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

Pablo Granado1, Eduard Roca1, Philipp Strauss2, Klaus Pelz2, and Josep Anton Muñoz1

1Institut de Recerca Geomodels, Departament de Dinàmica de la Terra i de l'Oceà, Universitat de Barcelona, Martí i Franquès s/n, 08028 Barcelona, Spain
2OMV Exploration and Production GmbH, Trabrennstrasse 6-8, 1020 Vienna, Austria

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 megafolds 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 Repository1 for details). The Northern Calcareous Alps have been divided into three large nappe systems (i.e., Bajuvaricum, Tirolicum, and Juuvikum 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 Wagreich, 1994); the latter commonly overlies Permian–Triassic evaporites as well.

The formation of the Neo-Tethys margin started with the Permain 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

1GSA 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.

CITATION: Granado, P., et al., 2018, Structural styles in fold-and-thrust belts involving early salt structures: The Northern Calcareous Alps (Austria): Geology, v. 47, p. 51–54, https://doi.org/10.1130/G45281.1.
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 contractual deformation that propagated northwestward (e.g., Faupl and Wagreich, 1994; Vöon Eynatten and Gaupp, 1999; Neu-52	Königsberg; G—Gamsstein. Compare to Figure 2 to note amount of northern Calcareous Alps at studied area. Geological map is modified from 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 Cre-caceous 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; Figs. 4D–4G) in Carnian–Norian times. The absence of thickening growth wedges and the separation of the pre-halokinetiic unit revealed in our restoration (Fig. 4) indicate that these minibasins most likely formed by downbuilding and
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 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.

ACKNOWLEDGMENTS

This is a contribution of the Institut de Recerca Geomodels (Universitat de Barcelona, Spain). Funding from 2014SGR467SGR and SALCONBELT (CGL2017–85532-P Ministry of Economy and Competitiveness [MINECO]) and European Regional Development Fund [FEDER], European Union) are acknowledged. OMV Exploration and Production GmbH is thanked for financial support and permission to publish. Reviews by Bruno Vendeville and Rod Graham are greatly acknowledged, and we thank editor James Schmitt for manuscript management. Wolfgang Thöny and Michael König (OMV) are thanked for discussions. Midland Valley provided Move’s software academic license.

REFERENCES CITED

Boyer, S.R., and Elliot, D., 1982, Thrust systems: American Association of Petroleum Geologists Bulletin, v. 66, p. 1196–1230.

Bryda, G., van Husen, D., Kreuss, O., Koukal, V., Moser, M., Pavlik, W., Schönlaub, H.P., and Wagneich, M., 2013, Geologische Karte der Republik Österreich: Erläuterungen zu Blatt 101 Eisenzer: Vienna, Austria, Geological Survey of Austria (GBA), 1 sheet, scale 1:50,000.

Callot, J.P., Trocmé, V., Letouzey, J., Albouy, E., Jahaní, S., and Sherkati, S., 2012, Pre-existing salt structures and the folding of the Zagros Mountains, in Alsop, G.L., et al., eds., Salt Tectonics, Sediments and Prospectivity: Geological Society of London Special Publication 363, p. 545–561, https://doi.org/10.1144/SP363.29.

Channell, J.E.T., Brandner, R., Spieler, A., and Stoner, J.S., 1992, Paleomagnetism and paleogeography of the Northern Calcareous Alps (Austria): Tectonophysics, v. 11, p. 792–810, https://doi.org/10.1016/0040-1951(92)90183-9.

Dahlstrom, C.D.A., 1969, Balanced cross-sections: Canadian Journal of Earth Sciences, v. 6, p. 743–757, https://doi.org/10.1139/e69-069.

Davis, D., Suppe, J., and Dahlen, F.A., 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153–1172, https://doi.org/10.1029/JB088iB02p01153.

Davies, D.M., and Engelder, T., 1985, The role of salt in fold-and-thrust belts: Tectonophysics, v. 119, p. 67–88, https://doi.org/10.1016/0040-1951(85)90033-2.

Faupl, P., and Wargreich, M., 1994, Late Jurassic to Eocene palaeogeography and geodynamic evolution of the eastern Alps: Mitteilungen der Österrei- chischen Geologischen Gesellschaft, v. 92, p. 79–94.

Frisch, W., and Gwolick, H.I., 2003, The nappe structure of the central Northern Calcareous Alps and its disintegration during Miocene tectonic extrusion—A contribution to understanding the orogenetic evolution of the eastern Alps: International Journal of Earth Sciences [Geologische Rundschau], v. 92, p. 712–727, https://doi.org/10.1007/s00051-003-0357-4.

Graham, R., Jackson, M.P.A., Pilcher, R., and Kilsdonk, B., 2012, Allochthonous salt in the sub-Alpine fold-thrust belt of Haute Provence, France, in Alsop, G.L., et al., eds., Salt Tectonics, Sediments and Prospectivity: Geological Society of London Special Publication 363, p. 595–615, https://doi.org/10.1144/SP363.30.

Haas, J., Kovács, S., Krystyn, L., and Lein, R., 1995, Significance of Late Permian–Triassic facies zones in terrane reconstructions in the Alpine–North Pannonian domain: Tectonophysics, v. 242, p. 19–40, https://doi.org/10.1016/S0040-1951(94)00157-5.

Hayward, A.B., and Graham, R.H., 1989, Some geometrical characteristics of inversion, in Cooper, M.A., and Williams, G.D., eds., Inversion Tectonics: Geological Society of London Special Publication 44, p. 201–219, https://doi.org/10.1144/GSL.SP.1989.044.01.03.

Jackson, M.P.A., and Harrison, J.C., 2006, An allochthonous salt canopy on Axel Heiberg Island, Sverdrup Basin, Arctic Canada: Geology, v. 34, p. 1045–1048, https://doi.org/10.1130/G22798A.1.

Jamison, W., 1987, Geometric analysis of fold development in overthrust terranes: Journal of Structural Geology, v. 9, p. 207–219, https://doi.org/10.1016/0191-8141(87)90226-5.

Kozur, H., 1991, The evolution of the Mélita-Hallstatt ocean and its significance for the early evolution of the eastern Alps and Western Carpathians: Palaeo- geography, Palaeoclimatology, Palaeoecology, v. 87, p. 109–135, https://doi.org/10.1006/jpsd.1991.9032-B.

Leitner, C., Weismair, S., Köster, M.H., Gilly, H.A., Finger, F., and Neubauer, F., 2017, Alpine halite-mudstone-polyhalite tectonites: Sedimentology and early diagenesis of evaporites in an ancient rift setting (Haselgebirge Formation, eastern Alps): Geological Society of America Bulletin, v. 129, p. 1537–1553, https://doi.org/10.1130/B31747.1.

Linzer, H.G., Moser, F., Nemes, F., Ratschbacher, L., and Sperner, B., 1997, Build-up and dismemberment of the eastern Northern Calcareous Alps: Tectonophysics, v. 272, p. 97–124, https://doi.org/10.1016/S0040-1951(96)00254-5.

Mandl, G.W., 2000, The Alpine sector of the Tethyan shelf—Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps: Mitteilungen der Österreichischen Geologischen Gesellschaft, v. 92, p. 61–77.

Neubauer, R., Genser, J., and Handler, R., 2000, The eastern Alps: Results of a two-stage collision process: Mitteilungen der Österreichischen Geologischen Gesellschaft, v. 92, p. 117–134.

Pilcher, R.S., Kilsdonk, B., and Trude, J., 2011, Primary basins and their boundaries in the deep-water northern Gulf of Mexico: Origin, trap types, and petroleum system implications: American Association of Petroleum Geologists Bulletin, v. 95, p. 219–240, https://doi.org/10.1016/j.mrpetgeo.2006.08.003.

Rowan, M.G., and Vendeville, B.C., 2006, Foldbelts with early salt withdrawal and diapirism: Physical model and examples from the northern Gulf of Mexico and the Flinders Ranges, Australia: Marine and Petroleum Geology, v. 23, p. 871–891, https://doi.org/10.1016/j.marpetgeo.2006.08.003.

Schnabel, W., Fuchs, G., Matura, A., Bryda, G., Egger, J., Krenmayer, H.G., Mandl, G., Nowotny, A., Rotzel, R., and Scharbert, S., 2002, Geologische Karte von Niederösterreich, 3B1: Vienna, Geological Survey of Austria (GBA), 2 sheets, scale 1:200,000.

Spötter, C., 1989, The Alpine Haselgebirge Formation, Northern Calcareous Alps (Austria): Permo-Scythian evaporites in an alpine thrust system: Sedimentary Geology, v. 65, p. 113–125, https://doi.org/10.1016/0037-0738(89)90009-9.

Stewart, W.A., 1977, Salt curtain in the North Sea Basin: A structural template for seismic interpreters, in Ries, A.C., et al., eds., Deformation of the Continental Crust: The Legacy of Mike Coward: Geological Society of London Special Publication 272, p. 361–396, https://doi.org/10.1144/GSL.SP.2007.272.01.19.

Stüwe, K., and Schuster, R., 2010, Initiation of subduction in the Alps: Continent or ocean?: Geology, v. 38, p. 175–178, https://doi.org/10.1130/G30528.1.

Tollmann, A., 1987, Late Jurassic/Neocomian gravitational tectonics in the Northern Calcareous Alps in Austria, in Flügel, H.W., and Faupl, R., eds., Geody- namics of the Eastern Alps: Vienna, Austria, Deuticke, p. 112–125.

Von Eyнатen, H., and Gaupp, R., 1999, Provenance of Cretaceous synorogenic sandstones in the eastern Alps: Constraints from framework petrography, heavy mineral analysis and mineral chemistry: Sedimentary Geology, v. 124, p. 81–111, https://doi.org/10.1016/S0037-0738(98)00122-5.

Wessely, G., 2006, Niederösterreich—Geologie der Österreichischen Bundesländer: Vienna, Austria, Verlag der Geologischen Bundesanstalt, 416 p.

Printed in USA