the hanging wall of the Grabenbach thrust). Parts (a) through (f) show the stepwise restoration from present-day to Late Triassic. The position of the Dachstein thrust sheet is not shown for steps (d) and (e).

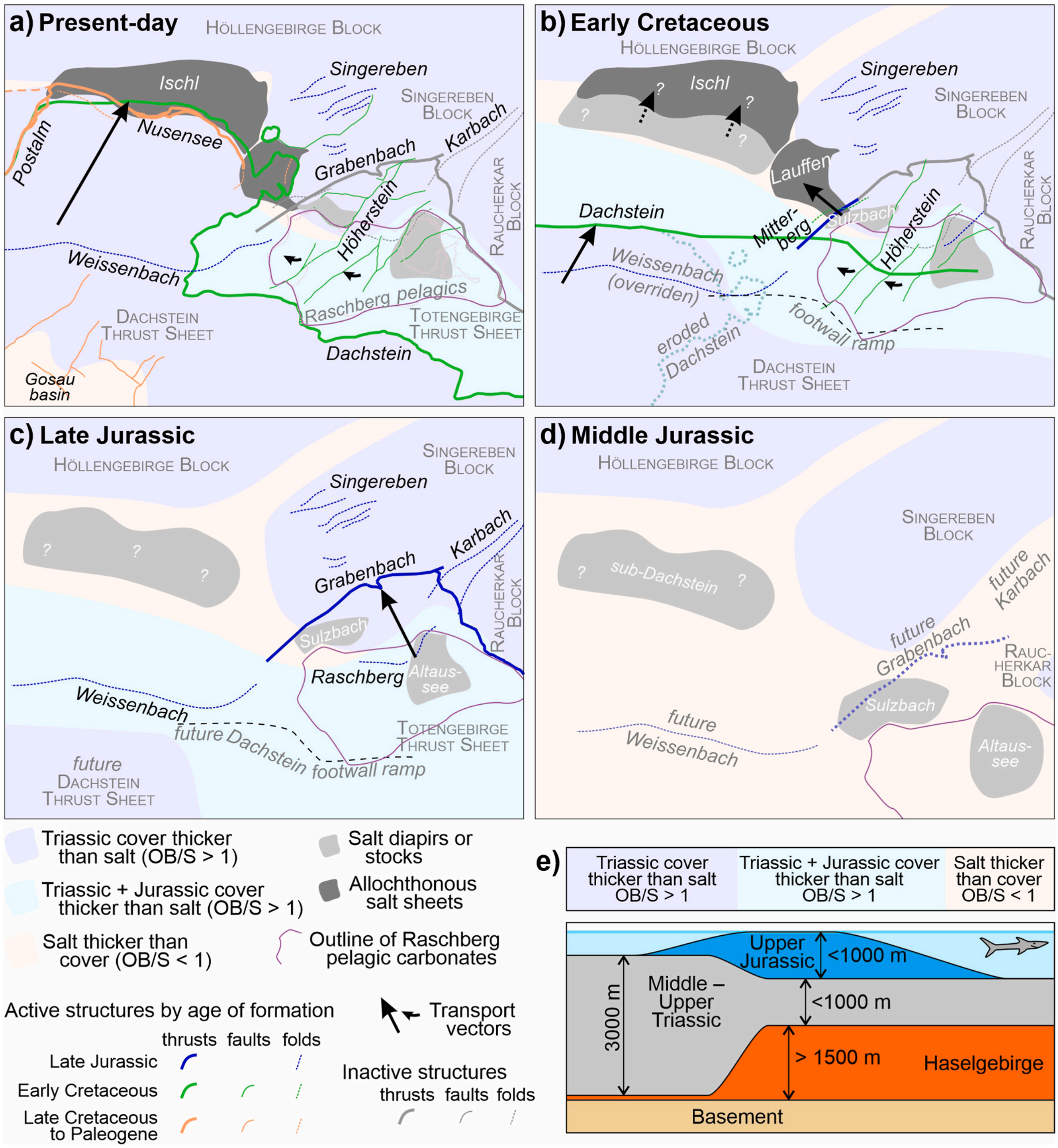

Fig. 10. Structural evolution of the study area from Middle Jurassic times (d), through Late Jurassic times (c), Early Cretaceous (b) and to present-day (a). The maps are shown in a reference frame fixed to the NCA independent of northward thrusting of the NCA over the Penninic and Helvetic domains. The relative thickness of Haselgebirge and Triassic to Jurassic cover is based on cross-sections in this contribution and cross-sections in Fernandez et al. (2022, 2024, 2025). The Dachstein footwall ramp shown in (c) is at the level of the Upper Jurassic (as that shown in Fig. 3c). Width of the Sulzbach and Altaussee salt stocks in (d) is sketchily shown to be greater than at present, although the exact magnitude of strain has not been determined. The area is the same as that shown in Fig. 3 e) Estimates of relative thickness of cover to salt (overburden to salt ratio, OB/S) are based on a simplified cross-sectional geometry. See text for details.

in Fig. 9. Fig. 10 covers the area shown in Fig. 3 and uses its northern edge as a fixed pin line to show the deformation history from a pre-shortening state in the Early to Middle Jurassic (Fig. 10d) up to the present-day (Fig. 10a).

The initial state shown in Fig. 10d represents the interpreted configuration of the area at the end of its development as a salt-rich passive-margin. The configuration shown has been derived from restoring displacement on the main thrusts and folding throughout the area based on local and regional cross-sections (Fernandez et al., 2024, 2025). In this initial state, the area is characterized by domains with thick Middle to Upper Triassic stratigraphy (>1 km thick carbonate platforms) that subsided into the autochthonous Haselgebirge, and domains with relatively thin Middle to Upper Triassic stratigraphy (<1 km thick of dominantly pelagic carbonates) that sat on relatively thick Haselgebirge. These domains of differing Triassic stratigraphic thickness have been represented in Fig. 10d as a function of a qualitative ratio in thickness between Middle to Upper Triassic (relatively rigid) carbonatic cover and the underlying (weaker) evaporitic succession (including the Lower Triassic clastics). This qualitative ratio (referred to hereafter as overburden-to-salt ratio, OB/S) is based on an estimate of 500 m water depth for pelagic units less than 1000 m thick, and minibasins 3000 m thick (Kenter and Schlager, 2009; Fernandez et al., 2024). In the domains of pelagic carbonates the Haselgebirge would have been at least 1500 m thick (and thicker than its cover, OB/S < 1) prior to deformation

(Fig. 10e).

The initial configuration of this area displays a southern domain of relatively thin pelagic Triassic, and a northern domain of relatively thick Triassic platform. The thick Triassic domain is formed by platform blocks (Höllengebirge, Singereben, Raucherkar) separated by two NE-SW trending “arms” of thin Triassic stratigraphy above inflated salt.

The southern domain of thin Triassic stratigraphy was locally pierced by diapiric stocks (Altaussee, Sulzbach). A possible elongate diapir, the potential feeder of the allochthonous Haselgebirge of the Ischl valley, is tentatively also shown in its inferred position. The Dachstein thrust sheet, which mostly consists of thick Middle to Upper Triassic stratigraphy is not shown in Fig. 10d as it lay to the SW of the area shown.

Most of the southern domain of thin Triassic stratigraphy has been thrust over by the Dachstein thrust sheet or involved into deformation in the Grabenbach thrust since the Late Jurassic. At present, the Middle to Upper Triassic cover of this domain only crops out extensively in the sector of the Hoher Raschberg mountain (between the Altaussee and Sulzbach diapirs, Fig. 3c). This outcrop block has been included in the map evolution of Fig. 10 (as the Raschberg pelagic carbonates) for reference.

Initial contractional deformation in the study area is associated to thrusting and folding along the TT contractional system (Weissenbach anticline, Grabenbach thrust, and Karbach folds) (Fernandez et al., 2025) (Fig. 10c). The Karbach folds developed in one of the “arms” of thin Triassic stratigraphy. The Grabenbach thrust in turn, nucleated along the NE–SW trending southern margin of the Singereben block. The Weissenbach anticline appears to have been possibly controlled, at least in its eastern end, by the pre-shortening configuration (Fig. 9).

Besides thrusting and folding, Late Jurassic shortening led to squeezing of the Sulzbach and Altaussee diapirs, leading to emplacement of Haselgebirge onto Upper Triassic and Jurassic rocks (Fig. 9). Squeezing of both diapirs relates to how they impinged on blocks of thick post-salt stratigraphy: the Altaussee against the Raucherkar block to the east, the Sulzbach against the Singereben to the north.

Shortening in the Late Jurassic in the area was accompanied by the deposition of hundreds of meters of reef carbonates and slope to basin calciturbidites (Plassen Lst, Tressenstein Lst and Oberalm Fm) (Fig. 4). The thickest accumulation occurred along a roughly E-W belt across the southern half of the study area, above the previous thin-Triassic domain (Fig. 10c). Non-eroded thickness can be seen above the Altaussee diapir (Mt Sandling) and in the Traun River valley under the Dachstein thrust. The addition of Jurassic stratigraphy significantly changed the overburden to salt ratio, such that much of the thin-Triassic domain became an area of thick post-Haselgebirge stratigraphy. The Dachstein thrust, which originally lay south of the area in Fig. 10d, accumulated under 100 m of Upper Jurassic sediments along its northern edge (label 16 in Fig. 3a) indicating it was already partially uplifted in the Late Jurassic. It is therefore shown as having been partially emplaced in Fig. 10c. Significantly, during posterior advance, deformation on the Dachstein thrust did not propagate below the thick Jurassic syn-tectonic succession that was deposited ahead of it. Rather, the thrust ramped up across the thick Jurassic syn-tectonics, leaving them in its footwall. A possible explanation for this could be that the Dachstein thrust was continuously emergent during deposition of the Upper Jurassic, such that it continually climbed up section and was never totally buried. As discussed above, Jurassic sediments also did not prevent the continuing growth of the Weissenbach anticline, that then lay ahead of the advancing Dachstein thrust sheet.

Thrusting on the eastern half of the Grabenbach thrust ended in the Late Jurassic or earliest Cretaceous, likely due to the convergence of the Raucherkar and Singereben blocks on either side of the Karbach folds, blocking further shortening (Fig. 10c). Likewise, northward propagation of the Grabenbach thrust was also likely blocked by the Singereben block acting as a backstop. Unaffected by this, shortening is interpreted to have continued along the western segment of the Grabenbach thrust, synchronous with growth of the Mitterberg anticline and continued growth on the Weissenbach anticline (Fig. 10b). Ongoing shortening in the area was responsible for further squeezing of the Sulzbach salt feeder, leading to the NW-directed extrusion of the Lauffen salt sheet. It is likely that the Höherstein extensional fault system started developing during this time to accommodate differential shortening across the area. Initial northeastward advance of the Dachstein thrust sheet is interpreted to have occurred synchronous with growth of the Mitterberg anticline and emplacement of the Lauffen salt sheet (Fig. 10b). The absence of Lower Cretaceous on the southern limb of the Weissenbach anticline under the Dachstein thrust (Fig. 3a) is interpreted to indicate that this thrust sheet had already emplaced over this area at this time. Furthermore, the absence of any Lower Cretaceous sediments between the Lauffen salt sheet and the Dachstein thrust (Fig. 6a) implies that the Dachstein thrust sheet was emplaced onto the salt allochthon very shortly after its extrusion. An early northeastward advance of the Dachstein thrust sheet provides a favorable configuration for this to have happened.

The leading edge shown for the Dachstein thrust sheet in Fig. 10b differs significantly from the present-day geometry of the thrust. The trace shown in Fig. 10b is based on the WNW-ESE trending footwall cutoff of the Upper Jurassic (labels 12in Fig. 3a–c, Fig. 10). Significant portions of the thrust sheet have since been eroded. In the reconstruction in Fig. 10 it is estimated that the Dachstein thrust sheet accumulated around 8 km of northeastward displacement.

Final emplacement of the Dachstein thrust sheet occurred between final deposition of the Rossfeld Fm and deposition of the basal Gosau Gp. The regional transport direction has been interpreted to be NNE directed, roughly parallel to the Postalm fault and consistent with the WNW-ESE trending footwall (frontal) ramp (Fig. 10) (Fernandez et al., 2024). The final position of the leading edge of the Dachstein thrust sheet was most likely controlled by the pre-shortening configuration of the area; the thrust sheet advanced until it reached the backstop formed by the Höllengebirge and Singereben blocks.

After Early Cretaceous emplacement, the leading edge of the Dachstein thrust was covered by Gosau Gp sediments (Fig. 7a) and was later cross-cut by the out-of-sequence Nussensee thrusts (shown for simplicity in the same time step with final Dachstein thrust sheet emplacement, Fig. 10a). Shortening on the Nussensee thrusts is interpreted here to feed northeastwards into the closure of the last “arm” of thin post-salt stratigraphy that remained between the Singereben and Höllengebirge. This domain closed after the Early Cretaceous as a faulted synclinal structure, with its age indicated by the presence of Gosau Gp sediments in its core (label 17 in Fig. 3a). Similarly, the Gosau basin (Fig. 10a) also developed as a subsiding area during this final stage of deformation. The origin for subsidence in the case of the Gosau basin is possibly distension in the hanging wall of the Dachstein thrust sheet (Fernandez et al., 2022) that could have originated due to differential amounts of shortening across the area.

Finally, the Dachstein thrust at present displays an antiformal geometry, folded by the Weissenbach anticline (Fig. 4b; Levi, 2023). The age of this folding is uncertain, but is potentially coeval with shortening along the Nussensee thrusts and development of the Gosau basin to the south. Ongoing growth of the Weissenbach anticline while its eastern termination (Grabenbach thrust) was pinned, likely led to counterclokwise rotation of the western part of the study area. Although the magnitude of this rotation has not been quantified, line-length unfolding of the Dachstein thrust geometry in Fig. 4b indicates that the Weissenbach anticline accumulated in the order of 500 m of roughly N-S shortening post-Dachstein emplacement. Growth of the Weissenbach anticline after the Grabenbach thrust had been sealed likely led to vertical-axis rotation of the system, and could be the origin of the Höherstein fault system and account for the heaves observed (10s of m on individual faults; Fernandez et al., 2025). Evidence for late activity on the Höherstein fault system comes from faulting that post-dates the Scharambach and Rossfeld Fms (label 11, Fig. 3b), and it is possible that it was synchronous with development of the Gosau basin.

6. Discussion

6.1. Deformation patterns

One of the most remarkable features of the study area are the variable directions of tectonic transport (Fig. 10). In the footwall of the Dachstein thrust, shortening is consistently NNW- to NW-directed from Late Jurassic to Early Cretaceous. In contrast, the Dachstein thrust sheet experienced NNE-directed transport.

The contrasting orientations of tectonic transport of the Dachstein thrust sheet and the Jurassic structures in its footwall have previously been regionally documented (Fernandez et al., 2024), but its origin is not yet fully understood. Relevantly, the analysis of tectono-sedimentary relationships presented here and illustrated in Fig. 10 indicates that structural evolution in the study area forms a temporal continuum from the Late Jurassic into the Early Cretaceous. Furthermore, there is indication that structures with contrasting shortening directions were active coevally (e.g., the Dachstein thrust and the Lauffen salt sheet in Fig. 10b). The direction of transport of coeval structures were potentially controlled by different elements. Whereas the Lauffen salt sheet likely was emplaced based on the local bathymetry (potentially into synclinal trough, Fig. 9c), emplacement direction of the Dachstein thrust depended on more regional controls.

Analogue modelling has shown that in settings with a thick and highly effective basal detachments, homogeneous regional shortening will lead to vertical axis rotation and oblique transport directions of the supra-salt units (e.g., Rowan and Vendeville, 2006; Duffy et al., 2021). More importantly, variations in the thickness ratio between the *décollement* and the overlying ‘rigid’ stratigraphy (variations in the OB/S) exert an important role in controlling the development of structural obliquity (Santolaria et al., 2024). Both elements likely played a role in the study area. Variations in the OB/S controlled the trend and location of structures (e.g., Grabenbach thrust, Karbach folds), but contrasting transport directions (e.g., between the Grabenbach and Dachstein thrusts) is best accounted for by the presence of a highly efficient *décollement* (irrespective of thickness) that allowed for relatively independent motion of different fault blocks. The contrast in post-salt thickness also played a role in limiting the progression of structures, as the blocks of thick Triassic stratigraphy acted as backstops to advancing structures (e.g., Singereben block as backstop to the Karbach folds and Grabenbach thrust; the Singereben and Höllengebirge blocks as backstops to the Dachstein thrust sheet).

The same detachment that controlled shortening, rooted the extensional faults of the Höherstein system and the faults bounding the Gosau basin (Fernandez et al., 2022). Extension in these areas likely responded to the obliquity in thrust sheet transport directions or vertical-axis rotation within thrust sheets (as discussed for the Wiessenbach anticline above). Similar features have been documented in other fold-and-thrust systems detached above salt *décollements* (cf., Balupor and Clamosa faults in Muñoz et al., 2013).

Salt-floored Cretaceous extension has also been documented along the Dachstein thrust, further west (in the Lammertal area by Fernandez et al., 2024). A genetic and temporal correlation has not been explored, but it is possible that widespread extension in the central NCA may be indicative of generalized structural obliquity during thrust emplacement (e.g., Linzer et al., 1995; Eisbacher and Brandner, 1996). Salt-floored extension due to oblique thrusting could provide a more local explanation for Cretaceous extension that is alternative or complementary to crustal-scale extension previously proposed (Faupl and Wagreich, 2000; Wagreich and Decker, 2001) and can explain the contrast in style of different Gosau basins in the NCA (cf., Ortner, 2001; Wagreich and Decker, 2001).

6.2. Submarine exposure of evaporites

During the Triassic to Middle Jurassic, the Haselgebirge in the central NCA was mostly draped by sediments, with no evidence for generalized submarine exposure of the evaporites (Fernandez et al., 2024, 2025). It is possible that locally, diapirs such as Altaussee and Sulzbach might have grown at or near the seafloor with no or negligible roof. It is however also possible, that the Haselgebirge in these structures only reached the seafloor during Late Jurassic shortening due to uplift and erosion of their roofs. In either case, both structures locally lack a pre-shortening roof. The Haselgebirge above the Altaussee stock is locally covered directly by the Tauglboden Fm (locally dated to be early Oxfordian, younger than 163Ma; Gawlick et al., 2007) (Fig. 3a and 4a). In contrast, the Sulzbach salt stock remained mostly uncovered until deposition of the Oberalm Fm and Tressenstein Lst (Kimmeridgian to Tithonian, around 157Ma) (Fig. 3b and 4). The salt stock must have further remained partially uncovered into the Late Valangian, as clasts of Haselgebirge and Werfen clastics have been documented in the Rossfeld Fm breccias (Krische and Gawlick, 2015 and references therein) and it also fed the submarine Lauffen salt sheet (around 133 Ma) (Fig. 9c). This implies a prolonged period (30 Ma) of exposure at the seafloor of the Haselgebirge of the Sulzbach salt stock, in a context of a developing foreland basin, and likely required a significant salt budget. Nonetheless, the Sulzbach diapir could still source a significant volume of salt to feed the Lauffen salt sheet. This evolution can be explained by a mechanism of diapir inflation during compression described by Dooley et al. (2009).

The prolonged seafloor exposure of the Haselgebirge of the Sulzbach–Lauffen system, during a period of documented influx of ophiolitic material into the basin (e.g., Krische et al., 2014), could help explain the entrapment of metamorphosed oceanic-affinity basalts documented in the Lauffen salt sheet (Vozarova et al., 1999).

Submarine exposure of the Lauffen Haselgebirge also calls into question the presumed Permian age of the Haloarchaea documented by Stan-Lotter et al. (2002.2003), as these could have been incorporated into the allochthonous salt during extrusion, similar to the exotic mafic clasts.

6.3. The Lauffen salt sheet and the Dachstein thrust

A question that arises from mapping and cross-section construction is where the contact between the Lauffen allochthonous salt sheet and the Dachstein thrust sheet is located. The Dachstein thrust sheet is detached at the level of the Haselgebirge (Fernandez et al., 2024). Therefore, the Dachstein thrust could theoretically lead to the juxtaposition of Haselgebirge in its hanging wall on Haselgebirge in its footwall (Lauffen salt sheet). The presence, in the hanging wall of the Dachstein thrust, of a thin (as proposed in Fig. 6a), or locally thickened (as interpreted in Fig. 4a west of the Traun valley) Haselgebirge cannot be completely ruled out. However, as mentioned above, shear sense indicators in the Lauffen sheet, where observed in the Erbstollen galley, are oriented at a right angle to the emplacement direction of the Dachstein thrust sheet. Furthermore, Haselgebirge and the Anisian carbonates are absent along significant outcrop portions of the Dachstein thrust (as at the location in Fig. 7b and around the Weissenbach anticline, Fig. 3a). Therefore, the thick accumulations of Haselgebirge in the *Sondenfeld* and surrounding areas have been interpreted here to form part of the Lauffen salt sheet (and footwall of the Dachstein thrust).

In fact, the Lauffen salt sheet is observed to be thicker in synclines and thinner on anticlines (e.g., Obereck in Fig. 4d). This could be due to tectonic erosion of the Lauffen salt sheet in the footwall of the Dachstein thrust occurring preferentially over anticlines. Pre-Dachstein folding of the Lauffen salt sheet provides a possible mechanism by which the allochthonous salt and its internal mylonitic fabric could have been preserved in synclines under the advancing Dachstein thrust sheet. However, it is also possible that the Cretaceous seafloor at time of the Lauffen sheet emplacement reflected the growing folds, and that the emplacement of the salt allochthon might have occurred into a structurally-controlled bathymetric trough (i.e., into a developing syncline with bathymetric expression). In this case, the thinning of the Lauffen salt sheet onto anticlines might be, at least in part, a primary feature.

6.4. Continuous deformation vs deformation phases

An important implication of the evidence collected in the study area, is that deformation occurred as a temporal continuum. At any given location, tectonic events can be identified as time-limited processes. However, when observed regionally, it becomes apparent that many structures have prolonged activity histories.

The most outstanding example in this case is that of the Weissenbach anticline and Dachstein thrust sheet. Both structures were mostly coeval, with activity on both spanning from the Late Jurassic into the Late Cretaceous (when thrusting on the Nussensee thrusts is included). This activity is recorded by structure-controlled thickness changes in the Upper Jurassic and Lower Cretaceous units on the Weissenbach–Mitterberg anticlines, and post-Dachstein emplacement folding of the Weissenbach anticline. In the case of the Dachstein, its footwall ramp, which cuts Upper Jurassic in the south and up Lower Cretaceous in the north, is indicative of progressive emplacement during this time. Post-emplacement folding is responsible for tilting of Gosau beds on the leading edge of the thrust sheet (Fig. 7a) and therefore likely coeval with the Nussensee thrusts. Growth recorded in successive stratigraphic units argues for uninterrupted shortening from the Late Jurassic to the Early Cretaceous, implying activity on both structures was ongoing for tens of millions of years. Assuming a Kimmeridgian age (~152–157 Ma) onset of deformation and cessation in the Hauterivian (~130–133 Ma), slip rate on the Dachstein thrust sheet (~8–10 km displacement) was in the range of 0.3–0.5 mm/yr, well within the ranges of other thrusts documented worldwide (Vita-Finzi, 2000; Kohn et al., 2004; Maesano et al., 2013; Bergen et al., 2017).

This picture of continuous Jurassic to Cretaceous shortening contrasts with the description by previous authors (e.g., Mandl et al., 2012; Levi, 2023) of exclusively Early Cretaceous emplacement of the Dachstein thrust sheet, and single-phase growth of the Weissenbach anticline. Likewise, prolonged exposure of the tops of the diapirs in the area during the Late Jurassic to Early Cretaceous is an indication that the area remained under compression throughout. Nonetheless, it was likely the dying out of individual structures (e.g., Grabenbach thrust, Raucherkar folds) that led to oblique displacements and vertical-axis rotations on still active structures. These in turn are interpreted to have been the origin of the complex pattern of shortening and extension documented here.

6.5. Salt allochthony in the central NCA

Salt allochthony of Late Jurassic age, driven by early Alpine shortening, has already been described across the entire central NCA (Kurz et al., 2023; Fernandez et al., 2025). However, the Lauffen salt sheet and the allochthonous salt of the Ischl valley are the first extrusive salt allochthons of Cretaceous age described as such in the area.

The gypsum body of Moosegg (located 30 km to the WSW of Bad Ischl; label M in Fig. 1a; Schorn and Neubauer, 2011) is proposed here to be a potential extrusive salt allochthon. As with the Lauffen and Ischl bodies, the Moosegg body lies in the footwall of the western prolongation of the Dachstein thrust (Fernandez et al., 2024) and is documented to lie above and below beds of the Rossfeld Fm (Petraschek, 1947; Plöchinger, 1990). The presence of overlying Rossfeld Fm sediments (Petraschek, 1947; and confirmed by the authors) is compatible with its extrusive nature and contradicts the thrust origin proposed by Schorn et al. (2013). As in the case of the Lauffen sheet, the Moosegg salt sheet has a mylonitic fabric and contains mafic clasts of diverse compositions, including serpentinites (Schorn and Neubauer, 2011; Schorn et al., 2013), whose metamorphism ages and composition are compatible with those expected in the Rossfeld Fm (Decker et al., 1987; Vozarova et al., 1999).

Further bodies of Permo-Triassic evaporites that are candidates to be Cretaceous-age salt allochthons in the region are:

1) A 300 m thick Haselgebirge body resting on the Rossfeld Fm that is overlain by rocks of the Oberalm Fm drilled in the Golling Thermal-1 borehole (4 km SW of Moosegg; Elster et al., 2016)
2) A body of Haselgebirge resting on Gosau Gp rocks in the locality of Bad Reichenhall (over 50 km west of Bad Ischl; label B in Fig. 1a) documented by Schauberger and Zankl (1976) and Zankl et al. (2022);
3) Patches of Haselgebirge mapped to rest on the Rossfeld Fm in the area of the Rossfeld peak (label R in Fig. 1a) (Plöchinger, 1990; Kellerbauer, 2022).

Finally, the presence of enigmatic mafic clasts, some with Mesozoic metamorphism, have also been documented in other salt bodies across the central NCA (Kirchner, 1979, 1980). As with the case of the Lauffen and Moosegg salt sheets, a phase of shortening-driven diapir uplift and unroofing during the Cretaceous could explain the incorporation of exotic clasts, as those seen in the Rossfeld Fm (Decker et al., 1987; Krische and Gawlick, 2015), into these salt bodies.

7. Conclusions

Late Jurassic to Early Cretaceous shortening in the Austrian Eastern Alps led to the development of complex structural patterns due to the presence of an efficient basal evaporitic *décollement* and an inherited configuration of thick and thin post-salt stratigraphy (variable overbruden to salt thickness ratios, OB/S). The patterns of OB/S further varied with time, as the onset of shortening was related to the deposition of hundreds of meters of syn-tectonic sediments. Salt structures that were active during shortening formed preferentially along the forelandward margin of domains of low OB/S. Areas of high OB/S cover acted as backstops to deformation of these salt structures. Late extensional collapse, associated to differential displacement occurred across areas that initially sat above inflated salt.

Our analysis shows that deformation occurred in the area in a temporal continuum. Although some structures were active for a relatively limited time, others were active over periods of tens of millions of years. This complex picture highlights the importance of local as well as regional analysis in determining the temporal evolution of fold-and-thrust belt systems.

The study area presents an excellently preserved example of a salt feeder and associated extrusive salt sheet in the Sulzbach-Lauffen system. Mylonitic fabric in the Lauffen salt sheet indicates northwestward emplacement. Extrusion of salt to the seafloor during the process of allochthony is proposed here as a mechanism for the incorporation of exotic mafic rock clasts and possibly also Haloarchaea described previously in the Lauffen salt allochthon.

CRediT authorship contribution statement

Oscar Fernandez: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Thomas Leitner:** Writing – original draft, Resources, Funding acquisition, Data curation. **Lino Eggerth:** Investigation, Data curation. **Diethard Sanders:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Hugo Ortner:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Michael Moser:** Writing – review & editing, Investigation, Data curation. **Mariusz Fiałkiewicz:** Writing – review & editing, Investigation. **Luke Hill:** Writing – review & editing, Investigation. **Bernhard Grasemann:** Writing – review & editing, Writing – original draft, Resources, Investigation, Funding acquisition, Formal analysis.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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