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Interactive comment on "Evolution of rheologically heterogeneous salt structures: a case study from the northeast of the Netherlands" *by* A. F. Raith et al.

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Response to the reviews on: "Evolution of rheologically heterogeneous salt structures: a case study from the northeast of the Netherlands"

(1) Comment (2) Answer (3) Changes

Referee #2

(1) R2:Line 16: rock salt: rock salt (taken here to consist mainly of halite (NaCl) (2) Since we are talking about mechanical properties of minerals, halite would fit better than rock salt. (3) Change "rock salt" to "polycrystalline halite"

(1) Line 28: bitterns to bittern brines (2) Ok (3) Change "bitterns" to "bittern brines"

(1) Figure 1 does not really show how the Groningen High fits into the North Sea- but fits the description. The first paragraph of Geological setting is wondrous. (2) The Groningen high is located onshore in the north east of the Netherlands near the (3) City of Groningen. Fig. 1 will be changed to point that out more clearly. - Change 1882-L5 "Groningen" to "city of Groningen" - Outline the "Groningen High" in the NL overview map (Figure 1)

(1) Fig. 3 top and bottom diagrams reversed relative to caption (2) Ok (3) Reversed the caption

(1) P. 1883, Line26. Two density stratified (?) OR with stale density stratification(?). (2) Coleweij 1978 postulates a deeper-water body in which concentration stratification is present: "In such a brine halite will precipitate from higher, less concentrated stratum, and carnallite with higher concentration/density from the lower one. Both minerals will precipitate simultaneously."

(1) Data and methods: a bit rough (2) Is something important missing or unclear? (3) P. 1884 L. 18 erase "Especially" P. 1884 L. 19 change "have been" to "were" P. 1884 L. 22 change "could be" to "were"

(1) P. 1884, line16, are publically available on the (2) That sounds better. (3) Change "the publicly available…" to "are publically available on the…" as suggested

(1) Figure 5. The seven scaling keys are too small to read in this version. EITHER replace all seven by a single much larger scaling key OR write about warm colours being thin and cold colours thick(?) in the caption. (2) The figure should to fill a full page but as remarked from the other reviewer it is still too small. A redesign will be done. (3) Split into two figures (Figures X and Y).

(1) Page 1886. Line20: change harmonic to in harmony with. (2) Ok (3) change "harmonic" to "in harmony with"

(1) Line 26 if this polygonal pattern is on the scale of each dome please say so. If it is smaller g Indicate approxmate scale or wavelength. (2) Here we are not addressing polygonal fault systems but polygonal fracture patterns as described by Abe et al. 2013 and Zulauf et al. 2009

(1) Page 1887. Lines 1+2, hard and soft to strong/stiff to weak? (2) Since this paragraph concerns the seismic response of the layered materials and not only the mechanical properties both options would fit. (3) change to "strong" and "weak"

(1) Page 1890, line 19. Add downslope and upslope movement where relevant? (2) On the regional scale the study area is at the edge of the Groningen High with a regional slope dipping towards SW. On the local scale of the study area, the base of the salt is crosscut by several faults forming a complex surface with several grabens and half grabens (see figure 1). The salt movement we postulate is not influenced by the slope in the basement structure and has downslope and upslope movement simultaneously.

(1) Figure 8: I cannot see labels a, b, or c. (2) They somehow got lost (3) Added to captions

(1) Page 1891: line 6 which don't show: without (2) Ok (3) "While the Jurassic is entirely missing (cf. Wong et al., 2007), the Lower Cretaceous interval is 50-140 m thick and does not thicken above the basins."

(1) Evolution of the internal structure of the salt= Improve English throughout e.g. (2) All suggestions will be changed. (3) P. 1892 L.11 change "Bischofite thickness up to 36m in the SAP wells that are located at the south-eastern flank of the Slochteren Pillow, are interpreted as local fold hinges or boudin-necks." To: "The up to 36 m thick bischofite in the SAP wells that are located at the south-eastern flank of the Slochteren Pillow, is interpreted as local fold hinge or boudin-neck."

P. 1892 L. 21 change "over" to "at" P. 1892 L. 23 change "pattern" to "patterns" P. 1892 L. 24 change "pillow" to "pillows" P. 1893 L. 1 erase second comma P. 1893 L. 14

change "s" to "is" P. 1893 L. 15 erase "side" P. 1893 L. 21 add a comma after "crest" P. 1893 L. 21 erase "a" before "radial" P. 1893 L. 21 change " salt high's center" to "center of the salt high" P. 1893 L. 24 change "acquired" to "created" P. 1893 L. 26 change "produce thinning and thickening of" to "lead to strong thickness variations in the"

(1) Page 1892: line 4. would have = had (2) Ok (3) Change "would have" to "had"

(1) Line 8: and to in or by? (2) There should stand an "in" (3) Change "and" to "in"

(1) Line 10: is not thinning= does not thin (2) Ok (3) Change "is not thinning" to "does not thin"

(1) Page 1893, lines 3-6: Separate into 2 sentences. (2) Ok (3) The presence of the broken stringer fragments at the start of pillow growth is interpreted to have made the internal deformation of the Veendam pillow more heterogeneous. This lead to the nucleation of smaller scale (few 100m) folds in the surrounding halite, which in turn formed saddle reef structures where the bischofite was thickened.

(1) lines 8-10: Separate into 2 sentences. (2) Ok (3) Later, the salt flowed from the subsiding basins also into the Veendam Pillow. The ZIII stringer was dragged with the salt, which locally led to compression structures like folds and thrusts.

(1) Figure 8 is good but could be improved (by more annotation?) Clarify that white spots indicate local deposition. (2) Ok (3) Figure 8 will be modified.

Referee #1 P1878

(1) L24 and 27 – Slight mixing of terms (e.g. K-Mg salts vs. carnallite-bischofite). Try to be consistent throughout the manuscript. (2) Since the internal deformation of the carnallite-bischofite layers in the K-Mg salts is not addressed in this paper, is better to stay with K-Mg salt here. (3) change "carnallite–bischofite layers" to "K-Mg salt"

P1879

(1) I loathe to recommend my own papers but in this case I think it's justified! You may

wish to read Jackson et al. (2014) – GEOLOGY and Jackson et al. (2015) – JSG and, if you find them relevant, cite them in the Introduction. These studies use 3D seismic reflection data from offshore Brazil, following-up on (and challenging) the earlier work of Fiduk and Rowan (2012). You may also want to cite Dooley et al. (2015) when you mention modelling studies of intrasalt structure, not to mention the earlier centrifuge work cited therein. (2) They are missing here and will be added. (3) Add Jackson et al. (2014), Jackson et al. (2015) and Dooley et al. (2015)

(1) L21-22 – Sentence is a little unclear. Please rephrase. (2) Ok (3) Compared to rock salt the effective viscosity of K- and Mg-salts is up to three orders of magnitude lower (Eekelen et al., 1981;Urai, 1983, 1985, 1987; Urai and Boland, 1985; Spiers et al., 1983; Langbein, 1987; Scott Duncan and Lajtai, 1993; Schenk and Urai, 2005; Urai et al., 2008), while anhydrite and carbonates have much higher viscosity than rock salt and thus form buckle folds during compression they brittle rheology also allows them to rupture in extension or compression (Müller et al., 1981).

(1) L24-25 – Sentence is a little 'wordy'. Please rephrase. (2) Ok (3) The interaction of layers with such high contrasts in viscosity and rheology during deformation must lead to the development of complex fold and boudin structures.

P1880

(1) L5 – Cite Jackson et al. (2014, 2015) here too? As well as Fiduk and Rowan (2012)? (2) Ok (3) Add Jackson et al. (2014) and Jackson et al. (2015)

(1) L11 – Cite Dooley et al. (2015) here too? (2) Ok (3) Add Dooley et al. (2015)

(1) L13-16 – Reference required for a statement like this. (2) The reference Poiate et al. described tachydrite in evaporites offshore Brazil. The reference should therefore be better placed at the end of the sentence. Now I looks like it just describes tachydrite. (3) Move Poiate et al., 2006 at the end of the sentence

(1) L20 – What do you mean by 'significant thickness'? (2) Economically significant

(more than just a few cm thick bischofite layer or low percentage in mixed evaporites) (3) Add "economically"

(1) L20-23 – References required for some of these example? Or are all these basins described in the Vysotskiy reference? (2) From Vysotskiy and Kislik, 1987: "Stratified bischofite rock is known at present in the salt bearing basins of Eurasia (Caspian and Kaidak basins in Kazakhstan, the Dneiper-Donets, Priyat and West European basins) and the pericratonic downwarps on the Atlantic side of the African platform(the Gabon and Congo basins). Deposits of bischofite rock may also occur in the salt-bearing basins of the Atlantic coast of Brazil." For Brazil this reference can be added: Cerqueira, R.M., Chaves, A.P.V., Pessoa, A.F.C., Monteiro, J.L.A., Pereira, J.C., and Wanderley, M.L., 1997, Jazidas de potassio de Taquari/Vassouras, Sergipe [Deposits of potassium, Taquari/Vassouras, Sergipe], in Schobbenhaus, C., Queiroz, E.T., and Silva Coelho, C.E., eds., Principais depositos minerais do Brasil, v. IV, Rochas e minerais industriais [Pricipal mineral deposits of Brazil, v. 4, Industrial rocks and minerals]: Brasilia, [Brazil] Departamento Nacional de Producao Mineral, p. 277-312. (3) Add Cerqueira et al. 1997

P1881

(1) L4-5 – Again, what do you mean by 'unusually thick'? Statement needs qualifying. (2) If bischofite forms layers these are usually just a few cm thick, while layers of several meters thickness are very rare. (3) Change to "meters thick"

L10-25 – Very interesting!

(1) L26 – Remove word 'then' (2) Ok (3) Remove word 'then'

P1882

(1) L20-21 – I come back to this later, but I cannot believe that contraction didn't play a role in the formation of the major salt pillows. (2) Here the phases are just summarized shortly. The initial development of many salt structures is before the regional

contraction in the Cretaceous. An influence of contraction during later development is likely. Nevertheless, we are lacking good indicators for regional contraction like inversion structures. So we adapt the existing models saying that an influence of contraction is possible but can be neglected, since all regional structures could be formed without any regional contraction.

P1883 (1) L1-5 – Fig. 2 is way too small and 'busy'; it is almost impossible to make a link between the stratigraphy and the seismic data. Furthermore, as I will come back to later, a proper synthetic seismogram is required to really convince people of the link between rocks and reflections. (2) It seem Fig. 2 has to be split into at least two figures. One showing at least 2-3 profiles and the structures in detail. The second figure should show the horizons in the salt in detail linked to a well log. The lack of a sonic log from the salt layers makes the creation of a synthetic seismogram rather difficult. Nevertheless, it is not necessary since the well-tops fit the horizons very well and the expected hard and soft-kicks for halite to K-Mg salt are obvious. (3) Redesign Fig 2+3

(1) L6 – I cannot locate the ZIIIAC stringer easily on Fig. 2. Also, you need to cite a figure to support the statements made in the paragraph L6-10. (2) this will be added in the Fig. 2 redesign

(1) L11-30 – It is very hard to follow this text using the somewhat cramped Fig. 2. This is not helped by the fact that the intra-Zechstein stratigraphic nomenclature is a total nightmare in terms of letters, numbers, roman numerals (2) Fig. 2 will be redesigned. (3) Change Z3 in the figure text to ZIII

(1) L11-30 – I am a little concerned that the intra-Zechstein proportions encountered in wells are used to derive an idea of how depositional conditions varied in the Late Permian. I guess my main concern is that post-depositional flow, as you argue for later in the manuscript, mixes up the original depositional distribution. I guess this isn't you work or, indeed, the specific aims of the present paper, but I thought I'd better mention

it. (2) The mixed mineralogy from co-precipitation clearly contrasts high strain mixture of different layers. Coelewij was surely able to see the difference between a highly strained material mix and a typical co-precipitation pattern.

P1884

(1) L4-6 – Comment here that the seismic-stratigraphic architecture of these units is used to constrain the evolution of the salt structures? (2) Here we are just describing the geological setting in the introduction. How we used the thickness of these layers to constrain the evolution of the salt structures is mentioned in the methods section.

(1) L13 – Use the term? Not sure it is formally defined, but a wise person once told me that a 'reflector' is a rock interface that generates the observed (and mapped) 'reflection'. (2) Here the reflections are offset, the reflectors are of course at the same place. (3) Replace "reflectors" with "reflections"

(1) 20 – What do you mean by "high resolution data"? (2) Log data of the ZIII subunits are interpreted in m-intervals (3) change "High resolution data" to " In meter intervals interpreted log data"

(1) L23 – Remove reference to specific software packages in the main body of text. You mention them in the Acknowledgements. (2) We usually mention the used software packages in the methods section, where someone interested would search for it.

(1) L15-30 – I think a synthetic seismogram is crucial in this study if you really want to link rocks to reflections and rheology to structural style. As it stands, I am very confused as to how each of the specific units you are describing (and mapping) are expressed in wells and in the seismic data. A well log, showing some wireline log data, would be very useful (and convincing). Furthermore, it would be nice to see the location of all these 136 wells on a map; this would really hammer home how robust your database is in terms of direct sampling of salt composition and thickness. (2) We best remove the number of 136 wells, for it gives the wrong idea. The wells are located in a few

local clusters (i.e., lots of production side tracks). The locations of these clusters are marked in figure 4. An interpreted well log will be added to the new figure 2. (3) change “Furthermore, a total of 136wells,” to “Furthermore, over 100 wells and side-tracks from 15 well locations,”

P1885

(1) L1-2 – Rephrase. You are mapping stratigraphic tops or horizons and not stratigraphic units. I’m being picky, but it makes no sense to say ‘stratigraphic units’ on L1 and then to list a series of ‘tops’ in the sentences that follow. Furthermore, some of the tops have age information (e.g. Top Upper Rot (Triassic)) whereas others do not (e.g. top Rupel Formation (North Sea Group)); i.e. what age is the top Rupel Formation? (2) That got mixed up, this are of course unit tops and not units. The North Sea Supergroup is of Tertiary to Quaternary age. The Rupel Formation is early Oligocene and therefore of Tertiary age. (3) Major stratigraphic horizons in the Zechstein’s overburden were interpreted to allow for a first-pass reconstruction of the study area’s salt tectonic evolution: (i) Top Buntsandstein (Triassic), (ii) Top Upper Röt (Triassic), (iii) Top Upper Marl Member (Cretaceous), (iv) Top Chalk (Cretaceous), (v) Top Mid Brussels Sand Member (Tertiary), and (vi) Top Rupel Formation (Tertiary). Additionally, one intermediate reflector in the Chalk was interpreted (Figs. 2 and 3)

(1) L7 – Not sure this sentence is needed. (2) The information that we used stratigraphic thickness is important. It might be better to include this information into the next sentence and delete the old one. (3) “Thickness maps of all units were produced using Petrel’s standard “stratigraphic thickness” algorithms. The thickness maps were used to identify local areas of increased sedimentation.” Is changed into: “Stratigrafic thickness maps were calculated to identify local areas of increased sediment deposition.”

(1) L7-9 – I would rephrase this sentence. Although the isopachs tell you about thickness and depocentre location, you don’t know if all depocentres are really like

Trusheim’s primary peripheral sinks, which have a very specific temporal connotation in terms of timing of formation relative to salt structure development. For example, some depocentres might be due to cover stretching-related graben formation above reactive diapirs; these depocentres are NOT primary peripheral sinks. (2) Trusheim was cited to describe the principal concept of sinking basins but doesn’t really fit here. We skip it, as we are not observing typical peripheral sinks after Trusheim. (3) New: “The thickness maps were used to identify local areas of increased sedimentation. These areas were therefore used to identify the amount of subsidence in the sedimentary basins, the timing of their development, and their variation in spatial extent and geometry, while thinning of sediments above salt highs is used to identify reduced or non-deposition, or even uplift and erosion due to active salt doming.”

(1) L9-11 – You don’t know this for sure; some relief may have developed during salt movement. Not all relief needs to have been levelled off’. (2) We agree.

(1) L20 – Label salt structures on Fig. 1. (2) that will help the reader. (3) Include pillow names.

(1) L24 – Maps too small and the layout is a little old (i.e. put the maps more clearly in age order?). In fact, the seismic profile is so small, I cannot make out the phases described in the text. This is a big problem, as the cover seismic-stratigraphy is critical to the model you later describe. This can be fixed though by making the figure larger and clearer. (2) The figure was meant to fill a A4 page but is still too small. The profile will be a single figure and vertically exaggerated.

(1) L25-26 – Sentence needs rephrasing; e.g. The Veendam Pillow strikes SW-NE and is 10 km long in the NE-SW direction and (2) Ok (3) The Veendam Pillow strikes SW-NE and is 10 km long in the NE-SW direction and 5km wide.

P1886

(1) L1-3 – Sentence a little unclear. Please rephrase. (2) Ok (3) The Slochteren Pillow

has a size of 10 km in E–W and 14 km in N–S direction, and a maximum Zechstein thickness of 1800m at the highest point of the pillow at 1000m depth below surface.

(1) L3-5 – It would be useful to see a depth map of a key overburden horizon at some point in the manuscript. Some of the fault geometries at that level are important to your story, but you do not convincingly provide primary data to illustrate their map-view geometry. (2) A depth map of the Cretaceous with annotations will be added.

(1) L8 – Cite lower profile in Fig. 3? L9 – Cite upper profile in Fig. 3? All in all, please be more specific in your figure call-outs. (2) Ok (3) New sentence: "The Top Salt surface of the two pillows is generally smooth, locally o set by faults in the post-salt sediments. These faults can be divided into two groups: (1) normal faults with small offsets (< 100 m) forming grabens above the pillows (fig 2 right side, fig. 3 top), and (2) normal faults with throws that can be traced from Top Salt up to the Mid Tertiary (fig. 2 left side, fig. 3 bottom), offsetting the postsalt sediments up to 350m for the N–S and 200m for the E–W trending faults, respectively.

(1) L11-12 – Do you mean salt rollers rather than salt anticlines (sensu Hudec and Jack- son, 2011). (2) What we mean are reactive piercement geometries (Hudec and Jackson, 2007 Fig 10 (a))

(1) L14 – Cite figure to illustrate the "bigger faults". (2) Ok (3) Add "Fig. 2&3"

(1) L20 – Structural trend (i.e. EEN-WWS) needs changing. (2) Ok (3) Change to ENE-WSW

(1) L19-23 – Are the fold upright, recumbent, etc? How are they distributed across the study area, especially in relation to the main salt structures? I get very little sense of the true geometry of the folds, especially because you provide no zoomed-in seismic images or maps showing the range of fold styles. I feel that this is the section that really needs more work to convince the reader of the styles of deformation and their distribution. Without this, I find it hard to be fully convinced of the structural model

you later propose. In Jackson et al. (2015) we provide detailed maps of the intrasalt structural styles and their distribution across the study area; you have excellent data that, I think, lends itself to similarly detailed structural mapping. (2) The new figure(s) 2 will have more profiles with horizons and annotations showing the structures. (3) New Fig. 2

(1) L26 – Lower bit of Fig. 7 doesn't really add anything. As stated above, some basic maps and sections would be far more valuable. (2) More profiles in Fig. 2

P1887

(1) P1-18 – This is a super-critical section but I find it very hard to visualize what you are describing, largely due to a lack of data (e.g. seismic profiles, maps, etc) that clearly illustrate the main structures and their spatial relationships. To keep on top of the slightly unwieldy intra-Zechstein nomenclature, I kept going back to Fig. 2, but this didn't really help much because of the aforementioned figure size issues. (2) Figure 2 will have more and vertically exaggerated profiles to help here.

(1) L23 – Which bit of Fig. 5 are you referring to? (2) Buntsandstein thickness map in the top left

(1) L24 - Rephrase; e.g. "... can be as little as 200 m thick...". (2) Ok (3) change "200m thin" to "as little as 200 m thick"

(1) L23-26 – Again, I have to work extremely hard to see these thickness relationships/changes in the regional map(s) shown in Fig. 5. It would be especially powerful to some zoomed-in bits of the maps, with complimentary seismic profiles, clearly showing some of the key relationships that underpin your main arguments. At the moment, I don't think this is done as well as it could be. (2) This will be added to the new figures.

P1888

(1) L2 – What is the orientation of the seismic profile in Fig. 5? (2) It is N-S orientated as shown in the top left corner. Figure 5 will be redesigned.

(1) L1-2 – Would be nice to cite a figure to illustrate this relationship in cross-section. (2) See before

(1) L3-22 – This section is a little 'list-like' and very descriptive. I wonder if some of the material in this section could come later, in Section 5.2, when you describe the overall salt tectonic model. In this way, the description and interpretation (still in separate paragraphs) would be more closely coupled. Furthermore, the Bundsandstein looks rather tabular to me in Fig. 2, at least about the Veendam Pillow, but I don't get a sense of this at all from the description you provide here and on the preceding page. (2) The Buntsandstein is rather tabular in the southern study area. A thicker part of this unit in the in the east of the Slochteren pillow on the other hand shows evidence for local depo-centres during the Triassic. A profile of this basin will be added to figure 2. We think it is necessary to rephrase this section to make clear that the spatially varying thickness of the Bundsandstein is a result of local subsidence and erosion during the Jurassic hiatus. Strozyk et al (2014) have already shown that extension and rafting of tabular parts of the Buntsandstein combined with its localized thickening and early salt withdrawal seeded the structures observed today.

(1) L25 – I can't tell green from grey in Fig. 4. Also, the green merges into the green areas on the underlying depth map. (2) Different symbols will be a better solution than different colours.

(1) L24 – Is the bischofite really abundant only in the southern area? It looks more widespread than that to me, only really being absent on the crest of the Slochteren Pillow. Maybe it's my mistake, seeing as I can't make out the well colours on Fig. 4 very well (2) There are only small findings in the SLO and ZVN wells, in the other wells only carnallite is present.

P1889

(1) L7-10 – What evidence do you have for this statement? Can you cite a figure? (2) For evidence, we have the lack of bischofite in this wells (fig. 4). The cumulative

thickness of bischofite was calculated from well logs and core data (in a few cases).

(1) L11-17 – I'm a little unsure whether cumulative thicknesses really are that useful. Something could be relatively thick but, at that specific location, still represent only a small % of the total evaporite thickness. In this way, the unit may then not be that rheologically significant, even if it is locally thick, with the bulk rheology being controlled by the volumetrically significant other units. (2) We are not sure if we understand this comment right. The thickness of the ZIII is typically between 200 to 500 m in the study area. The thickness differences are mostly accumulated in the K-Mg salt layers, especially in the ZIII-1b. The cumulative thicknesses up to 100 m are clearly significant on this scale. Nevertheless, at this point of the paper we are not talking about bulk viscosity. Here we want to illustrate where we find the most carnallite and bischofite in the study area in absolute numbers. Considering iso-stress (Reuss) conditions and shear deformation, the influence of a meter thick bischofite layer is important, even in a salt package of several hundred meters.

(1) L21-24 – Could the same general statement not also hold true for halite and, in fact, pretty much any other layer contained in the salt structure; i.e. thickness variations may be depositional of tectonics? (2) Yes, but 1. We are talking about K-Mg salts here. 2. K-Mg salts are softer and therefore react much stronger to this process.

P1890

(1) L1-5 – I like this idea, but why wouldn't the top salt become flat after subsalt faulting? Is the salt bulk viscosity that high that it can 'sustain' relief generated by subsalt faulting? Is this realistic? You may also want to cite the original pod-intepod paper by Hodgson et al. (1992), which advocates a similar thing (without providing any physical basis for it). (2) The cited studies work with the concept that sedimentation takes place faster than the flattening of the salt surface. The sulphate stringer stratigraphy and thickness were taken as an evidence for that. Still they work on a much bigger scale than we have in the study area. Since fault-movement and salt precipitation are rather

fast processes the model seems likely but as you said, are not proven yet. This would be a great project for a numerical study with the big challenge the get the right paleo rheology for the salt.

(1) L12 – See earlier comment; put seismic-stratigraphic description of overburden units at the relevant points in section 5.2 to more closely link descriptions and interpretations? Just a suggestion to tighten things (2) We prefer to keep the results and discussion classically separated.

(1) L22 – Label salt structures on cross-sections and maps in Fig. 8, otherwise it is difficult to link the text with the figure. N.B. See also Dooley et al. (2015), who show thickening of low-viscosity layers into the crest of inflating salt diapirs during initial rise. (2) Ok this will be added to the revised figures.

(1) L22-24 – I am confused here. Above the Schloreten Pillow the Bundsandstein layer seems to thin by truncation at its top surface (in Fig. 2) rather than by onlap onto the salt. In fact, it seems to have a concordant lower contact with the salt. Furthermore, lower down the flanks of the Slochteren Pillow the unit looks tabular, like it does across all of the Veendam Pillow (Fig. 3). Thus, I see no reason why salt movement occurred at this time. In fact, as I argue below, the Bundsandstein layer pre- rather than synkinematic to me (2) See other comments

P1891

(1) L5-6 – Rephrase sentence; e.g. "... the Lower Cretaceous interval is 50-140 m thick and does not thicken...". (2) ok (3) "While the Jurassic is entirely missing (cf. Wong et al., 2007), the Lower Cretaceous interval is 50-140 m thick and does not thicken above the basins."

(1) L9 – Based on: (i) the overburden geometries; (ii) the shape of the salt pillows; and (iii) the nature of the contact between the salt and overburden, isn't it more likely that the salt structures grew in response to contraction rather than, as I think you are

advocating, passive diapirism? I see no inward-dipping 'fan' of normal faults detaching into the crest of the pillows and structurally thinning the overburden, hence reactive diapirism also seem an unlikely trigger. Instead, the faults higher in the overburden could be due to outer-arc being during contraction. In fact, wasn't the Late Cretaceous a time of Alpine-related shortening, hence you have a regional trigger to play with. Whatever you think the trigger is, I think you need to argue more strongly for your preferred model (2) During the Triassic there were extensional conditions. Normal faulting of the Bundsandstein into rafts is commonly observed in the Zechstein basin (see also Mohr et al., 2004) and we see reactive piercement structures. Unlike the profile in figure 2 the Bundsandstein does not look completely tabular in the north. With the onset of compressional conditions during the cretaceous both salt structures were already defined. For that reason, we argue that salt movement started already during the Triassic in the north and continued during the Jurassic leading to erosion of the Buntsandstein above the Slochteren Pillow. Thinning of the late Triassic sediments above the Veendam Pillow seems to be exclusively caused by erosion. Contraction during the late cretaceous might play a role, too. We see tabular reflectors only in the lower part of the Cretaceous, so it is likely that the alpine contraction triggered new/additonal salt movement towards/within the already present salt highs. Unfortunately we cannot determine the exact age when the change happened. (3) Rephrase of P.1890 L.19 to 1891 L. 3: During the Triassic, localized differential loading in the early postsalt sediments induced salt withdrawal below the Veendam area and salt flowed towards the area of the later Slochteren pillow, as indicated by strong variations in Buntsandstein thicknesses above both present-day pillows (Fig. 8). Thickening of Buntsandstein towards the basin center in the north (Fig. 3 bottom) indicates that salt movements occurred during very early stages. However, the rather tabular Buntsandstein geometries in the southern and western study area indicate that large areas weren't affected by early differential loading and salt flows, and most of the salt deformation took place in the Late Triassic and Jurassic. The significantly thinner (i.e., 100 m) Triassic sediments above the Slochteren Pillow are therefore result of erosion of a tabular sediment layer that was truncated during the Jurassic hiatus. We infer that salt that was withdrawn from the subsiding basins flowed mainly from the south and the east towards the Slochteren Pillow and also into the much slower evolving Veendam Pillow. Coevally, reactive piercement structures in Triassic sediments above the Veendam Pillow evolved and formed small-scale Top Salt anticlines.

(1) 17-24 – I find this model a little contrived. Couldn't the overburden faults simply be due to outer-arc bending during contraction and salt pillow growth? Also, this model implies that the sub-salt faults were active in the tertiary; do you have any independent evidence for this? You cite Lewis et al. (2013), but the fault geometries, relationship to the salt, salt thickness, etc, are very, very different in that example, thus I am not entirely sure how relevant the analogue is. In that paper we could independently constrain movement on the sub-salt faults, and thus demonstrate their age-equivalence to the overburden faults. I don't think you can do this here. You've got way more salt between the fault populations. (2) We don't see a clear evidence that the subsalt faults were active during the Tertiary. Since this question is not really in the focus of this study and very speculative we take it out. (3) erase "The coincidence of location, orientation and movement of faults (Fig. 5c) indicates a correlation 20 of supra- and subsalt faulting in this area, most likely triggered from corresponding internal shear zones in the salt (also see data by Lewis et al., 2013)."

P1892

(1) Section 5.3 – I found this all a little hard to follow, mainly because, as stated earlier, I don't think some of the key thickness relationships, structural styles, etc, are dequately illustrated or described. Furthermore, I think this model needs to be illustrated in another summary cartoon, focused on the details of what is going on inside the salt; I don't think Fig. 8 really is detailed enough in this respect. (2) A more detailed figure two showing the development inside the salt and in the overburden in more time steps seems necessary to clarify 5.2 and 5.3

(1) L14 – Not sure what you mean by "passively or actively deform". Please clarify. (2) Here the movement of the salt was differentiated between passive drag together with the whole salt package or strain localization in the K-Mg salts meaning independent strains/flows/movements. Since the sentence is more confusing than helpful and the important information is repeated later, it will be taken out. (3) erase: "As part of the salt package, the K-Mg salts can passively or actively deform in the flowing salt. The large viscosity contrast makes this possible, especially if the bischofite body is much larger than the wavelength of the fold structures so that significant stress gradients can develop to cause bischofite redistribution."

(1) L23-25 – Cite a supporting figure. (3) Add (fig. 7)

Additional changes

P. 1883 L. 12: change : "(Geluk, 2007Fig. 2)" into "(Fig. 2b)" P. 1884 L. 12: Add Fig. 2 to "(Fig. 4)" P. 1884 L. 24-27. New: "The interpreted horizons are Base Salt (= Top ZII-A), Top ZIII-AC ("stringer"), Top ZIII-1a, Top ZIII-1b, Top ZIII-2a, Top ZIII-2b+ ZIII-3a + ZIII-3b, Top ZEIII-4b and Top Salt (Top ZIV) (Fig 2a+b). Layers ZIII-2b to ZIII-4b are not resolved in the seismic volume 2." P. 1885 L. 6 change "(Fig. 2 and 3) to (Fig. 2a and 5a) P. 1885 L. 20 & P. 1886 L. 5: add Fig 6 to "(Fig. 1)" P. 1887 L. 3: change "(Fig. 2)" into "(Fig. 2b)" Caption Figure 2 Figure 2a N–S profile through the study area with the Slochteren Pillow in the north (volume 2) and the Veendam Pillow in the south (volume 1). The black lines indicate a normal fault at the south margin of the Slochteren Pillow and smaller faults above the Veendam Pillow forming a crestal collapse graben. The basin between the pillows shows significant thickening of most layers. The Z3 stringer is separated under the basin and folded and thrusted in the pillows. Bottom: Detailed view of the salt layers in the top of the salt bodies.

Figure 2b VDM-4 Well-log and expected seismic response compared to the real seismic response.

Caption Figure 3: Top: NWN–SES profile through the Veendam Pillow showing thickening of the ZIII-1b (green) above the AC-stringer synclines and crestal collapse grabens above the pillow. Bottom: ESE–WNW profile through the Slochteren Pillow. Enhanced area is showing thickening of the Triassic towards the basin center.

Caption Figure 5: Supersalt thickness maps of the units mark in the profile at the bottom. Due to the influence of faults in the superasalt the thickness information in the center of the pillows is faulty. The dotted line in the chalk indicates the change from phase 2 to phase 3 (Fig 5b). The thickness maps show substantial thickening above the basins in phase 1 and 3 (Fig 5b) and constant thicknesses in phase 2.

Caption Figure 6: Detailed Top Salt map (black box indicates location of seismic volume 1) with surface inquiries (black lines) as a result of crestal collapses above salt pillows. The white lines indicate faults offetting the Top Salt contact at the Slochteren Pillow. Thickness maps of top ZIII-1a to top ZIII-3b and top ZIII-1a to top ZIII-1b and a detailed map of the Subsalt surface (modified after Strozyk, 2014). Layers show significant thickening to the crest and under crestal collapse structures. On the depth map of the Lower Cretaceous faults offsetting the layer are marked in black.

Caption Figure 7 Map view of the ZIII stringer showing the different rupture patterns in the two pillows with several profiles.

Caption Figure 8 Conceptual sketch of salt deformation in the study area: maps on the left indicate movements in the bischofite deposit; the profile sketches on the right side indicate corresponding deformation of the Zechstein (incl. ZIII AC stringer and K-Mg salts) and the suprasalt sediments. Black arrows indicate movements in the suprasalt sediments (e.g., extension and subsidence), white lines movements in the salt (e.g. salt withdrawal below sediment basins): (a) tectonic movements in the subsalt allow for localized bischofite deposition in the area of the later Veendam Pillow; (b) differential loading and extension in the Triassic sediments and during Jurassic erosion cause salt withdrawal and boudinage of the ZIII stringer in the area of the later Veendam Pillow, while salt accumulation and doming farther north triggers the formation of the

Slochteren Pillow; K-Mg salts are initially deformed by extensional features in the salt's overburden; (c) ongoing subsidence and salt withdrawal below sedimentary basins cause the formation of the Veendam Pillow and further grow of the Slochteren Pillow. The bischofite deposits are dragged into the Veendam Pillow, where they deform due to ZIII stringer deformation and structures in the supra-salt.

Interactive comment on Solid Earth Discuss., 7, 1877, 2015.

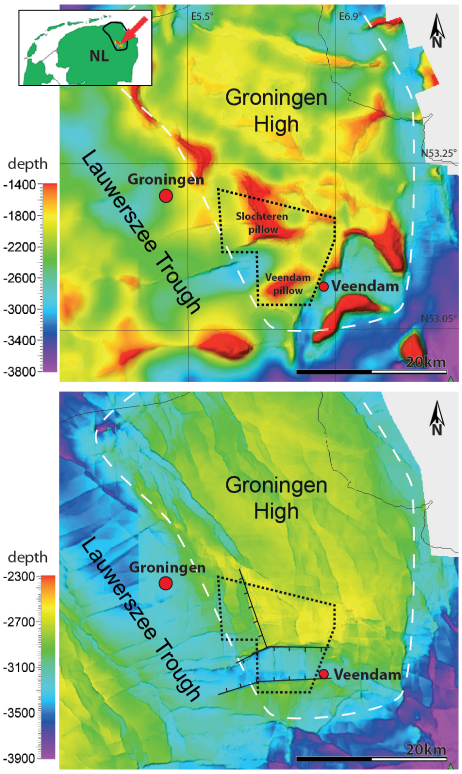


Fig. 1. Fig 1

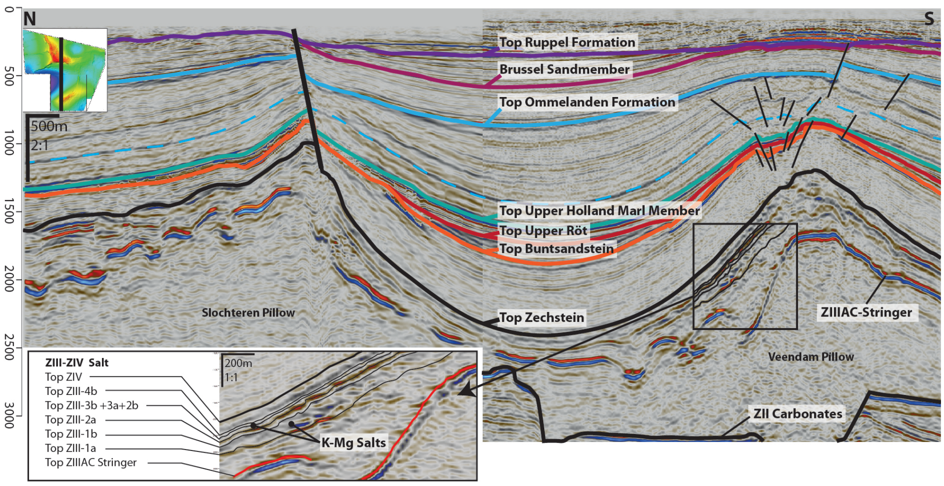


Fig. 2. Fig. 2a

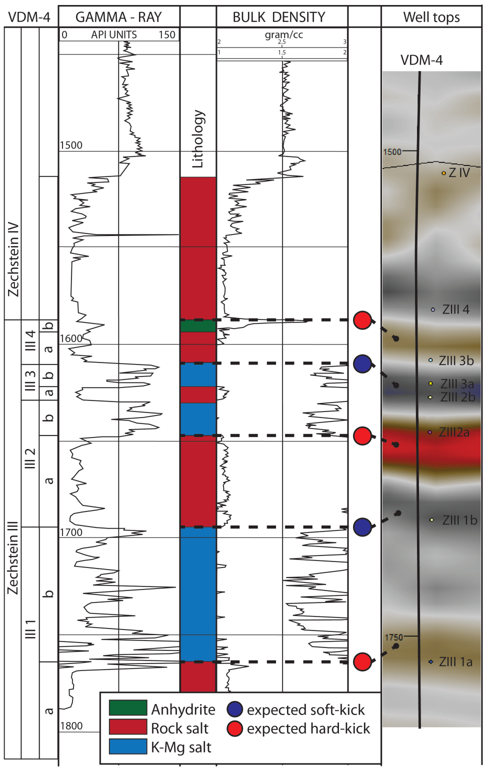
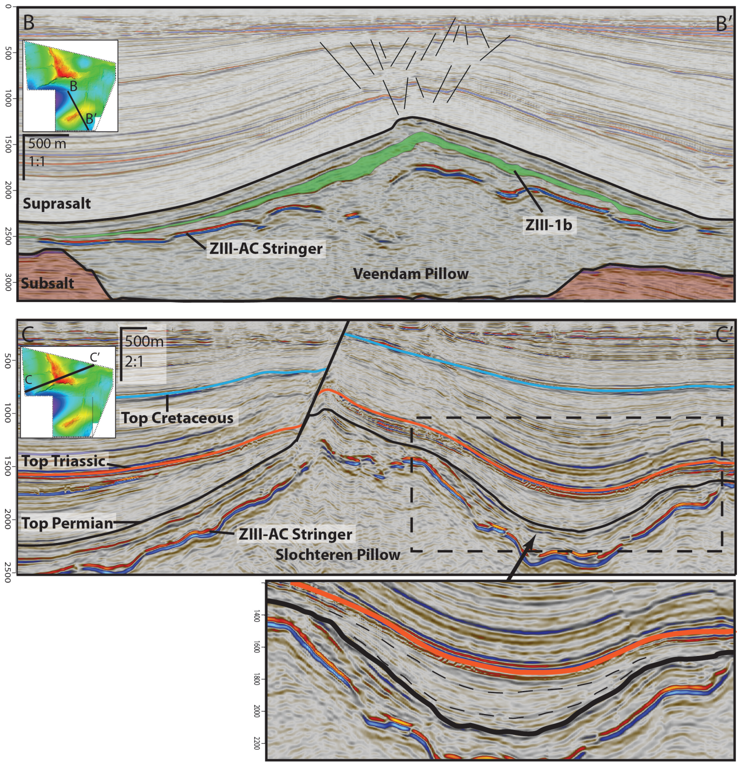


Fig. 3. Fig. 2b



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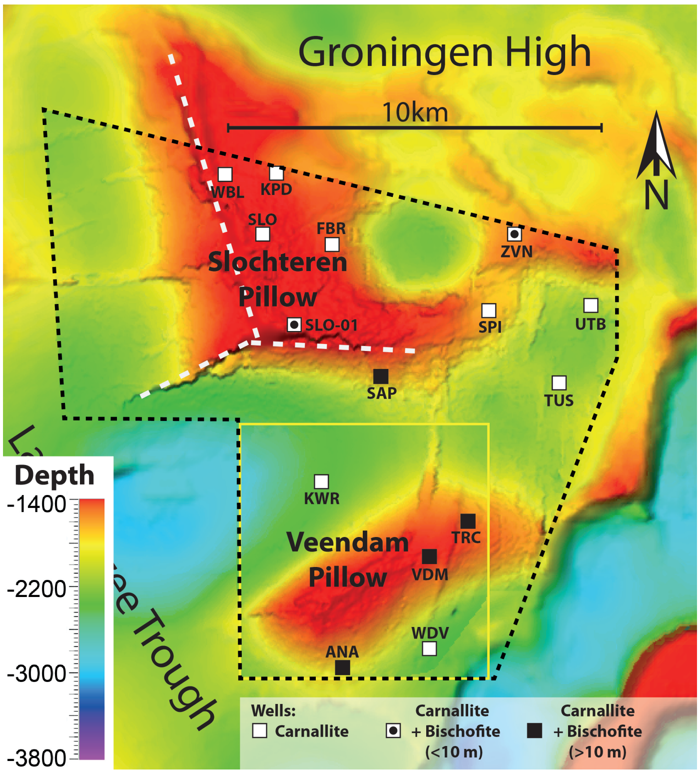

Fig. 5. Fig. 4

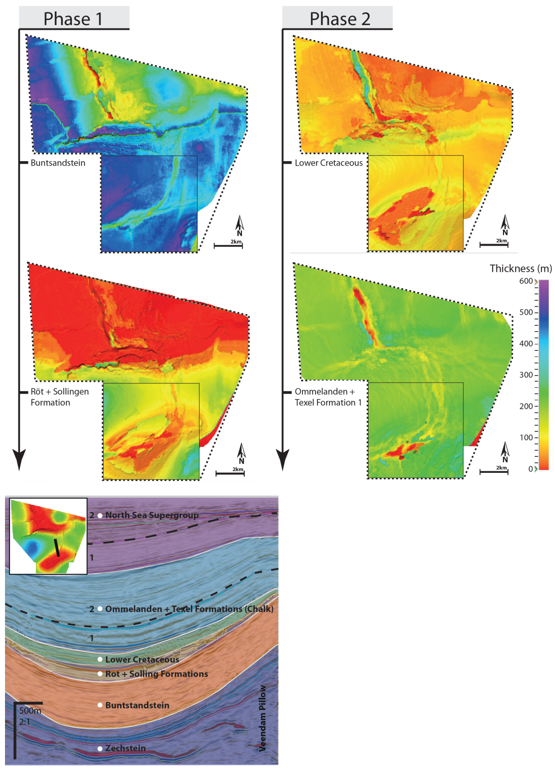

Fig. 6. Fig. 5a

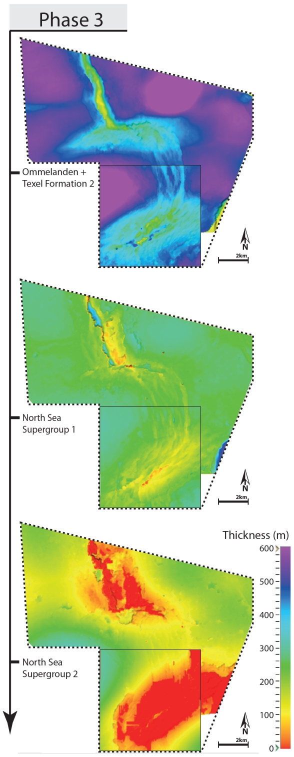

Fig. 7. Fig. 5b

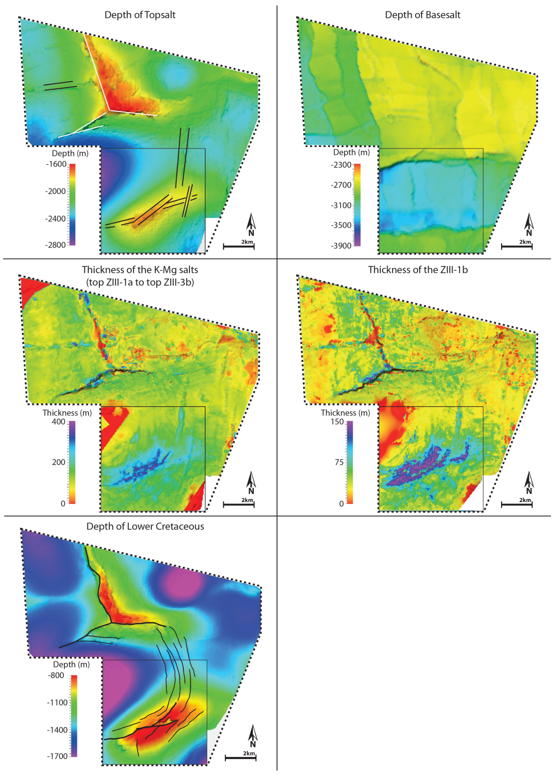

Fig. 8. Fig. 6

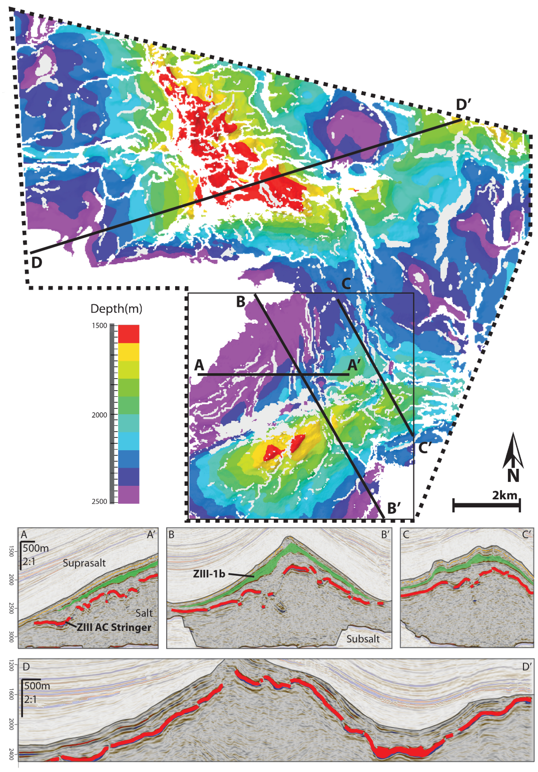

Fig. 9. Fig. 7

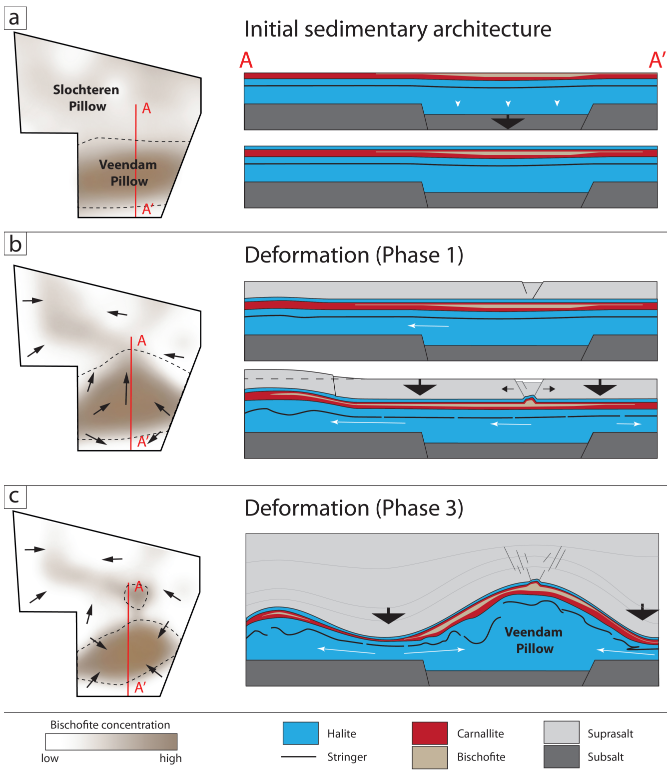

Fig. 10. Fig. 8