Reply to the comment of Schollnberger on '*Subsidence analysis of salt tectonics-driven carbonate minibasins' (Northern Calcareous Alps, Austria), published on* Basin Research 2020; 00: 1– 23 doi:10.1111/bre.12500

https://onlinelibrary.wiley.com/doi/abs/10.1111/bre.12577

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INTRODUCTION

We kindly take the opportunity to reply to the comments raised by Schöllnberger (2021) on our recent publication "Subsidence analysis of salt tectonics-driven carbonate minibasins (Northern Calcareous Alps, Austria)" by Strauss et al. (2020). We here provide a lengthier discussion in relation to the parameters applied to the subsidence modelling phase and the reason for having chosen those; we hope our reply serves to better illustrate the applied methodology, and allow peers to validate and modify it accordingly when applied to other natural case studies.

RATIONALE OF THE STUDY

The initial interest in the area arose to find a geologically reasonable way of explaining the observed (and already described in detail) stratigraphic record of the NCA Middle and Upper Triassic carbonate platforms. In particular, we found remarkable the systematic association between shifted carbonate depocenters (both in space and time) and the salt structures than can be inferred from the observed tectono-sedimentary relationships between the upper Permian-lower Triassic Haselgebirge evaporitic formation and its overburden, consisting of different Triassic formations (Granado et al. 2019). Since a simple and reasonable fault system kinematics, in agreement with modern understanding of passive margin evolution, cannot easily explain such lateral depocenters shifts and facies distribution by the accommodation space created by basement-involved faults, we decided to explore other mechanisms and to carry out a subsidence history analysis to better understand and further constrain the pre-orogenic tectono-sedimentary architecture of the NCA.

BUT, WHAT IS “SALT”?

There is one point we would like to stress up front in our reply: *what do we refer as salt?*. Rock salt is a crystalline aggregate of halite; however, since pure halite sequences are rare, in salt tectonics terms “salt” most commonly refers to any rock composed of halite plus other associated evaporitic and non-evaporitic rocks; there are numerous works that use this term as such (Rowan & Vendeville 2006; Rowan 2014; Teixell et al. 2017; Jackson et al. 2018, just for mentioning some). In fact, it may be more appropriate to use the term “layered evaporitic sequence”, which commonly include halite, other evaporites, plus different amounts of carbonates and siliciclastics. Since layered evaporite sequences are non-exclusively constituted by evaporites, the salt tectonics community tends to refer to those as “salt” for short.

We address this point here since the work by Schaunberger (1986) is mentioned in the comment raised by Schöllnberger (2021), where “*Das ostalpine Salinar, includes all evaporites appearing in the NCA between Innsbruck and Vienna, consisting of chloridic and sulphatic salts with all genetically related carbonate and pellitic sediments not younger than Lower Triassic in age*” (Schaunberger 1986, page 218). Hence the term salt – including all the varieties of evaporitic and non-evaporitic lithologies – was already applied for the whole upper Permian-lower Triassic layered evaporitic sequence of the NCA. We may have failed in reference his work, but it is common usage to refer to evaporitic formations as *salt*.

Following this point, Schöllnberger (2021) refers in his comment to the rheological and mechanical implications of such variegated lithologies comprising *Das ostalpine Salinar. We* adhere to his comment that a deeper understanding of flow and deformation behaviour of the mixed lithology Haselgebirge (e.g., Leitner et al. 2017) is necessary. Recent insight in this matter comes from works in the North Sea by Jackson et al 2018, showing that minibasin formation is clearly enhanced by thick, halite rich salt deposits; overall, they found that the evolution of the supra-salt stratigraphy could be a viable proxy for the original composition of the salt.

~~Our work describes one end member of a shelf evolution where the supra-salt depositional sequence was fully decoupled from the basement by thick salt, hence no normal faults linked to extension in the basement were involved in creating the observed differences of facies and thickness of the supra-salt carbonate stratigraphic sequence.~~

CRITICAL MODEL INPUT

Assessment of initial salt thickness

Other key point raised by Schöllnberger (2021) addresses how the initial salt thickness was modelled, and what "salt" thickness figures were chosen as input values to the 1D modelling. We want to clarify that the aim of our work was to investigate whether the rapid growth of carbonate platforms on the NCA rifted margin could have been achieved by salt evacuation and thermal subsidence only, with no significant participation of thick-skinned (basement involved) extension of the pre-salt crust. We run several model realizations aiming at matching the stratigraphic observations in the field. In this respect we clarify that the estimation of the original salt thickness was done to complete the stratigraphic record in order to allow the subsidence model to run, and not to investigate the original salt thickness. The salt thickness figure is, in fact, a result of the modelling carried out.

In more detail, the value of 1320m initial salt thickness we found in our study reflects a minimum thickness of salt necessary to model all observed sedimentary features in the three neighbouring minibasins. The value for salt thickness represents the best fitting result after several model runs. We therefore remark that the figures of initial salt thickness given by Strauss et al. (2020) is only directly applicable for the studied area.

In agreement with observations from other salt dominated margins, we argue there may have been areas on the NCA margin with more or less initial salt, depending on the pre-salt (i.e. basement) topography (e.g. Rouby et al 2003 or Quirk et al 2013); there may have been areas south of the Gamsstein area in distal sectors of the shelf with even larger initial salt thicknesses. Differences in the original depositional salt thickness may have resulted from inherited basement topography following thick-

skinned extension and (Jackson et al. 2018), and the diachroneity of crustal thinning across the rifted margin in respect to salt deposition (Rowan, 2014). In fact, salt may have also thickened basinwards as a result of gravity drainage during the thermal subsidence.
In terms of rheology and mechanical properties we fully agree with the comment raised by Schöllnberger (2021) that more understanding of flow and deformation behaviour of the mixed lithology Haselgebirge (e.g., Leitner et al. 2017) is necessary. Such was well beyond the scope of the original contribution, but it is already being considered for future works. In this sense, new insights on such matters has been raised from recent work in the North Sea by Jackson et al (2018), where minibasin formation is known to have been clearly enhanced by evacuation of thick, halite-rich salt deposits. Overall, those authors found that the evolution of the supra-salt stratigraphy could be in fact a proxy for the original composition of the salt. We assume similar conditions as for the growth of the minibasins in the NCA as described by Jackson et al 2018 in the North Sea and further insight to the salt composition in the NCA could be gained by adapting their analysis from the North Sea to the NCA.

~~Regarding the mechanical properties for the Haselgebirge, numerical and physical modelling of mixed compositions for the layered evaporitic sequence would be the next necessary step. From such modelling we would not only gain the boundary conditions for minibasin growth, but we would also gain a better understanding of the productivity carbonate platform producing organisms. This would be a major step forward in understanding carbonate platform growth, since by now we are only able to give average sedimentation rates for carbonates in general. But work by Schlager 1981 suggests that carbonate production might have happened at way faster rates than the 1.2 mm/yr in average sedimentation rate we found in our study when compared to present day examples.~~

The assessment of the salt thickness was carried out in several steps prior to modelling by collecting observations on the depositional and subsidence history of the 3 described minibasins (i.e. Gamsstein, Königsberg and Oisberg). These are commented on the following sections. ~~The salt thickness as such as well all ultimately~~

~~available sedimentation space is in the end defined by the basement subsidence of which an estimate was an outcome of the study as well.~~

Boundary conditions for modelling

We started our modelling by evaluating the stratigraphic record in the field and comparing it to that reported by previous studies in terms of sedimentary thickness, and associated water depth from sedimentary facies (Fig. 1a & b), besides the time constraints given by the palaeontological record (e.g. Lein et al. 2012; Moser & Tanzberger, 2015). In this sense, we again point out the unique high-quality chronostratigraphic control present in the study area, which makes it a great case study for subsidence history analysis. These data provided a stratigraphic framework and boundary conditions for the subsidence modelling and constitute the key input parameters in any subsidence analysis.

For the minibasins presented in our study those values were obtained from published geological maps and works (Ruttner & Schnabel 1988; Schnabel et al. 2002) and complemented and further constrained by our own geological mapping and cross-section construction (Granado et al. 2019). Comparing the depositional history of the minibasins made obvious that the major differences in sedimentation happened in Carnian times, in terms of rates and sedimentary composition. Water depth constraints are strong since most of the stratigraphic record consists of shallow- to very shallow water carbonates. Weakest constrained boundary conditions are at the end of the Ladinian (as represented by the Partnach Fm.), where water depth could be in the range of 200-500m (see Figure 1 a & b, Table 1 and Strauss et al 2020). It is important to note that the upper Carnian Opponitz Fm. in the Oisberg minibasin was deposited in shallow water to even intertidal conditions, so the underlying depocentre of middle Carnian Lunz Fm. had to be filled in completely by that time, and salt evacuation was taking place to accumulate the stratigraphic thicknesses.

At this point, we consider worth commenting that all stratigraphic thicknesses are field observations, meaning that from a modelling point of view those are compacted thicknesses that have to be decompacted during modelling in PetroMod®.

SUBSIDENCE HISTORY

Middle Triassic

The Gutenstein Fm. developed in both analysed minibasins with a sedimentation rate of 0,03 to 0,05 mm/yr. Minibasin development was not observed for the Gutenstein Fm. nor the Ladinian Fms in the studied area; hence we consider the subsidence rate to be similar or equal to the sedimentation rate. Such subsidence trend continued to result in water-depths of some 200 or even 500m by the end of the Ladinian.

Carnian

The condensed yet complete stratigraphy of the middle and upper Carnian in the Gamsstein minibasin suggests the end, or at least a significant slowdown in downbuilding for Wetterstein platform growth. Such slowdown had to happen, shortly before middle Carnian since only 50 m Lunz Fm. and 80 m Opponitz Fm. were deposited afterwards in middle and upper Carnian times (compare to the ca. 600m of Lunz Fm. and 700m of Opponitz Fm. in the adjacent Oisberg minibasin). In the Oisberg minibasin downbuilding started later than in the Gamsstein minibasin and this can in fact mask the basement subsidence in that position (compare Fig 9 in Strauss et al 2000).

Norian

Another important observation is that nearly 500m less of Hauptdolomit Fm. were deposited in the Gamsstein minibasin compared to the Oisberg minibasin (Granado et al. 2019; Strauss et all. 2020). This results incontrasting (averaged) sedimentation rates of 0,047 mm/yr for the Gamsstein minibasin and 0,075 mm/yr for the Oisberg minibasin in the same time interval (compare Fig 9 in Strauss et al 2000).

DISCUSSION

The initial modelling input values for original salt thickness in the studied area results from the observations listed above based on geologically reasonable assumptions. The original salt thickness was estimated by careful subsidence history analysis and basin modelling using data from maps, stratigraphic sections, balanced cross-section construction and sequential restoration. All these observations were linked together in relatively simple terms: subtracting the paleo-water depth before subsidence related to salt evacuation from the final stratigraphic thickness would provide a reasonable estimate for salt thickness values as input for the modelling (see Table 1).

~~due to extension and thinning of the sub-salt stratigraphy but due to the complete detachment of the supra-salt stratigraphy from its base there is no assessment based on field evidence possible.~~

Stage	Formation	Ois Thickness	Gs thickness	downbuilding Ois thickness	downbuilding Gs thickness	Upper Ladinian water depth	Salt thickness estimeates: downbuilding thickness minus Upper Ladinian waterdepth – Ois	Gs
Nor	Hauptdolomit	1428	900	528		200	1498	1590
						250	1448	1540
U Karn	Opponitz	700	80	620 – 1698		300	1398	1490
						350	1348	1440
M Karn	Lunz	600	50	550		400	1298	1390
						450	1248	1340
UL Karn	Wetterstein	10	1800	→	1790	500	1198	1290

Table 1: primary estimate before the 1D modelling of salt thickness. Ois=Oisberg minibasin, Gs = Gamsstein minibasin, red=sediment thickness related to downbuilding, blue is sediment thickness related to thermal subsidence. Values for upper Ladinian waterdepth are subtracted from downbuilding thickness in Oisberg and Gamsstein minibasins, yielding possible salt thicknesses between 1198m and 1590m. Ois: Oisberg minibasin; Gs:Gamsstein minibasin.

Following this working hypothesis, the estimated thicknesses for initial salt have a range between 1590m and 1198m (Table 1 and Fig. 1c and 1b) with a mean value at 1394m in respect to water depths from 200m to 500m prior salt inflation and sediment infill (Table 1 and Figure 1c and 1d). This analysis shows that in general, the deeper the Ladinian basin had been, the lesser salt thickness would have been needed to form the Oisberg and Gamsstein minibasins. The best fit to the stratigraphic record was found with 1320m in 1D modelling after several modelling runs.

Strauss et al. (2020) display the depositional history plot of one of many modelling solutions created in PetroMod® illustrating the stratigraphic record before compaction. Since the Haselgebirge Fm. has a mixed lithology (i.e. halite, gypsum, anhydrite, clay, etc.) and the Werfen Fm. is locally developed in a shaly to silty and carbonate facies, this will reflect in the uncompacted thickness. Choosing a high initial salt thickness estimate of 1590m leads to an uncompacted thickness of 1800m which is displayed in

Figure 6 of the original paper. We take the chance here to clarify that the thickness figures portrayed by Figure 6 from Strauss et al. (2020) are uncompacted thicknesses.

Importantly, based on the values obtained for salt thickness, it is possible to obtain a model-derived estimate of basement subsidence (note that each different salt thickness used in modeling would result in a different amount of basement subsidence, since it is directly dependent on the overall stratigraphic column!). Due to the incompleteness of the geological record as to the pre-salt units in the NCA (eroded sections in the orogenic hinterlands), all these were combined into one basement unit to provide a “base” to the salt allowing the modelling software to calculate the basement subsidence.

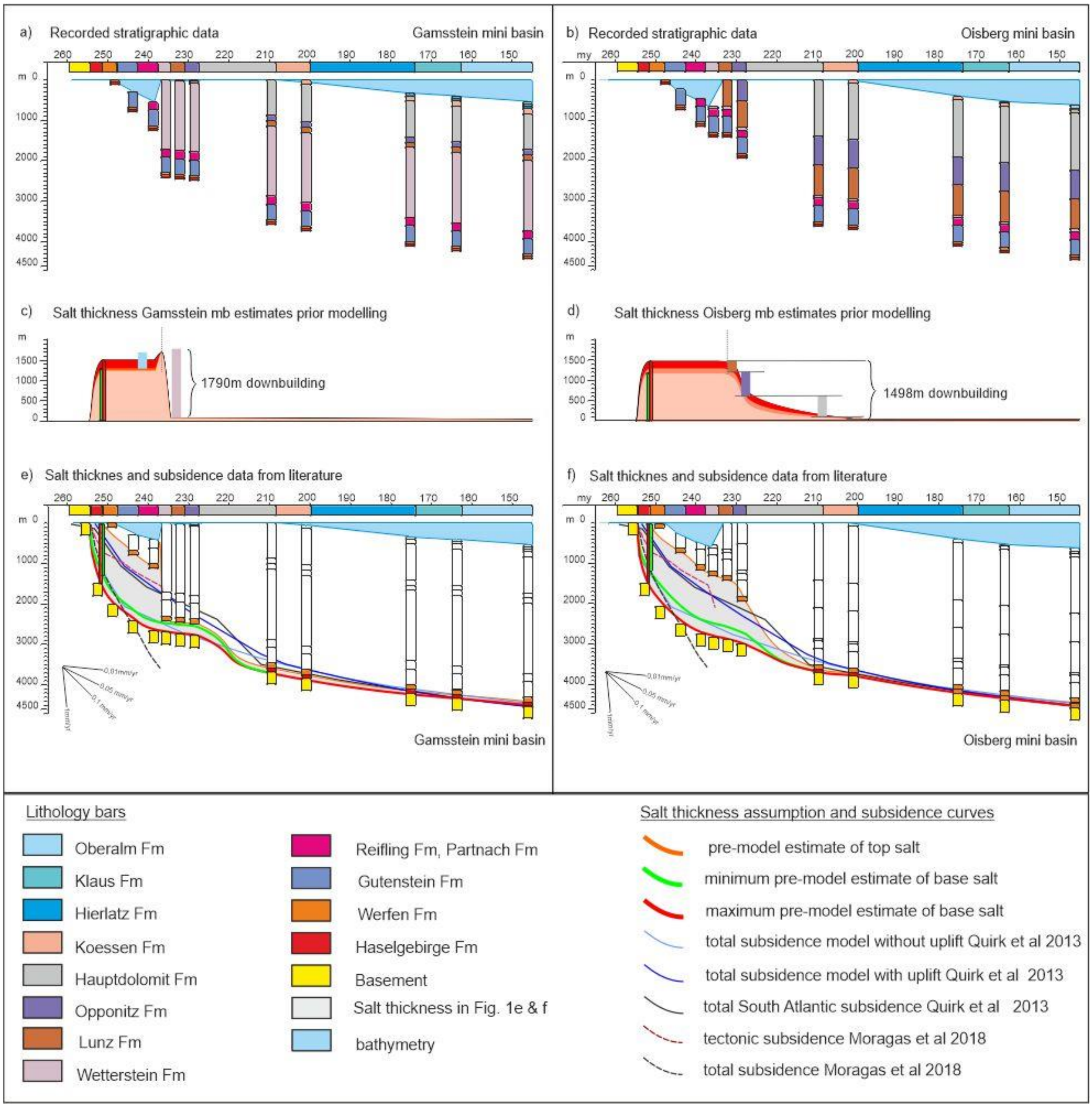

Figure 1: Relationship of recorded stratigraphic data and resulting thicknesses of salt. a & b): stratigraphic record of Oisberg and Gamsstein minibasins. c & d): display of the salt thicknesses necessary for the downbuilding phase. e & f): comparison of the salt thickness with subsidence curves from Quirk et al (2013) and Moragas et al (2018) to evaluate the position of the basement based on the assumed salt thickness.

The slope of the basement subsidence curve resulting from our modelling (see Strauss et al. 2020), represents the cooling history of the lithosphere, and also defines the ultimately available space for sedimentation, especially the salt.

~~Since there is hardly any record of the sub-salt stratigraphy of the NCA at all to constrain the modelled basement subsidence, we can only cross-check its plausibility by comparing the base of the salt (i.e. top of basement) to documented syn-rift histories in the literature (the comparison is done in Figure 1e&f with subsidence curves from Fig. 8b Moragas et al 2018 and Fig. 11a Quirk et al 2013).~~

By doing so we found that the basement subsidence models presented by Moragas et al (2018) and Quirk et al (2013) for an aborted rift system, and a fully developed passive margin, respectively, lie within the range of our pre-model estimates of the salt thickness? (see Fig 1e & f).

Our approach creates no circular argument whatsoever since we do not aim to proof a certain thickness of salt nor we restore stratigraphic sections higher up in the stratigraphy based on a randomly selected salt thickness. Neither we aim to proof certain stratigraphic evolutions in the NCA elsewhere based on the derived basement subsidence curve. Instead, we define a certain salt thickness range necessary to explain the Middle and Upper Triassic stratigraphic record in terms of thickness, facies (water depth evolution) and age. To summarise, the original salt thickness proposed in our study is the result of the best fit of 1D modelling with the stratigraphic record in the studied sections. However, we consider the contribution of Straus et al. (2020) as leading the way to future works in the NCA, in other salt-influenced rift to passive margins as well those fold-and-thrust belts developed from them.

THE WETTERSTEIN PLATFORMS: A PARADOX NO MORE

The seminal work by Schlager and Schöllenberger (1974) caught our attention since it displays the apparent paradoxical situation with carbonate platforms in the bathymetric lows and thick growing basins on highs. It was not the aim to negatively criticise their original paper, but rather the ideas that arose over the years from later interpretations of it. In fact, we see the work of Schlager & Schöllnberger (1974) as of great inspiration since the concepts on lithospheric stretching were still developing at that time.

In their original paper Schlager & Schöllenberger (1974) did not specify the basement or the syn-rift stratigraphy below the carbonate depositional sequences on the shelf, most likely because these are barely preserved today due to erosion in the hinterland and besides, the large Alpine displacement of the whole NCA along the evaporite detachment makes frankly difficult to relate the subsidence history of the Triassic carbonates with the structures responsible for the crustal thinning during rifting. However, as indicated by Strauss et al. (2020), regional geological and temporal constraints (i.e. deep water radiolarites of early Ladian age) portray the development of the large Wetterstein platforms well into the thermal subsidence phase of the margin. Based on this, and supported by the subsidence modelling presented, and clarifications herein, the Gamsstein platform growth was strongly assisted by the evacuation of the Permian-Triassic salt under thermal subsidence.

Although probably unintended by the authors, over the decades the common interpretation manifested that the appearance of the thick platforms in the basinal position and the actual basin sediments on the hanging-wall displayed in Fig 1b in Schlager & Schöllnberger 1974 were the result of basement involved extensional faults. For that same reason, we understand that the role salt may have had on the carbonate platform development was ignored as well, or not assessed in detail. Applying modern salt tectonics concepts to the NCA led to a fundamentally new and different understanding of the carbonate stratigraphic sequence deposited on the northern margin of the Neo-Tethys as well as the complex structural styles that today define the NCA fold-and-thrust belt.

Acknowledgements

This work is a contribution of the Institut de Recerca Geomodels (Universitat de Barcelona) supported by the project ‘Tectónica Salina en Cinturones Contractivos' (SALTCONBELT-CGL2017-85532-P), funded by Agencia Estatal de Investigación (AEI) and Fondo Europeo de Desarrollo Regional (FEDER) and by OMV Exploration and Production GmbH. Editor Craig Magee is thanked for careful manuscript handling.

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