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# Emplacement and associated sedimentary record of the Jurassic submarine salt allochthon of the Wurzeralm (Eastern Alps, Austria)

Maditha Kurz[1], Oscar Fernandez[1], Lino Eggerth[1], Bernhard Grasemann[1], Philipp Strauss[2]

[1] Dept. of Geology, University of Vienna, Josef-Holaubek-Platz 2 (UZA II), 1090 Vienna, Austria

[2] OMV, Trabrennstrasse 6-8, 1020 Vienna, Austria

**Corresponding author:**

Oscar Fernandez
@itsoscarsfault
oscar.fernandez.bellon@univie.ac.at
+43 1 4277 53609
Dept. of Geology
UZA2 B446A
Josef-Holaubek-Platz 2
1090 Wien, AUSTRIA
ORCID: 0000-0003-1584-2684

**Abstract**

A fossil salt sheet emplaced in the Jurassic in submarine conditions is described in the Eastern Alps of Austria, providing unique insights into the emplacement of similar submarine structures and their potential control on depositional systems. The salt sheet is a plug-fed extrusion emplaced due to squeezing of a salt diapir under compression. The preserved mylonitic shear fabric in the evaporites indicates radial, south-directed emplacement of the salt sheet. Tectono-sedimentary relationships record the evolution of the salt structure, from initial diapiric growth, to salt sheet extrusion and posterior collapse. Syn-extrusion sediments record the variable bathymetry of the extruding salt sheet, with reefal carbonates building up on the crestal bulge while their deeper water equivalents accumulated on the extruding salt lobe. This is the first description of a salt allochthon still linked to its source diapir in the Eastern Alps.

## Introduction

Allochthonous salt bodies are common features of salt basins worldwide and have been abundantly documented in both convergent and passive margin settings (Hudec and Jackson, 2006; Rowan, 2017). The mechanism of emplacement of these bodies has been studied in detail in the Zagros *namakiers*, emplaced in a subaerial setting (Schleder and Urai, 2007; Mansouri et al., 2019; Závada et al., 2021). In other contexts, outcrop conditions (weathering, vegetation), tectonic overprint or inaccessibility (as in submarine examples) make similar analysis impossible.

In this paper we present a uniquely well-preserved example of a plug-fed extrusion (*sensu* Hudec and Jackson, 2006) emplaced in a submarine setting in the Late Jurassic. The allochthonous salt sheet is located in the Northern Calcareous Alps (Eastern Alps, Austria), and has been mostly preserved in its original geometry, in spite of post-extrusion Alpine deformation. The extruded evaporite body (made up at present mostly of gypsum) excellently preserves original extrusion shear fabrics and syn-emplacement roof sediments. This paper summarizes the available field evidence to provide a kinematic and tectono-sedimentary model for salt sheet extrusion in submarine settings.

## Geological Setting

The Northern Calcareous Alps (NCA) are a set of imbricate thrust sheets detached from their Variscan basement that carry in their hanging wall stratigraphy ranging from Upper Permian to Eocene (Wagreich and Faupl, 1994; Linzer et al., 1995; Schmid et al., 2004). NCA stratigraphy was deposited from Late Permian to Middle Jurassic times on Adria, a continental block part of the northern passive margin of the Neo-Tethys (Mandl, 2000; Schmid et al., 2008). From Middle to Late Jurassic, Adria rifted and separated from Europe forming the Alpine Tethys (Mandl, 2000; Schmid et al., 2008). An early phase of Alpine orogenesis in the Late Jurassic caused initial inversion of the margin and limited shortening deformation in the NCA (Frank and Schlager, 2006; Gawlick and Missoni, 2019). From Early Cretaceous to Paleogene times the NCA were thrust over the Alpine Tethys and European continental margin (Linzer et al., 1995; Stüwe and Schuster, 2010).

Mandl (2000) provides an overview of the NCA stratigraphy, summarized here (Fig. 1a). An initial Upper Permian red bed series deposited during rifting is overlain by the Upper Permian Haselgebirge Fm, a thick sequence of evaporites and shales (Leitner et al., 2017). These units are followed by late rift Lower Triassic epi-continental clastics (Werfen Fm) and Middle Triassic shallow water carbonates (Gutenstein Fm). Thermal subsidence and salt-evacuation during the Middle to Late Triassic provided accommodation space for the deposition of a 2 to 3 km thick sequence of shallow platform carbonates (Wetterstein and Dachstein Limestones). These units record syn-depositional diapir growth in the form of rapid thickness changes and folding (Fig. 2) (see also Fernandez et al., 2021; Strauss et al., 2021). The shallow water Dachstein and Wetterstein Limestones transition laterally to equivalent deeper water carbonates (absent in the study area): the Reifling Fm and the Hallstatt Limestone.

Continued subsidence in combination with reduced carbonate productivity during the Early Jurassic led to the drowning of platforms and the accumulation of a condensed (up to tens of meters thick) deep water red crinoidal limestone (Adnet or Hierlatz Fms). Locally, the Lower Jurassic includes an over 100 m thick turbiditic succession of dark marls (Allgäu Fm). The Middle Jurassic is characterized by further condensed stratigraphy (up to few tens of meters): the Mn-nodule rich, red Klaus Fm and/or the Ruhpolding Fm radiolarites and siliceous limestones. A major change occurred in the Upper Jurassic, with the deposition of both shallow water reefal limestones (Plassen Limestone) and their deeper water marly limestone equivalent (Oberalm Fm). The Upper Jurassic is also characterized by the presence of localized pockets of breccias (Rofan Breccia, *sensu* Ottner, 1990).

The youngest deposits in the area are syn-orogenic clastics of the Gosau Group (Wagreich and Decker, 2001).

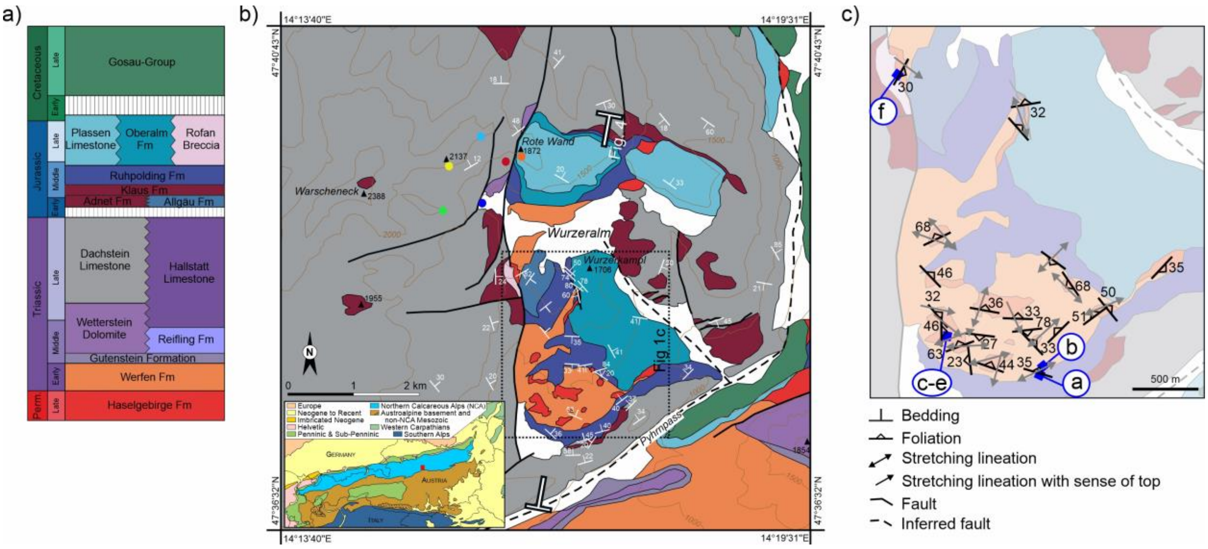


Fig. 1 a) Simplified stratigraphic chart of the area roughly scaled for the relative thickness of units in the area. b) Detailed geological map of the Wurzeralm and surrounding area (after Ottner, 1990; Moser and Pavlik, 2014; Kurz, 2022; and mapping by the authors) with bedding dip measurements. The color legend follows the scheme in (a). The inset shows the location of the study area within the Eastern Alps (red box). The colored dots in the area of the Warscheneck-Rote Wand are points shown also in Figure 2 for location reference. The location of (c) and of the profile in Figure 4 are shown. c) Detail of the Wurzeralm salt sheet with foliation (and their dip magnitude) and stretching lineations measured in Haselgebirge Fm gypsum. Lineations that are accompanied by shear sense indicators are shown as unidirectional arrows indicating "top-to-the" direction. The location of the photographs in Figure 3 is indicated by labels a-f.

## The Wurzeralm salt sheet

The Wurzeralm salt sheet is located on the trailing (southernmost) edge of the preserved central NCA thrust sheets. The Wurzeralm diapir and salt sheet outcrop defining a roughlyN-S rectangular area characterized by a somewhat patchy arrangement of Jurassic units and Permo-Triassic Haselgebrige and Werfen Fms (Fig. 1b). The diapir is completely surrounded by the Dachstein Limestone, overlain by condensed Jurassic limestones (Adnet/Hierlatz and

Klaus Fms) (Fig. 1b). West of the Wurzeralm, the Dachstein Limestone thins against the diapir, indicating syn-diapiric deposition (Fig. 2).

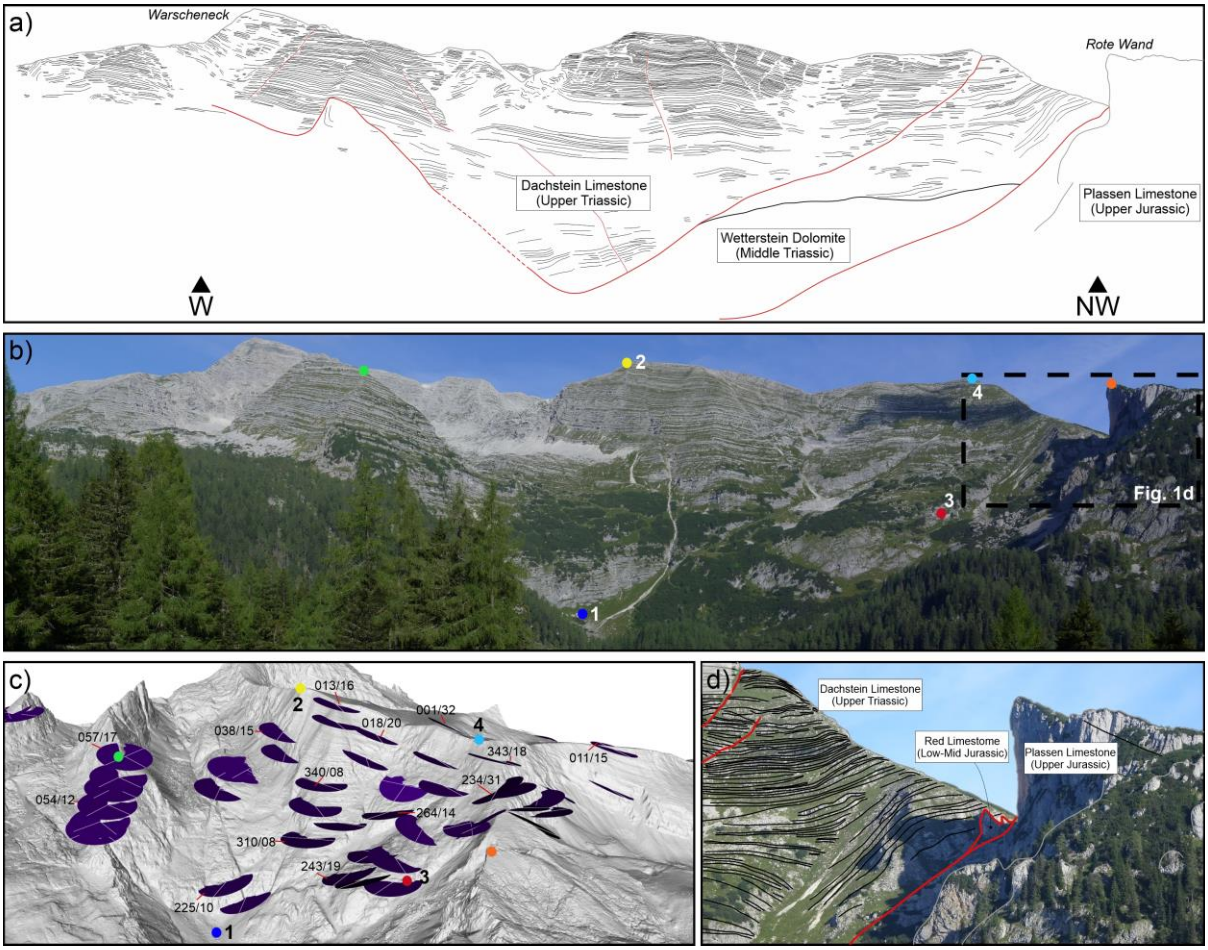


Fig. 2 a,b) Panorama looking west of the Wurzeralm, and line drawing showing a thinning of the Dachstein Limestone towards the Wurzeralm diapir. The Plassen Limestone of the Rote Wand sits above the collapsed Wurzeralm diapir. c) Oblique view of a Lidar digital terrain model of the area in the panorama in (a) (digital terrain model data obtained from Land Oberösterreich - data.ooe.gv.at, under CC-BY-4.0 license). Blue disks represent bedding dip and show progressive rotation of the beds, from the bottom to the top of the Dachstein Limestone. Colored dots represent reference points in (b) (shown also in Figure 1b). The stratigraphic thickness of the Dachstein Limestone reduces from 800 m between dots labelled 1 and 2, to 500 m between dots labelled 3 and 4. d) Detail from the panorama in (a) showing a small-scale syncline developed in the Dachstein Limestone in the proximity to its contact with the diapir.

Along its southern outcrop edge, the Permian Haselgebirge Fm of the Wurzeralm rests directly on Middle Jurassic siliceous limestones of the Ruhpolding Fm. The contact between both units is not observed directly in outcrop, but is interpreted cartographically to dip northeastward, parallel to bedding of the underlying Ruhpolding Fm (Fig. 3a, Supplemental information). Whereas the Ruhpolding Fm is undeformed and concordant with the underlying stratigraphy, the Haselgebirge presents a penetrative mylonitic fabric indicating south-directed emplacement (Fig. 3b, Supplemental information). Isolated levels of

Dachstein Limestone sedimentary breccias have been found within the Ruhpolding Fm under the salt sheet (Fig. 3a).

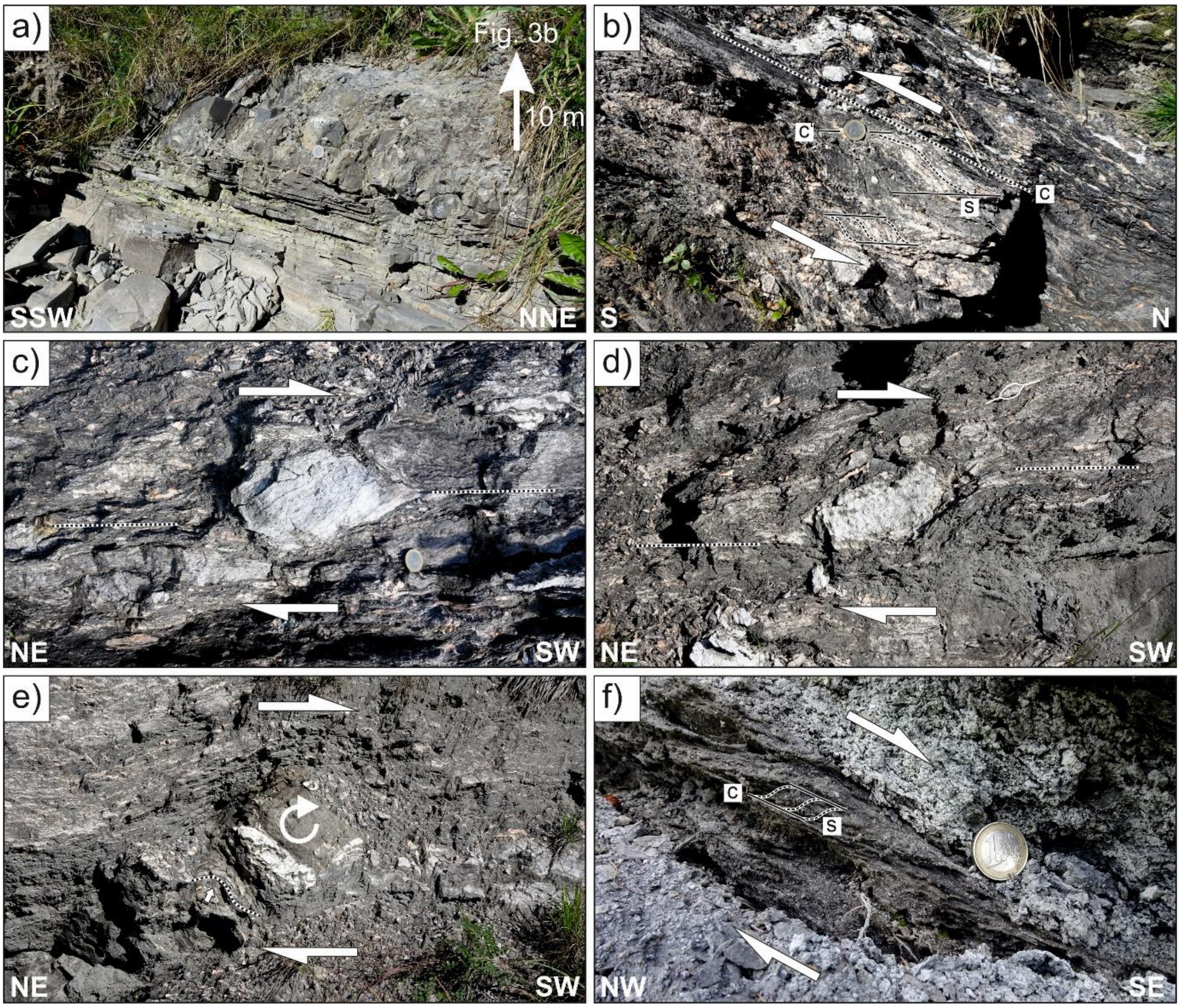


Fig. 3 a) Conglomerate layer with up to 15 cm large limestone components in the otherwise planar cm-bedded siliceous limestone of the Ruhpolding Fm. This outcrop (UTM33 446336E, 5274432N) is 6 meters stratigraphically below the Haselgebirge (Fig. 3b). b) Mylonitic Haselgebirge (UTM33 446333E, 5274444N) with scc' fabric indicating top-to-the south shear sense (c-plane 350/38, stretching lineation on c-plane 005/36). c and d) Sigmoidal shaped anhydrite components stabilized with long axes inclined against the shear direction. Note, the stair stepping of the foliation in the Haselgebirge indicating top-to-the SW shear sense (UTM 33 445676E, 5274675N). e) Rolling structure of an angular sandstone clast coupled with the foliation in the Haselgebirge (UTM33 445690E, 5274658N). The clear embayment of the foliation in the Haselgebirge (grey arrow) suggests a co-shearing rotation of the clast indicating top-to-the SW shear sense. f) Sigmoidal secondary foliation s (305/08) in the Haselgebirge dips against the top-to-the SE shear sense on the c-planes (114/33). The stretching lineation (126/32) on the c-planes is roughly perpendicular to the intersection of the s- and c-planes (UTM33 445288E, 5276731N).

The Haselgebirge Fm in the area is characterized by mylonitic fabric similar to that observed along its southern margin (3c-f). Stretching lineations and shear sense indicators in the gypsum consistently show top to the south shearing (ranging between southwest and southeast) (Fig. 1c). Along the southern outcrop border, the stretching direction is somewhat variable, recording non-plane-strain finite deformation (Fig. 1c).

The Haselgebirge Fm is overlain mostly by the Lower Triassic Werfen Fm and locally directly by the Jurassic Allgäu and Ruhpolding Fms (Fig. 1b). The beds of the Ruhpolding that sit above the salt present intense folding, with fold axes trending in two perpendicular directions. One trends NE-SW (azimuth 020-070) and the other NW-SE (azimuth 300-320). The NE-SW fold trend is not observed in any other lithologies, nor does it coincide with the local shearing direction in the Haselgebirge Fm and is therefore potentially related to soft-sediment deformation above the Wurzeralm diapir during deposition. The NW-SE trend in turn, coincides with the trend of a set of younger thrusts involving the Oberalm Fm and the Haselgebirge Fm southwest of the Wurzerkampl (Fig. 1b).

The Wurzeralm diapir is capped by the Upper Jurassic Plassen and Oberalm Fms. The reefal Plassen Limestone in the north transitions to the deeper water Oberalm Fm to the south, and serve as indicators of Late Jurassic bathymetry. At present, the Plassen Limestone of the Wurzeralm lies at an elevation equivalent to that of the Dachstein Fm west of the Wurzeralm diapir due to activity of a post-Jurassic eastward dipping normal fault (Figs. 1, 2).

Along the western margin of the diapir, Rofan Breccia deposited along the edge of the evaporite body contain reworked limestone fragments of the Dachstein, Allgäu and Oberalm Fms, dark shale fragments that likely originate from the Haselgebirge Fm, and isolated clasts of Hallstatt Limestone (Ottner, 1990).

**Discussion**

The structure and outcrop distribution of the study area is interpreted to show the relict structure of a southward-directed plug-fed extrusion (Fig. 4). Extrusion of the Haselgebirge Fm onto the seafloor above Middle Jurassic sediments occurred during the Late Jurassic (Fig. 5) and required shortening of the diapiric salt stock. Similar aged emplacement of Haselgebrige Fm on a Middle Jurassic seafloor has been observed at other locations in the NCA but without being documented as resulting from salt allochthony (e.g., Plöchinger, 1996; Suzuki and Gawlick, 2009; Mandl, 2016).

The Plassen Limestone reef is interpreted to have built up above the shallowest seafloor during extrusion formed by the uplifted northern flank of the diapir and the crestal bulge of a southwards extruding salt sheet (formed above the original diapir stock) (Fig. 5). Tilting and uplift of the northern diapir flank, coupled with submarine erosion, could help explain the local absence of Lower to Middle Jurassic stratigraphy under the Plassen Limestone north of the Rote Wand and west of the cross-section trace (Fig. 1b).

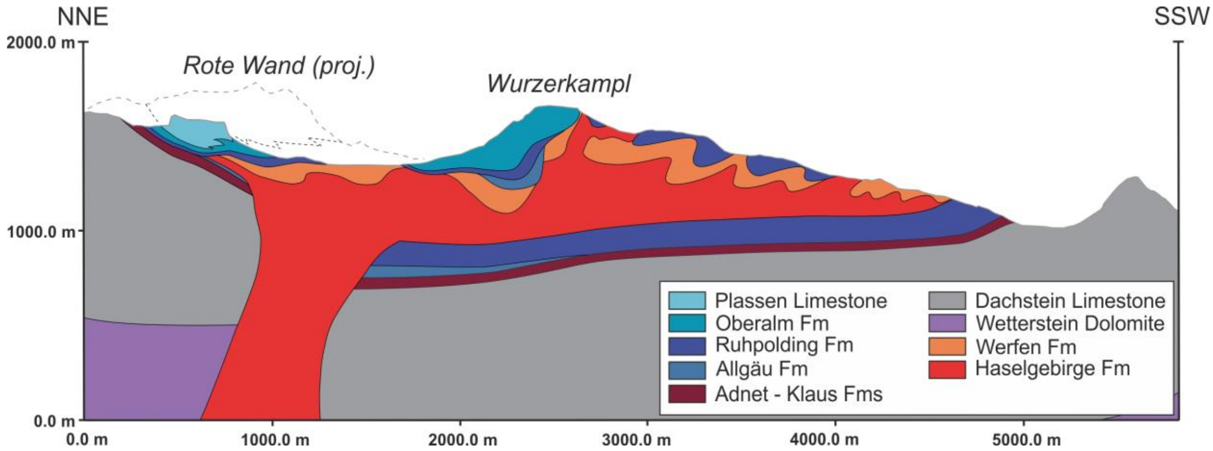


Fig. 4 Structural cross-section across the Wurzeralm salt allochthon. Structure at depth is inferred, including the regional thickness of the Dachstein Limestone derived from constraints beyond the study area.

Stretching lineations along the southern edge of the salt sheet locally indicate E-W stretching, perpendicular to the south-directed radial flow (Fig. 1c). Such a pattern contrasts with that in present day examples of the Zagros (Závada et al., 2021) in which transport is directed purely away from the feeder and stretching is parallel to the shearing direction. The origin of this cross-directed flow in the Wurzeralm could relate to the lateral spreading of evaporite along its leading edge and transition from transpressional to transtensional flow (similar to that reported in velocity fields in glaciers; Mayrhofer et al., 2022)

Notably, the orientation of structures measured in the units overlying the salt sheet are not aligned with shear directions in the evaporites but it is still likely that roof units were involved in deformation with the evaporites. As discussed above, the presence of a NE-SW fold trend in the Ruhpolding Fm that is absent in younger and older units possibly indicates the syn-sedimentary nature of deformation, potentially linked to instability atop the diapir and incipient salt sheet. This instability potentially also affected surrounding areas, as recorded by the presence of the Dachstein Limestone breccias in the sub-allochthon Ruhpolding Fm (Fig. 3a). Beyond this early deformation, roof units were most likely passively dismembered during emplacement and partially rolled over the open-toe front and accumulated in Rofan Breccia bodies. The source of the Hallstatt Limestone clasts in the Breccia remains uncertain due to the lack of outcrop in the area. Sediments under the advancing salt sheet were not deformed during salt emplacement.

Although the Wurzeralm structure has previously been explained as the result of gravitational northward gliding (Ottner, 1990; Tollmann, 1987), emplacement of the salt sheet was southward-directed and can be accounted for by an episode of Jurassic compression-driven allochthony (Fig. 5). The salt tectonics origin of the Wurzeralm thrust sheet is in line with the recent observations of Granado et al. (2019), Fernandez et al. (2021) and Strauss et al. (2021) on the relevance of salt tectonics in the NCA. Furthermore, the mylonitic fabric present in the gypsum of the Haselgebirge Fm, likely developed through pressure solution-precipitation creep (e.g., Závada et al., 2021), requires rates of deformation that are more compatible with a gradual allochthony.

Similar fabrics in Haselgebirge Fm gypsum and anhydrite have been observed by Schorn and Neubauer (2011) some 100 km to the west of the Wurzeralm, in the Moosegg body that rests on top of Lower Cretaceous sediments. Although these authors interpreted this body as a thrusted sheet based on the mylonitic fabric, the presence of exotic igneous, metamorphic and sedimentary blocks within the salt body as well as fragments of Haselgebirge within the Lower Cretaceous sediments (Schorn and Neubauer, 2011), hints at the possibility that this body is a fossil roofless allochthonous Haselgebirge salt sheet emplaced in the Early Cretaceous (synchronous with Alpine thrusting). An equivalent situation is that of the Bad Ischl salt accumulation, which rests on Lower Cretaceous sediments (Mandl et al., 2012) and contains multiple exotic blocks (Vozarova et al., 1999) that were possibly incorporated during emplacement. In conclusion, the description of the Wurzeralm Haselgebirge body as an allochthonous salt sheet opens the tantalizing possibility that further allochthonous bodies in the NCA may have gone unrecognized to date.

Beyond the implications for regional tectonic evolution, syn-extrusion sedimentation in the Wurzeralm also provides important insights into the bathymetric evolution of the area. It is generally accepted that the NCA underwent significant deepening during the Early to Middle Jurassic culminating during deposition of the Ruhpolding Fm (Lein, 1987; Mandl, 2000). Shallowing ensued during the Upper Jurassic. However, the exact magnitude of shallowing in the Jurassic and its driving mechanism are still debated. Based on the Upper Jurassic facies distribution in the Wurzeralm, it can be proposed that seafloor uplift was driven by the rise of salt (leading to an allochthon at least 500 m thick, Fig. 4) and uplift of the diapir flanks (Fig. 5). For the seafloor to reach water depths in the photic zone apt for reef development, pre-allochthony water depth of the Ruhpolding Fm radiolarites is unlikely have been greater than 1000 m (a water depth consistent with that of other Tethyan Jurassic radiolarites, Baumgartner, 2013).

Finally, one of the most remarkable features in the Wurzeralm is the presence of faults that cross-cut the platform surrounding the diapir and define the western and eastern edges of the diapir (Fig. 1b). One of these faults displaces the Jurassic Plassen Limestone down to the same elevation as the Dachstein Limestone (Fig. 2), defines the western edge of the diapir to the south, and also arches and cuts into the Dachstein Limestone with a gradually decreasing offset (Fig. 1b). A second fault, immediately to the west juxtaposes the Dachstein Fm against the Wetterstein Fm (Fig. 2) and also progressively curves and dies out towards the southwest (Fig. 1b). These faults are interpreted to be faults detaching within the Haselgebirge Fm and likely played a protracted role in the development of the diapir: they accommodated variable subsidence during Middle to Late Triassic deposition, and re-activated after allochthony in extension (possibly during the Late Cretaceous, similar to structures documented in a similar setting further west by Fernandez et al., 2022).

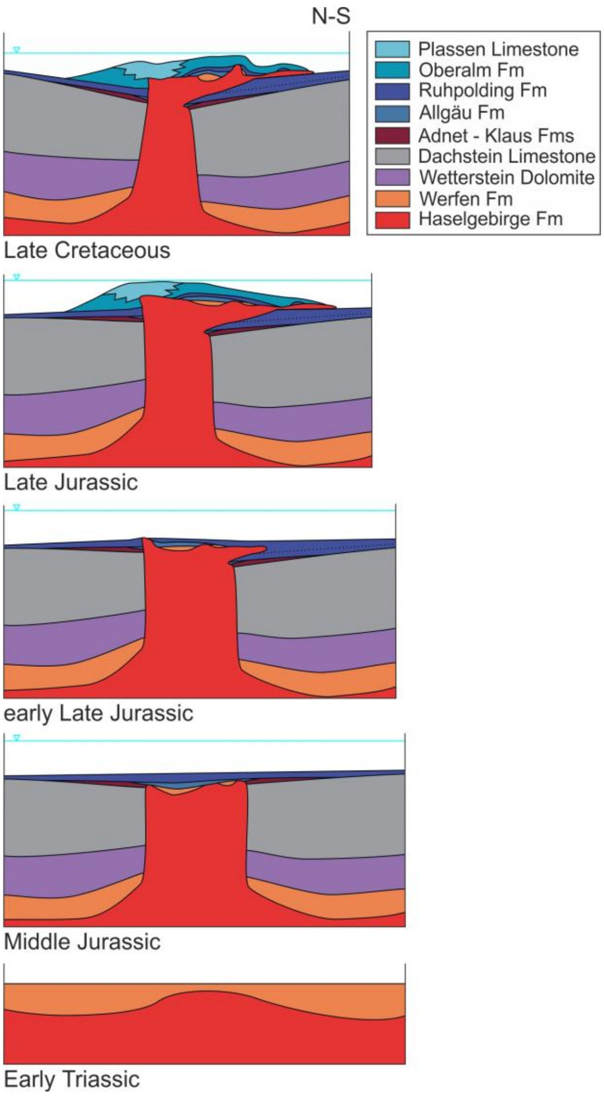


Fig. 5 Conceptual evolutionary model of the Wurzeralm salt sheet. The Triassic evolution of the structure was dominated by passive growth of a diapir and deposition of the Wetterstein and Dachstein Fms in flanking minibasins. This was followed by a period of quiescence and partial subsidence of the diapir during Early to Middle Jurassic. During this period, condensed red limestones (Adnet/Klaus Fms) deposited on the shallower minibasins flanking the diapir and the Allgäu Fm mainly over the subsiding diapir. This whole suite was draped over by the Ruhpolding Fm. Initial shortening in Late Jurassic times led to initial allochthony, synchronous with deposition of the youngest Ruhpolding Fm. Allochthony developed fully snychronously with the emplacement of the Upper Jurassic Plassen and Oberalm Fms, with the shallower Plassen Fm depositing preferentially above the salt stock feeding the southward-extruding salt sheet. Squeezing of the diapir was coeval with tilting of the flanking minibasins. Finally, during Late Cretaceous times, the salt structure collapsed partially to its almost present-day structure.

## Conclusion

Despite the magnitude of Alpine overprint in the area, the Jurassic-age Wurzeralm salt sheet presents an almost intact structure and is a striking example of a submarine-emplaced allochthonous salt body with syn-emplacement roof sedimentation. This salt sheet constitutes the first instance of a preserved diapir and its associated allochthon documented in the Eastern Alps, underscores the relevance that salt tectonics played in this area, and highlights the need of revisiting the interpretation of other salt bodies in the Eastern Alps.

## Acknowledgements

Mapping of the Wurzeralm by M. Kurz and L. Eggerth was possible thanks to funding by the Austrian Geologisches Bundesanstalt and the W. Schollnberger Student Fund. Research by O. Fernandez is supported by the FFG and Salinen AG FFG-Bridge Project ETAPAS (FO999888049) and the FWF Project POLARIS (I5399-N). Academic licenses of Move software are provided by Petex Ltd.

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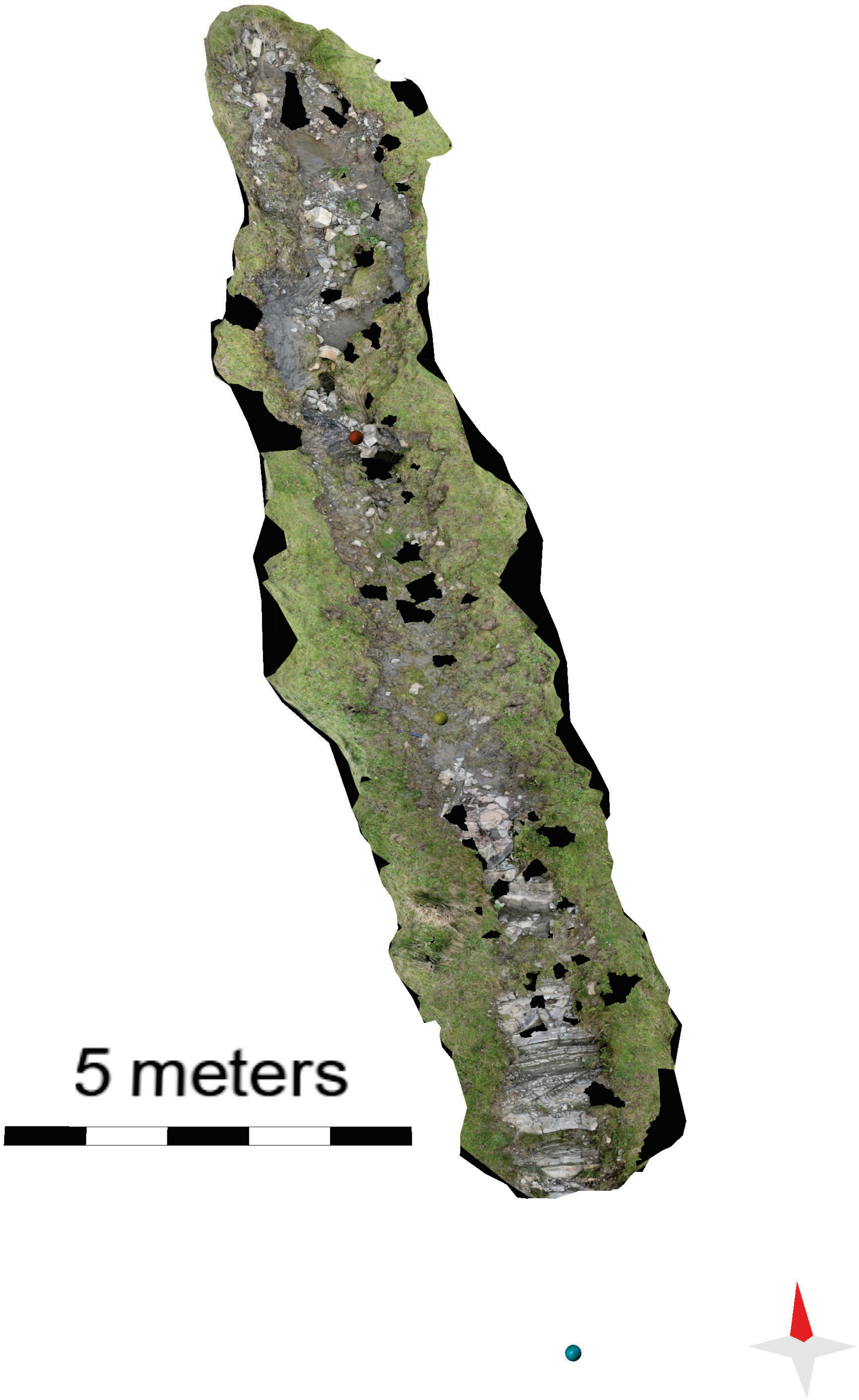
**Supplemental information**

The 3D model below has been generated from oblique photographs taken with a handheld digital Panasonic Lumix DMC-FZ1000 II camera with 20 Megapixel CMOS-1" sensor. Images have been processed Structure from Motion algorithm (Agisoft Metashape Professional v. 1.8.3, www.agisoft.com) to generate a point cloud with 24,469,626 points and a textured mesh with 1,408,843 faces. The model has been georeferenced and scaled based on outcrop control points.

In the model the location of Fig. 3a and 3b are shown by the blue and dark orange spheres respectively (the blue sphere lies beyond the southern extent of the mesh). The yellow sphere indicates the location of the top of the Jurassic Ruhpolding Fm siliceous limestones and base of the allochthonous evaporite unit. The lowermost 3 meters of the evaporite unit are not directly visible and are covered by mud.

Basal contact of the Wurzeralm (Eastern Alps, Austria) Haselgebirge Fm salt allochthon

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