se-2021-153 Review

Reconstructing 3D subsurface salt flow

Stefan Back et al

To the authors:

This is a good piece of work, well worthy of publication. The manuscript as submitted is OK but there are several things that in my opinion need to be improved by way of clarity and by way of content.

My first impression on reading this is that it appears to be an important body of work, but it is very hard to see what is actually going on geologically. The bulk of the explanation is in the form of words of text, plus maps showing salt thicknesses.

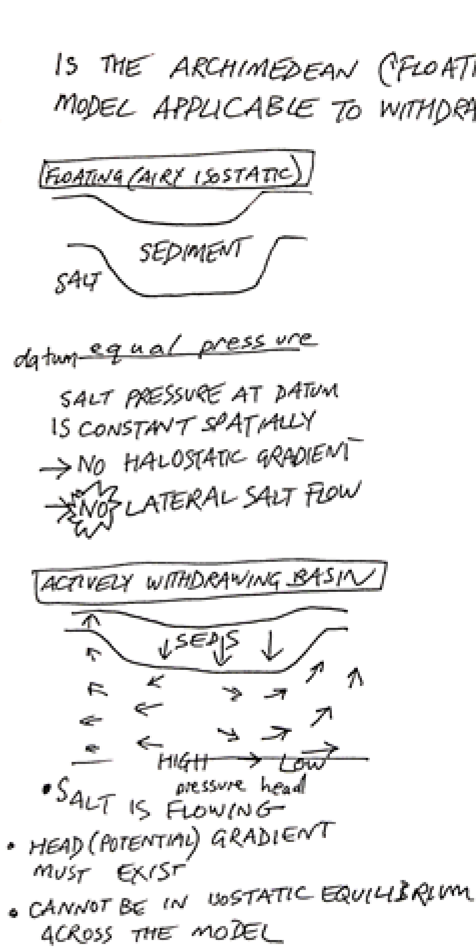
The impact of the manuscript as it stands is critically limited by a reliance on maps alone to show the restorations, and on words alone to explain the processes. I really struggled to understand either the restoration process or the geological results when presented in this way; I believe that the addition of cross sections would help enormously.

The figures in the form of cross sections should be of two types :

(i) Schematic sections that illustrate the principles – how the restoration process worked, the nature of salt flow, etc.;
(ii) Selected geological sections through the 3D restoration that illustrate both the sequential evolution of the structure and thickness of salt and the inferred flow of salt through time.

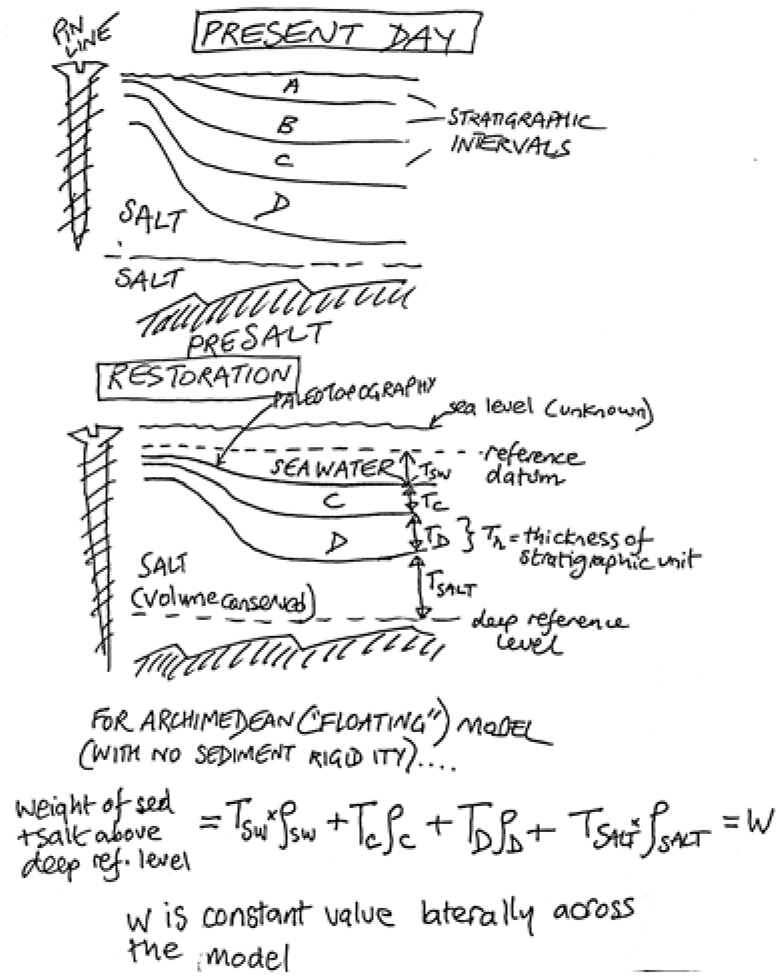
I have included some rough sketches that are all in the form of sections, please excuse the poor quality of these (drawn by hand on an airplane). I hope that these are clear in intent.

My first major point is that the method assumes that the basins are in Archimedean equilibrium (floating) – this is a static equilibrium. However, all actively subsiding withdrawal basins are to some degree out-of-equilibrium, and all actively subsiding basins sit higher than a static floating basin would. This is because the salt has non-zero viscosity. The authors state that a viscous fluid cannot support a shear stress; this is not entirely correct. Importantly, it only applies to a non-deforming viscous fluid. A fluid that is undergoing shear strain does support a shear stress that is proportional to the viscosity and the shear strain rate. The surfaces of the cargo carrier in your Figure 1a will experience significant shear stress (water resistance) as soon as the ship starts to move.

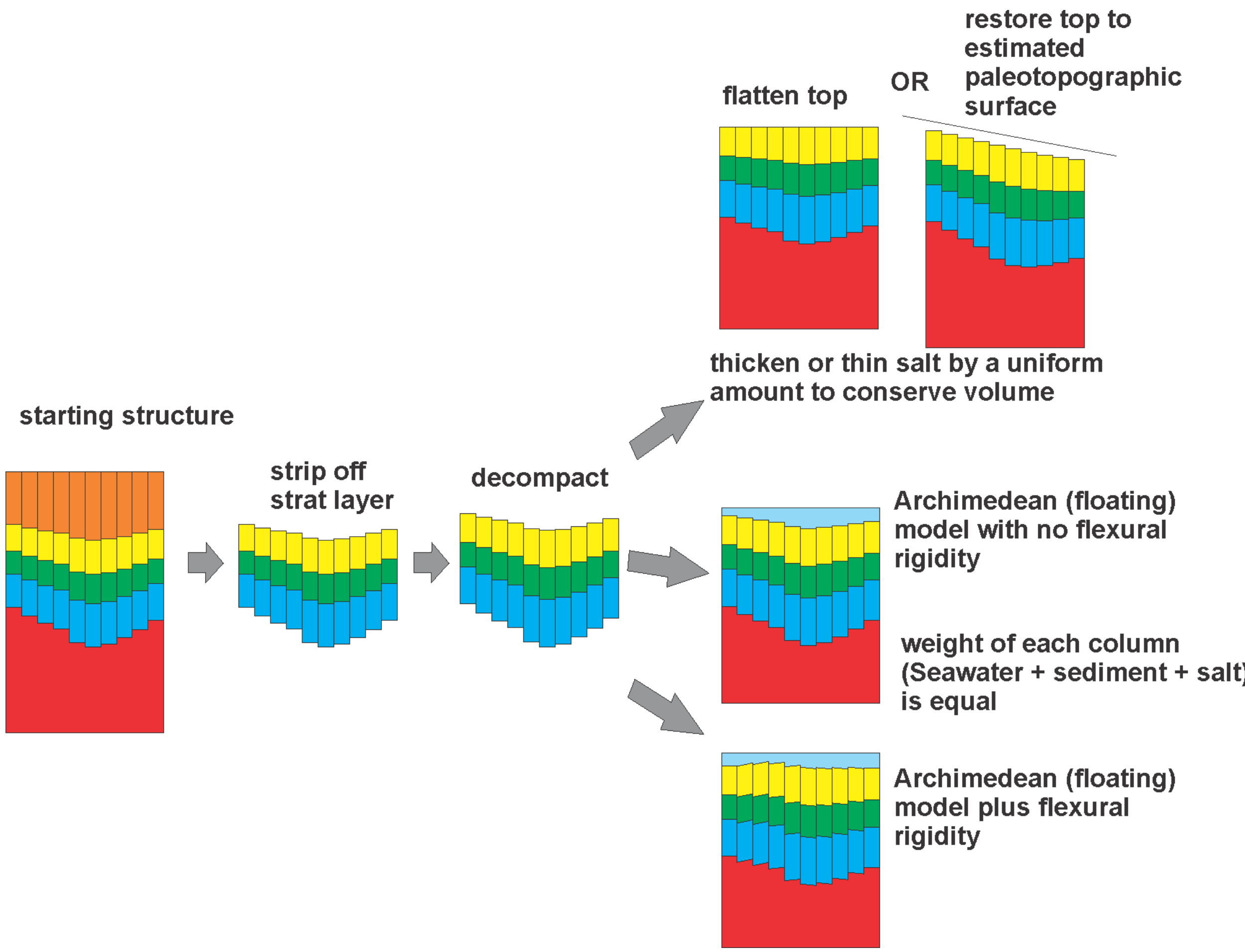


The manuscript needs to recognize and discuss this. You should explain what difference it would make, and discuss why it might be a reasonable approximation to use a static Archimedean (floating) model – I would suggest that the primary justification might be that lateral salt flow is very slow in this region, particularly when compared to withdrawal basin systems such as seen in the Gulf of Mexico or Pricaspian, so the non-static stress supported by the salt is less of an issue. But this is for the authors to decide.

The explanation of the restoration method is inadequately described. This is another case where explanatory sketches would be a huge help. I had to guess what the process you use is, and here is my rough sketch.



It would also help to explain the difference between a standard vertical-shear reconstruction, and the Archimedean approach used here. Again, here is my rough sketch.



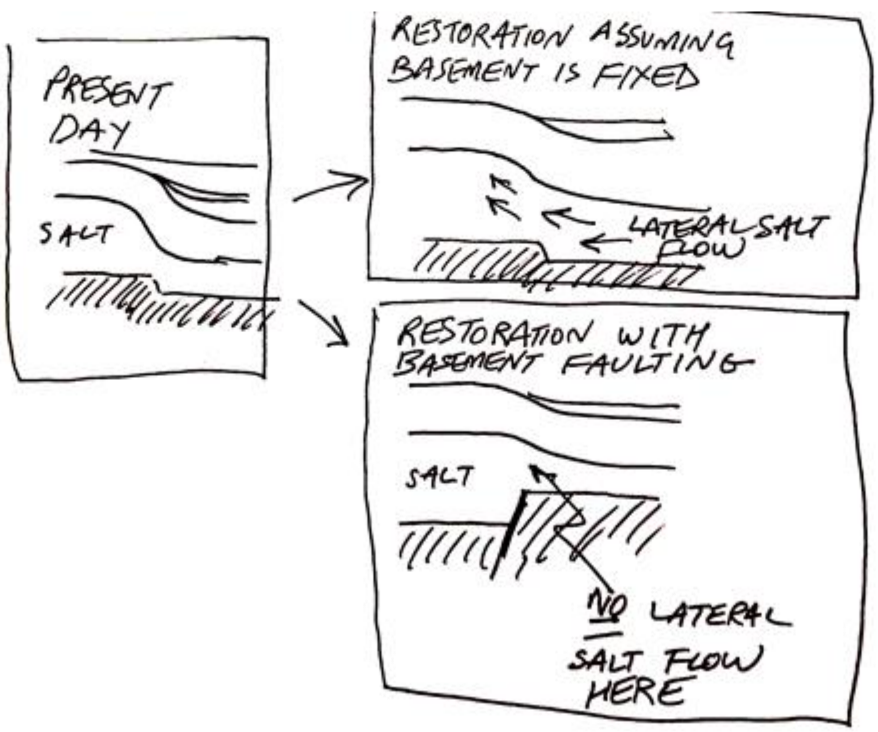
Because you do not explain what the process is, I had to guess: this is my best guess. In a standard vertical-shear restoration, the top surface is restored to either a flat horizontal surface, or to some estimated paleotopography. It sounds like, in your method, the top surface is defined by making each vertical column of sediment “float” on the salt, - and as a result there is a residual topography on the top surface of the restoration. This top-surface topography seems to be a necessary part of an Archimedean restoration. If there is not top-surface topography in the restoration, it is simply a flattening not an Archimedean restoration. While we can accept that you do not constrain the absolute elevation of the restored top surface, it would seem necessary that your model does give a prediction of relative topography of the restored top surface. This is an important point, and one that you need to make in the paper. I would like to see a discussion about the amount and shape of the top surface topography that appears in your restoration. If it turns out that after you do the full Archimedean restoration, the calculated restored top-surface topography appears to be near to horizontal, this is an important point to make, because it would be strong evidence that the method is valid.

Further, you need to state what you used for the density of the space above the top of the sediment pile in the restoration . Did you assume that it is seawater or air?

Please forgive me if I have misunderstood the nature of your restoration process. If I have misunderstood, it would show that the description provided in the manuscript is not clear or complete.

Another important point that is glossed over in the paper is that the restoration process for the suprasalt may be independent of any basement tectonics affecting the subsalt. It may also be independent of any imposed thin-skinned translation of the cover, as long as the cover is neither shortened nor thickened.

But your quantified analysis of inferred salt flow (which derives from your restoration) is NOT independent of subsalt deformation. The very rough sketch below illustrates this point.



In this sketch, a base-salt offset is created by an inverted rift fault. If the section is restored without also taking into account the movement of the basement (top panel) then a large volume of lateral salt flow would be required. Conversely, if the basement faulting is restored (bottom panel) then the amount of lateral salt flow may be minimal. This example is used because the effect of basement tectonics is clearest, but the same principle will apply to any movement of the basement that is not uniform upward/downwards motion – even a gentle regional tilting of the basement would change the apparent salt flow.

The presentation of results is entirely in the form of maps. These are OK as far as they go but they do not do justice to the work that has been done; they need to be supplemented with a set of good cross sections from the restoration that show the subsalt, salt and suprasalt layers, and which illustrate the sequential evolution of the section through time. This is standard practice for a very good reason; it is easy to see how the geology evolves in cross section, but if you only show maps of salt thickness, it does not give an understanding of how the salt thickness relates to the suprasalt geology. If a 3D restoration has been carried out, it should be a simple matter to extract the cross sections from this. The cross section lines should be chosen so as to illustrate the main results of the salt flow analysis, and the flow direction of the salt at each time should be shown on the sections. This will greatly increase the intelligibility and impact of the manuscript.

Page 3 lines 60 onwards – wrong use of Early – Mid – Late (chronostrat terminology) vs. Lower – Middle – Upper (lithostrat terminology) . Lower Cretaceous rock units, Early Cretaceous deposition.

Page 4 - this study treats the Zechstein as one evaporite unit behaving as a fluid . How reasonable an approximation is this, given that the Zechstein consists of a layered sequence which includes thick, competent non-evaporite units? Discuss and justify.

P4 lines 75-80 need to state whether 3D data sets are in TWT or in depth

P5 figure. Vertical axis is NOT depth. Relabel as TWT (mS). Note capital S in mS.

P6 line 90 evaporite not evaporate

P6 explain density/depth model better. What does "density" in Table 1 mean – is it density of material at surface (i.e. with initial porosity), or density when porosity is reduced to zero? What density do you assume for the pore-filling fluid? (we assume that you do include the weight of the pore fluid in the weight calculation but this is not specified).

P 11. You need to be clearer about what salt gain or loss mean. My interpretation of what I think you mean is that it is only the local gain or loss, representing the lateral flow of salt within the model. If I am reading this correctly, you should state that salt loss = local salt withdrawal and lateral expulsion; salt gain = region of local salt inflation by lateral influx.

P12

lines 160 onwards – unclear wording, especially line 162. Replace "top salt" with "suprasalt".

P13.

Line 165 v unclear, rephrase.

Lines 166- 170 unclear.

line 169-70 – this is the first mention of allochthonous salt. If allochthonous salt sheets are present, the whole reconstruction model would be invalid. Also, do you reallly mean allochthonous salt? I am not aware of significant allochthonous salt bodies being present in this region.

Line 180 – this refers to the movement of salt above reactivated subsalt faults. But as discussed above, if there is significant movement of any fault below the base salt, this would invalidate the reconstruction logic.

P14

Line 191 – we don't need to know about Archimedes

Line 207 – suggest delete the sentence "spatial evaporite…. "

P 15

Line 235 there is not a “lack” of Zechstein. Suggest replace “lack” with “volume deficit” or something similar

P16

Lines 243-245 these three clauses do not describe different geometries, they are essentially the same thing. Salt canopies ARE allochthonous salt sheets and big sheets may be called nappes.