

# Structural styles in fold-and-thrust belts involving early salt structures: The Northern Calcareous Alps (Austria)

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## ABSTRACT

**Shortened salt-withdrawal minibasins and associated salt welds are exposed in the Mesozoic strata of the Northern Calcareous Alps fold-and-thrust belt (Austria). Geological mapping and sequential restoration of a balanced cross section have indicated that these salt and salt-related structures developed during the postrift stage of the Neo-Tethys continental margin by evacuation and inflation/deflation of uppermost Permian to lowermost Triassic salt. Middle to Late Triassic minibasins were formed by down-building and downslope translation, flanked by megafaults and salt walls. Salt and salt structures were rejuvenated by salt-wall fall and formation of bowl minibasins as a response to Penninic rifting since Rhaetian times. Complex structural styles, including younger-on-older contacts, tight folds, and kilometer-scale fully overturned panels resulted from the shortening of early salt structures upon the onset of Jurassic regional convergence. Salt tectonics can reconcile the stratigraphic development and internal structure of the long-debated Northern Calcareous Alps. Our work also provides a new line of research for understanding other fold-and-thrust belts developed from the Neo-Tethys continental margin (i.e., the Carpathian Mountains, the Southern Alps in Europe, the Dinaric Alps) and sets guidelines for other salt-influenced fold belts.**

## INTRODUCTION

The understanding of fold-and-thrust belts is based on the critical taper theory (i.e., Davis et al., 1983), along with thrust tectonics (e.g., Boyer and Elliot, 1982) and basin inversion concepts (i.e., Hayward and Graham, 1989). These pioneering works emphasized the importance of balanced cross sections (e.g., Dahlstrom, 1969), which gained significance by the commonplace use of thrust-related folding templates (e.g., Jamison, 1987). In this sense, salt-detached fold-and-thrust belts have been described as having an extremely narrow cross-sectional taper, a regular structural spacing, and the lack of a clearly defined structural vergence (e.g., Davis and Engelder, 1985); some of these structural templates remain true and applicable. However, there are many salt-detached fold-and-thrust belts that show pre-orogenic basins and structures inherited from the continental margin stage, which, overall, lead to significant structural complexities (i.e., multiple structural orientations, strong plunges, large panels of overturned stratigraphy, mechanical contacts omitting or repeating stratigraphy). Some of these examples have been explained by invoking

several deformation phases, strike-slip tectonics, or even the gravitational emplacement of thrust sheets. Only recently have early salt tectonics been brought into the equation (e.g., Jackson and Harrison, 2006; Rowan and Vendeville, 2006; Callot et al., 2012; Graham et al., 2012).

An example from the Northern Calcareous Alps of Austria (Fig. 1), traditionally interpreted as a gravity-driven belt (i.e., Tollmann, 1987) overprinted by strike-slip faulting (i.e., Linzer et al., 1997), is here coherently explained by salt tectonics processes. Here, we show how minibasins (i.e., small basins largely surrounded by and subsiding into salt) and welds (i.e., surfaces joining strata in direct contact, but originally separated by salt) developed on the Neo-Tethys margin, and how those became rejuvenated. Our findings open a new line of research for the studied area, and they provide important constraints applicable to other salt-influenced fold-and-thrust belts.

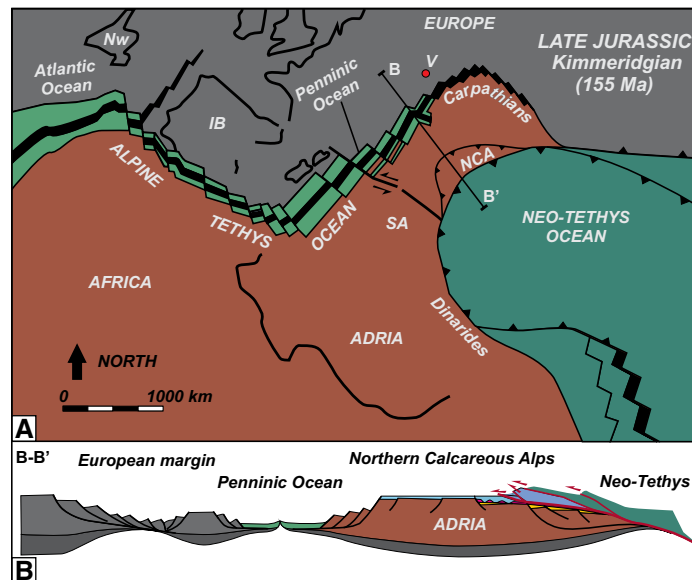
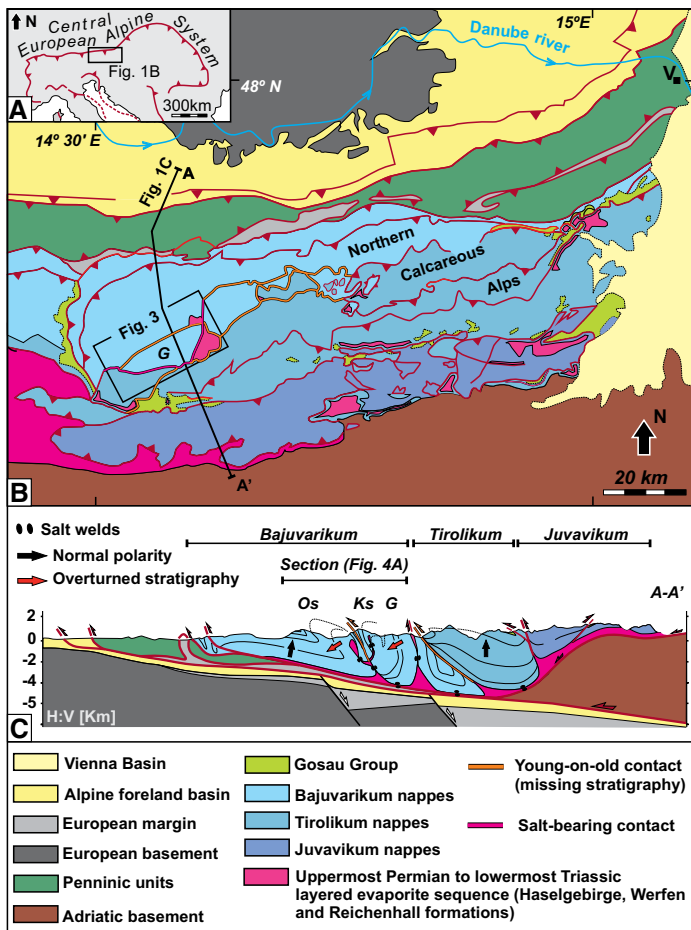
## NORTHERN CALCAREOUS ALPS

The Northern Calcareous Alps are a north- to northwest-directed, salt-detached, fold-and-thrust belt belonging to the European Alpine orogenic system (Fig. 1A). Its broad structure consists of ENE-WSW–striking thrust sheets involving a Mesozoic sedimentary cover with significant changes in sedimentary thickness and facies (see the GSA Data Repository<sup>1</sup> for details). The Northern Calcareous Alps have been divided into three large nappe systems (i.e., Bajuvarikum, Tirolikum, and Juvavikum Nappes; Fig. 1B), the stratigraphy of which defines an approximate north-to-south deepening trend for the Neo-Tethys margin (see Mandl, 2000; Frisch and Gawlick, 2003). Structurally speaking, parts of this fold-and-thrust belt are characterized by large panels of overturned stratigraphy and frequent steep mechanical contacts that can repeat but also omit significant parts of the stratigraphic sequence (Fig. 1C). Importantly, all these features are systematically associated with an uppermost Permian to lowermost Triassic layered evaporitic sequence (i.e., the Haselgebirge-Reichenhall Formations; Spötl, 1989). In the studied area, the belt is unconformably overlain by synorogenic strata of Early Cretaceous age, followed by the Late Cretaceous–Eocene Gosau Group (e.g., Faupl and Wagerich, 1994); the latter commonly overlies Permian–Triassic evaporites as well.

The formation of the Neo-Tethys margin started with the Permian rifting of Pangea. During the latest rifting stage, the widespread Haselgebirge-Reichenhall salt basin was developed (i.e., Leitner et al., 2017), soon after followed by continental breakup around late Anisian times (e.g., Kozur, 1991; Channell et al., 1992; Haas et al., 1995). The Northern Calcareous

<sup>1</sup>GSA Data Repository item 2019012, brief description of the Northern Calcareous Alps geodynamic context and related tectono-stratigraphy, is available online at <http://www.geosociety.org/datarepository/2019/>, or on request from [editing@geosociety.org](mailto:editing@geosociety.org).

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**Figure 2. Late Jurassic paleogeography of European Alpine system. A:** Plate-tectonic framework (modified from Schmid et al., 2008). **B:** Crustal sketch illustrating position of Northern Calcareous Alps in between spreading Penninic Ocean to northwest and closing Neo-Tethys Ocean to southeast at onset of shortening in Kimmeridgian times (ca. 155 Ma). IB—Iberia; NCA—Northern Calcareous Alps; Nw—Newfoundland; SA—Southern Alps; V—Vienna.

of and beneath the main nappes, involving younger units and, locally, exotic basement blocks (e.g., Schnabel et al., 2002). In addition to these features, unequivocal stratigraphic and structural features supporting an earlier salt tectonics scenario have been recorded during our work to the south of Hollenstein an der Ybbs (Fig. 3), across the states of Styria, and Lower and Upper Austria. These are (1) strong thickness variations in the Triassic postrift sequences shifting through space and time (Figs. 3 and 4), indicating an anomalously large but strongly localized subsidence compared to the expected thermal subsidence rates and wavelengths for a passive margin; (2) truncation of stratigraphic units against steep and deformed salt bodies, or against meter-thick strips of severely deformed clays, carbonate, and sandstone breccias (i.e., welded evaporites; Fig. 3); (3) geological contacts frequently characterized by steep to overturned stratigraphy (Figs. 3 and 4); and (4) tight folds developed in the thinner sedimentary sequences indicating an efficient shallow detachment (Fig. 4A). All these features indicate subsidence, sedimentation, and deformation largely controlled by the inflation and deflation of Permian–Triassic salt.

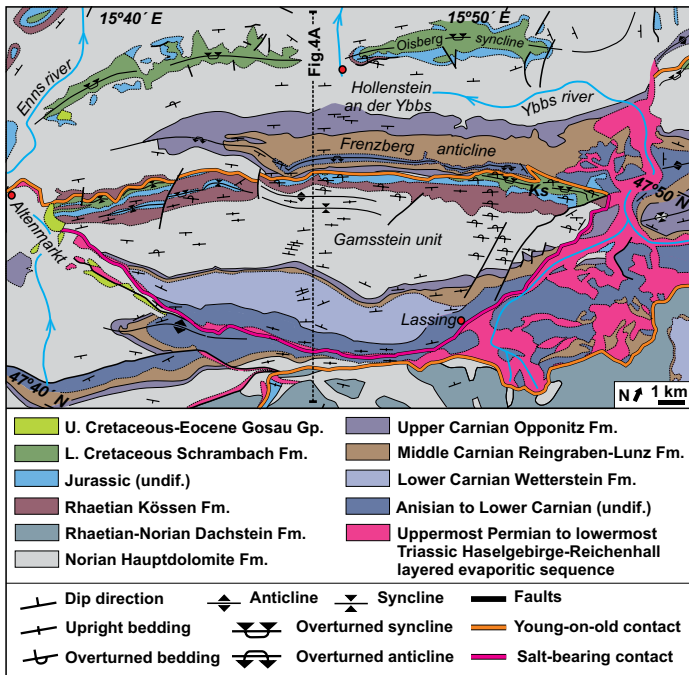
#### FORMATION AND DEFORMATION OF MINIBASINS

In the studied area, salt walls and adjoining minibasins were shortened by north- to northwest-directed convergence probably since Early Cretaceous times. These structures became completely detached from their pre-salt, rifted basement. Restoration of our balanced cross section (Fig. 4) indicates a minimum shortening of ~40%. Salt walls were squeezed to secondary welds (i.e., vertical welds formed by contraction and squeezing of salt), preserved today as deep-seated pedestals (Fig. 4A); thin salt wall shoulders (Fig. 4B) and bowl minibasins (i.e., a minibasin that sinks into a previously formed diapir or salt wall; Fig. 4C) were isoclinally folded, whereas megafolds were rotated to increase their degree of overturning; for example, the Gamsstein minibasin underwent ~50° of rotation around a horizontal axis. Two postrift minibasins (i.e., Gamsstein and Oisberg) were separated by a salt wall (i.e., Königsberg salt wall; Figs. 4D–4G) in Carnian–Norian times. The absence of thickening growth wedges and the separation of the pre-halokinetic unit revealed in our restoration (Fig. 4) indicate that these minibasins most likely formed by downbuilding and

Alps developed as the south-facing platform of the Neo-Tethys margin. From the latest Triassic to Middle Jurassic, this margin was rifted apart from Europe as the Penninic Ocean developed to the northwest (e.g., Channell et al., 1992; Fig. 2A). The Neo-Tethys Ocean was closed by southeast-directed subduction starting in Late Jurassic times (Fig. 2B), generating a contractional deformation that propagated northwestward (e.g., Faupl and Wagreich, 1994; Von Eynatten and Gaupp, 1999; Neubauer et al., 2000; Frisch and Gawlick, 2003). The Mesozoic cover was completely detached from its pre-salt, rifted basement and became the leading upper plate over the southeast-dipping Penninic subduction zone until continental collision between Adria and Europe in Eocene times. As a result, these nappes experienced very large overthrusting, from their original autochthonous Adriatic basement to their present location on top of the European continental margin (e.g., Schmid et al., 2008; Stüwe and Schuster, 2010).

#### EVIDENCE FOR SALT TECTONICS IN THE NORTHERN CALCAREOUS ALPS

The Permian to Triassic Haselgebirge-Reichenhall evaporites have been known for thousands of years (Spötl, 1989). Today, these evaporites outcrop as highly strained clay-mantled gypsum/anhydrite bodies (e.g., Leitner et al., 2017) and constitute the basal detachment of the Northern Calcareous Alps. These evaporites form tectonic mélanges in front



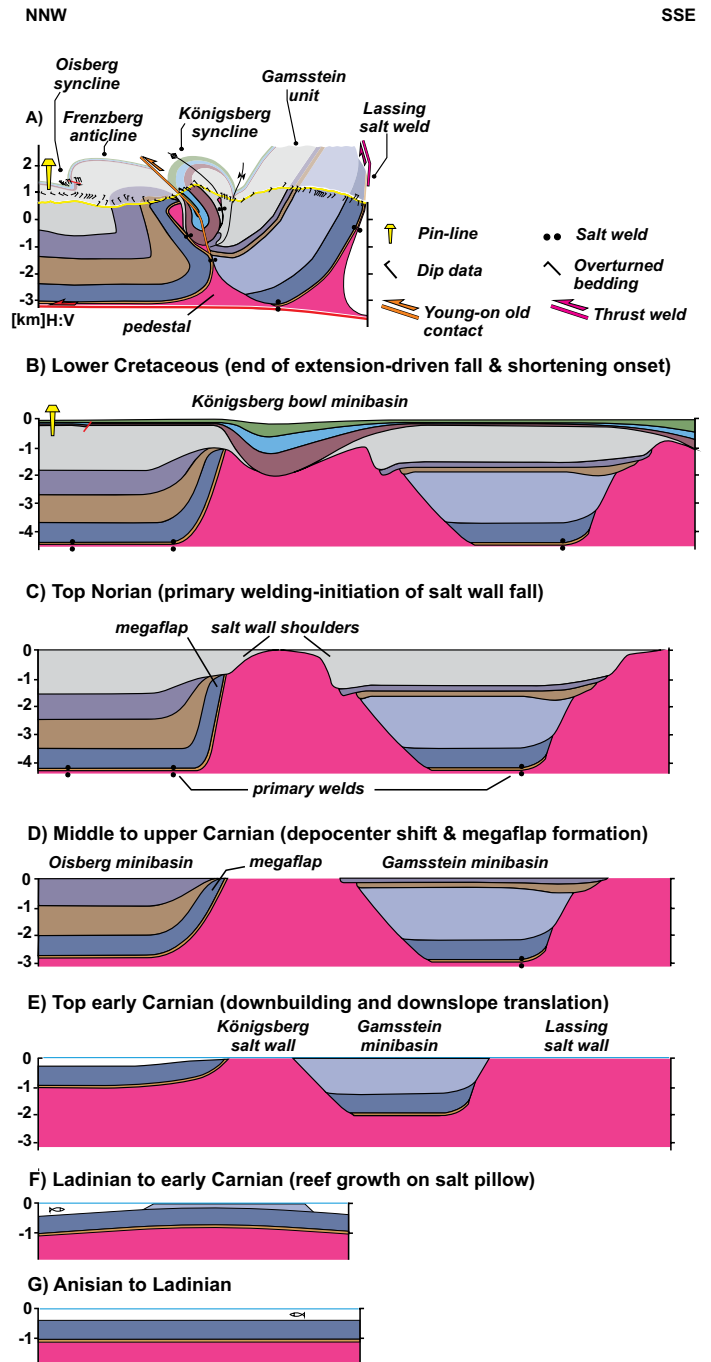
**Figure 3.** Geological map of Gamsstein and surrounding units at Hollenstein an der Ybbs area, Austria (modified from Schnabel et al., 2002). Note that map has been clockwise-rotated to highlight bowl-shaped geometry of Gamsstein unit. Ks—Königsberg syncline; U—Upper; L—Lower.

downslope translation, with a depocenter shift and a related megaflap (i.e., Rowan et al., 2016), bound laterally by salt walls (Fig. 4C). Once these minibasins were grounded by primary welding (Fig. 4C), formation of a Rhaetian to Early Cretaceous bowl minibasin (i.e., Pilcher et al., 2011) by salt deflation and salt-wall fall (Fig. 4B) took place as a response to regional extension, presumably related to the onset of Penninic rifting (e.g., Channell et al., 1992).

## CONCLUSIONS

The large-scale stratigraphic geometries and structural styles described here are consistent with contractional rejuvenation of structures involving inflated salt. Our study shows that salt tectonics concepts can to a large extent reconcile the stratigraphic record and the internal structure of the Northern Calcareous Alps, without invoking the gravity-driven emplacement of thrust sheets to explain geological contacts omitting stratigraphy (e.g., Tollmann, 1987) or tens of kilometers of lateral displacement by strike-slip faulting (e.g., Linzer et al., 1997). In fact, the pre-orogenic architecture of this part of the Neo-Tethys margin is remarkably similar to that of the European Zechstein salt basins (e.g., Stewart, 2007). Squeezing of salt walls was accommodated by shortening up to secondary welding, along with strike-slip or oblique reactivation, such as in other salt-influenced fold belts (e.g., Rowan and Vendeville, 2006). Many of the large strike-slip faults previously described in the studied area display pierced remnants of the Permian–Triassic evaporites and synorogenic strata, with nearby overturned panels, and separate thick Middle to Late Triassic platforms. This structural suite suggests that some of these large strike-slip faults most likely were salt ridges bounding minibasins that became squeezed, secondarily welded, and reactivated as thrust welds during regional shortening.

Complex structural styles departing from the classical Rocky Mountain–Appalachian structural suites (e.g., Boyer and Elliot, 1982; Davis and Engelder, 1985) can develop in fold-and-thrust belts when early salt structures are involved; as deformation is focused on the weakest parts of the wedge (i.e., salt diapirs and walls), the inherited structural relationships and geological contacts can remain preserved (i.e., younger-on-older



**Figure 4.** A: Geological section produced in this work across study area. B–G: Sequential restoration by flexural slip unfolding showing formation and deformation of the Königsberg salt wall, flanking Oisberg and Gamsstein minibasins, and Königsberg bowl minibasin. No vertical exaggeration; H:V—horizontal:vertical. Base of salt is unspecified. See legend in Figure 3.

contacts). Estimates of the amount of orogenic shortening, structural spacing, and the degree, styles, and sequences of thrust stacking need to be carefully addressed for thrust belts that involve early salt structures. Our approach brings a new understanding for the Northern Calcareous Alps and suggests that other orogenic systems that involved the Neo-Tethys margin, such as the Carpathians, the Dinaric Alps, or the Southern Alps in Europe (Fig. 2A), may have undergone a similar history.

Some points should be carefully addressed when studying salt-influenced belts: (1) the original distribution of salt and its stratigraphic

position in relation to major geodynamic events; (2) the nature of salt-sediment contacts (i.e., either depositional, tectonic, or both); and (3) depocenter distribution and timing around salt bodies (or their welded remnants). Application of modern salt tectonics concepts will be fundamental to unraveling the geometry and kinematics of salt-influenced fold-and-thrust belts, evaluating basin histories, and reducing geological uncertainty.

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