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THE NORTHERN CALCAREOUS ALPS: GEODYNAMICAL CONTEXT AND TECTONO-STRATIGRAPHIC FRAMEWORK

The Northern Calcareous Alps of Austria comprise Permian to Eocene rocks which became involved in the Eastern Alps tectonic wedge since the beginning of the Eo-Alpine shortening (e.g., Schmid et al., 2008). The Northern Calcareous Alps are dominated by thick non-metamorphic Triassic carbonates deposited on the northern shelf of the formerly south-facing margin of the Neo-Tethys Ocean. With the onset of N- to NW-directed convergence and closure of the Neo-Tethys Ocean, the former passive margin became an active fold-and-thrust belt since Middle-Late Jurassic times. Traditionally, the NCA have been divided in three major tectonic units, which from south to north are the Juvavikum nappes, the Tirolikum nappes and the Bajuvarikum nappes (Fig. 1B). To some extent, these nappes reflect the former configuration of the Triassic Neo-Tethys margin, showing a deepening trend into the oceanic basin from N to S. However, significant controversy still exists in regards of their paleogeographic distribution, as well as in the ages, sequence, and mechanisms of thrust staking (see Tollmann, 1987; Mandl, 2000; Frisch and Gawlick, 2003). It is generally accepted that the Juvavic nappes overthrust the Tirolic nappes by Late Jurassic times, and that both together overthrust the external Bajuvaric nappes since Early Cretaceous times, but the scarcity of synorogenic strata hampers the dating of events. In the studied area, only uppermost Permian to Paleocene units are present; these are briefly described in the following. For detailed descriptions, the reader can refer to Tollmann, (1976a,b; 1985), Faupl and Wagreich (1994), Von Eynatten and Gaupp (1999), Mandl (2000) and Gawlick, Frisch (2003) and Leitner et al., (2017).

Uppermost Permian and latest Triassic - rift to post-rift and evaporite sedimentation

Permian sedimentation was controlled by the break-up of Pangea and the subsequent opening of the Neo-Tethys Ocean. Massive red-colored alluvial fan deposits of the syn-rift Prebichl Fm. were unconformably deposited as fault-bound wedges on Variscan metamorphic basement. During the syn- to post-rift transition in Late Permian times, the Haselgebirge Fm. evaporites were deposited. These can consists of up to 70% of halite, but generally about 55%, with the remaining proportion of variegated claystones, gypsum and anhydrite. With the sedimentation of transgressive red-colored shallow-water sandstones occasionally interlayered with thin limestone beds (i.e., Werfen Fm.) in the latest Triassic, the post-rift phase of the Neo-Tethys begun. The Lower Triassic Reichenhall Fm. was deposited on top and consists of anhydrite, gypsum and carbonate breccias. The Haselgebirge-Werfen-Reichenall Fms. can be potentially considered all together a layered evaporitic sequence. As today, this sequence occurs as highly-strained clay-mantled gypsum/anhydrite bodies and rauhwacke (i.e., a distinct type of evaporite dissolution breccia constituting the weathered and leached remnants of what were once 'weak' salt-entraining layers (see Warren, 2006; p 486). Under stress, their evaporitic precursors act as rheological inhomogeneities providing décollement-prone surfaces during orogenic shortening. Halite, anhydrite and gypsum are the main constituents of these décollement layers.

Middle Triassic – onset of salt tectonics on the Neo-Tethys continental margin

By Middle Triassic times, ceasing clastic influx allowed the build-up of shallow marine ramp carbonates rimming the Neo-Tethys shelf. Thick isolated reefs (i.e., the Steinalm/Wetterstein Fms.) developed throughout the Anisian to early Carnian. The Wetterstein platforms accumulated significant amounts of carbonates (up to 1.75 km vertical thickness in the Gamsstein unit; Figs. 3, 4) in short periods of time (i.e., ca. 3 Myr.) during a well-established post-rift stage regionally dominated by thermal subsidence. Between those platforms, highly diverse basinal facies developed, from restricted shallow water environments (i.e., Gutenstein Fm.) to deep water basins showing slope and basin transitions (i.e., Reifling Fm. and Partnach Fm., respectively). During the middle Carnian, carbonate growth halted during an eustatic sea-level drop and a global phase of increased humidity. During this period, shale, sandstones and coal were deposited (i.e., Reingraben and Lunz Fms.) within the basinal areas between the thick carbonate platforms of the Bajuvarikum and Tirolikum nappes. Sea level rise during the upper Carnian resulted in renewed carbonate production and precipitation of anhydrite/gypsum (i.e., Opponitz Fm.). The Middle Triassic of the studied area within the Bajuvarikum nappes is characterized by strong changes in facies and thickness, shifting through space and time, indicating an anomalously large and strongly localized subsidence compared to the expected thermal subsidence rates for a passive margin. All these features indicate subsidence and sedimentation largely controlled by the evacuation, inflation and deflation of the uppermost Permian to lowermost Triassic salt.

Late Triassic - Penninic rifting and fall of Middle Triassic salt structures

In Late Triassic times, an extensive Norian to Rhaetian carbonate shelf developed. Locally, this shelf reached as much as 2500 m thickness; however, it also displayed sharp changes in both facies and thickness. During the Norian, reefs developed along the shelf rims, but most of it consisted on a regionally extensive carbonate platform. Carbonates on the southern parts of the shelf were deposited in sub-tidal environments (i.e., Dachsteinkalk Fm.), whereas on the northern part of the shelf, intra- to supratidal conditions dominated the sedimentation of a wide dolomitic lagoon (i.e., Hauptdolomite Fm.). In the Rhaetian, localized subsidence aside of the Middle and Late Triassic depocentres caused the sedimentation of the Kössen Fm., a very heterogeneous carbonate system including deep basin facies fringed by coral build-ups and tidal flats, and unconformably overlying the Norian strata and the salt. Subsidence concentrated on the inflated salt was most likely caused by the onset of regional extension associated with the opening of the Penninic Ocean to the north (e.g., Channel et al., 1992); as the inflated salt areas represented the weakest parts of the stratigraphic section, these reacted to regional extension by widening, leading to subsidence concentrated on the salt walls formed during Middle Triassic times, allowing the formation of a new array of minibasins (i.e., bowl minibasins) in between the Middle Triassic ones. Such process has been termed diapir fall (e.g., Vendeville and Jackson, 1992).

Jurassic – Penninic rift to drift and onset of Neo-Tethys closure

Whereas the Triassic was dominated by large carbonate factories, the Jurassic shelfs and basins hardly produced any platforms. Jurassic sediments were deposited on deep water starved basins (i.e., locally represented by bowl minibasins), including chert-bearing carbonates, layers of manganese oxide, hardgrounds and a local enrichment of ammonite and crinoid fauna. Only during the latest Jurassic, the carbonate reef production was re-established, with massive bodies of breccias and shallow water reefs indicating the onset of convergence and uplift related to the Neo-Tethys closure. While the central and northern part of the Northern Calcareous Alps shelf was affected by extension since the Rhaetian, the southern parts were already within an active N- to NW-directed fold-and-thrust belt. Evidence for this is found by the thrusting of the southernmost units over Middle Jurassic sediments (e.g., Gawlick et al., 1999).

Cretaceous Eo-Alpine and Gosau shortening phases

The Cretaceous period of the Eastern Alps is characterized by two mayor tectonic phases: the Eo-Alpine phase in Early Cretaceous and the Gosau phase in Late Cretaceous-Paleocene times (Schmid et al., 2008). The Eo-Alpine phase is the continuation of the Jurassic convergence and closure of the Neo-Tethys, with the Tirolikum and Bajuvarikum nappes involved in the shortening accompanied by synorogenic sedimentation. A foreland basin began in Jurassic times, and continued throughout the Early Cretaceous mostly sourced by southerly-derived synorogenic sediments. During Late Cretaceous times, a wedge-top basin developed in a large part of the Northern Calcareous Alps. The pre-Gosau erosional relief was diachronously transgressed from northwest to southeast by shallow marine, and then slope facies reflecting the gradual descent of the Alpine orogenic wedge towards a Penninic subduction trench (e.g, Faupl and Wagreich, 1994). Synorogenic deep sea fans were deposited on the Northern Calcareous Alps thrust wedge by the end of Eocene. The Northern Calcareous Alps were completely detached from their autochthonous crustal root and tectonically stacked onto the Penninic units.

Alpine shortening and late orogenic collapse

By the end of Eocene, the Adriatic and European continental lithospheres collided. Both, the salt-detached Northern Calcareous Alps fold-and-thrust belt and its synorogenic cover acquired an additional structural overprint during this stage (e.g., Wessely, 1992). During the Early Miocene, the fold-and-thrust belt was covered by an extensive wedge-top basin, while around Middle Miocene times, the European basement became involved in the Alpine shortening (e.g., Granado et al., 2016). Soon after, collapse of the hinterland parts of the Alpine tectonic wedge and related sedimentation took place during lateral extrusion and related strike-slip faulting (e.g., Ratschbacher et al., 1999; Strauss et al., 2001).

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