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Main questions from Prof. Hou to NAM about the water injection studies

- Are the two carbonate reservoirs hydraulically connected? Production/field data should give this information.

  Is it a closed system or an open system?

  Available data cannot provide conclusive answers to the above question. All reservoirs and fields are at or near hydrostatic conditions and not over pressured. Original pressure data are not sufficiently clear to determine if the Z2 and Z3 share similar or different Gas-Water contacts (only Gas-Down to's have been established with a large uncertainty on FWL). In the case of the Rossum-Weerselo field there is evidence based on pressure data that the two reservoirs (Z2 and Z3 Carbonate) are in pressure communication during production. The available pressure data from the Tubbergen field during production do not allow conclusive statements about inter-connectivity of the Z2 and Z3 reservoirs.

- The NAM doesn't make coupled calculations. The process in reality is coupled with Hydraulic, Mechanical and Chemical interaction. (HMC). What is the expected difference in the approach?

  Is it expected that a (potential) cavity under hydrostatic pressure could grow upwards, towards groundwater, with the much higher horizontal stress in salt?

  NAM agrees that the processes acting in the subsurface are coupled. Coupling involves, however, complex numerical models and data that can constrain, calibrate and validate the physics involved. The Twente study can best be considered as a scoping study based on conservative assumptions with the calculation of end members to be the objective. The assumptions used and results of the calculations therefore provide an upper bound for the uncertainty domain for the effects of injection and demonstrated that, even when using these conservative assumptions, no severe effects are to be expected. Our opinion is that the involvement of more realistic physics and assumptions would lead to results that are less severe.

  With respect to the question on the potential upward movement of a cavity NAM believes that on a *geological time* scale this might be the case because of the density contrast between the fluid in the cavity and the surrounding salt. There are two processes that could reduce the volume of the cavern on the way up. The first process involves the permeation of brine out of the cavern when pressures increase close to lithostatic values invoked by the creep process of the salt (e.g. Berest, 2005 observations from the Etrez solution mine) which reduces the volume of the cavern. The second process is important in a layered subsurface with an alteration of viscous evaporates and brittle clastic and carbonate rocks where aggressive brine can destabilize brittle roof material, a mechanism observed in the abandoned AKZO salt caverns in the Twente area. This is a process that will kill itself because the bulk volume of the roof material that drops in the cavern is always larger that the intact rock bulk volume. Also, the cavity should first reach the brittle rocks, which requires an enormous volume of salt to dissolve in a very limited area, only likely if highy undersaturated brine is injected directly in the salt cap rock, rather than in the carbonate formation. In the AKZO case the cap salt was solution mined away on purpose some decades ago, for which the Tubbergen water volumes are too small.

Even with the conservative assumptions used, the model results show that the dissolved volumes are limited and there is no situation where actual caverns in the classical sense are expected to form. Even is a cavern were to form, the relative long 'travel distance' combined with the coupled mechanical effects described above, would render significant upward migration of the cavern unlikely.

- Why is a constant dissolution rate of 20 m3/year calculated?

  The potential for solution in a cavern is much larger than in a fracture. The cave volume will increase, the contact surface will grow. The dissolution rate will not be constant.

  The dissolution rate deducted from the data in Figure 5.1 is the outcome of the modelling. The limiting factor here is the flow capacity through a crack in the cement surrounding the casing of the well bore. The flow capacity is calculated to equate to approximately 3% of the injected water volume (*"The amount of water that passes through the leak point (compared to the total water injection rate) is limited by the conductivity of the cement crack; in our simulations approximately 3% of total injected water passes through the leak point. This amount remains constant throughout the injection period.")* The limiting factor is therefore the leaking water volume, not the surface area of the cavern.

- Why are there discrepancies between the Kv / Kh ratios? Why are different numbers used in the dissolution and subsidence report? E.g. in unfaulted reservoirs 10-2 should be used.

  In the reservoir dissolution modeling report the Kv/Kh has been used as a variable to test the sensitivity of the model results to this factor (Kv/Kh of 10^{-3} and 10^{-4} was used in most cases). For the sensitivities around establishing convection cells Kv/Kh ratios of 10^{-3} and 1 were used. All cases show that reservoir heterogeneity expressed as Kv/Kh is a very important parameter which strongly dictates the capacity for vertical fluid flow and therefor dissolution rate.

  In the Subsidence models a single Kv/Kh of 10^{-2} was used. This is on the homogenous end of the spectrum that can be expected based on the geology and will still result in the establishment of convection cells at a 1000 year time scale.

- The question "how much halite could be dissolved in the 20 years injection phase" was not answered in all the 6 cases.

  The answer to this question is limited by the resolution of the model. The grid size in the model is 40 m in the X direction so the shown outcome is rather binary: either no dissolution or 40 m dissolution: a cell is already shown to be active in dissolution once it's porosity change is above 0.1% porosity units). Therefore if a cell is shown to be "dissolved" it can mean that the actual dissolved volume may vary between 0.1% and 100% in none of the 6 models more than one cell was shown to be "dissolved". In model 2 no cell was "dissolved". So most likely if a model is shown to have a cell dissolved the dissolution volume tends to be much closer to the 0.1% rather than the 100% porosity end of the spectrum. Detailed model inspection revealed a Zaveraged porosity change of less than 2% in all cases (corresponding to on average less than 30 m3 dissolved volume per meter in the Y direction). There are local variation, most notably in cases 3 and 4 (short distance between well and fault plane) where in the direct vicinity of the well larger porosity changes occur. But again nowhere this local variation exceeds a dissolution of 100% over more than 40m distance.

Case	cumulative height of partially dissolved region (activated cells - porosity increase > 0.001) (in m)	width of partially dissolved region (in m)	max porosity change (fraction)	min porosity change (Fraction)	max volume of halite dissolved (m3 (per m in Y direction))	min volume of halite dissolved (m3 (per m in Y direction))
1	10	40	1	0.001	400	0.4
2	0	0	1	0.001	0	0
3	25	40	1	0.001	1000	1
4	25	40	1	0.001	1000	1
5	15	40	1	0.001	600	0.6
6	5	40	1	0.001	200	0.2

The modelling suggests that along the length of the reservoir (in the Y direction), where the carbonate layer is directly juxtaposed against salt, a shallow dissolution zone (most likely only several 10's of cm's deep) will form with locally deeper dissolved areas (<15-40m) which are concentrated around the top of the juxtaposed salt layer (all models) or directly adjacent to the well (In case 3 and 4). The result also indicates that the formation of classical caverns (as suggested in question 1) is not expected.

- Which number of injection rates (2,500 m3/day or 4,000 m3/day) is correct? Different numbers are used in different reports.

  In the Halite dissolution report, which aims at investigating the salt dissolution in the area around an injection well, a rate of 2,500 m3/d is used. This rate represents the expected maximum injection rate per well.

  In contrast, in the subsidence model, the relevant rate is linked to the total volume injected in a single reservoir rather than the injection volume in a single well. This equates to about 4,000 m3/d.

  On p.15 of the report it is mentioned that "The dynamic reservoir model, as described in section 2.4, was used to model the distribution of injection water for the case where 4000m3/d water, which is the planned Tubbergen injection rate, was injected into the ZEZ3C formation over a period of 20years". In the Tubbergen reservoir, water injection occurs via wells TUB-7 and TUB-10 for which expected injection rates were 2000 m3/d per well. Hence, total injection rate amounts to 4000 m3/d

- According to the reviewer, the maximum subsidence in the center could finally be larger than 14 cm. With very conservative assumptions the maximum could be 0.26 m (long term). NAM should clarify the x- and y- axis of figures 3.2, 3.3, 3.4, 3.5 and 3.6 to show the influence area at the surface. Remark: the subsidence rate will be very small.

  Below are the noted figures with the outlines of the modeled areas indicated (Fig 3.2 and 3.3 cover a smaller area than Fig 3.4 to 6). As expected, the subsidence area is clearly wider that the area where the shrinkage at reservoir level takes place (see Fig. 3.4 below).

We do not recognize the 26 cm surface subsidence. We recognize that in our models the worst case vertical displacement at top Zechstein is about 24 cm but this translates to a maximum surface subsidence of 14 cm. This worst case is derived from the concentrated dissolution case which assumes that all water is concentrated in a small part of the field rather than (what is expected) migrates and distributes over all flanks of the field with an accumulation of gas building up in the crest. Please also note that the total volume of salt that can be dissolved is finite, because it is limited by the dissolution capacity of the finite volume of water that is injected. Also it is assumed that the injected water can become completely salt saturated which is a highly conservative estimate given that even after many millions of years the original aquifer water in the reservoir is not fully saturated. In addition it is assumed that salt dissolution will only take place from the interface with the overlying cap salt only. This is again a conservative estimate given that some salts will be dissolved from the lower salt layers and some water will not have direct access to salt (for instance by the remaining gas cap).

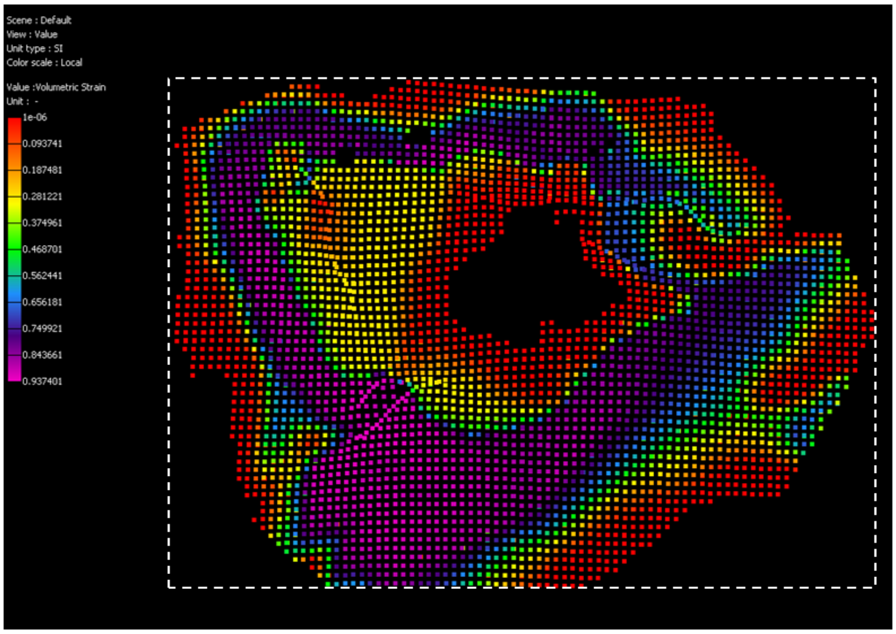

Figure 3.2: Total water saturation change (S_w^*) distribution after 1000 years shut in, used to predict salt dissolution. The purple area is the area of fresh water injection. In the middle, there is still high gas saturation and at the edges, the water (brine) saturation was initially high.
Easting: 253928-262176 / Northing: 492563-498496

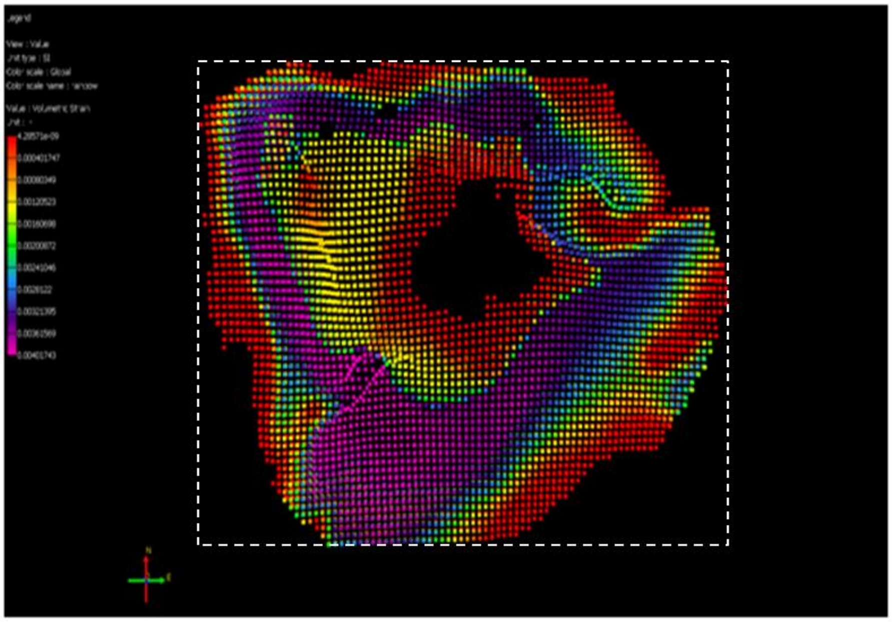

Figure 3.3: Shrinkage strain assigned to the carbonate to represent the salt dissolution volume.
Easting: 253928-262176 / Northing: 492563-498496 (same area as Fig 3.2)

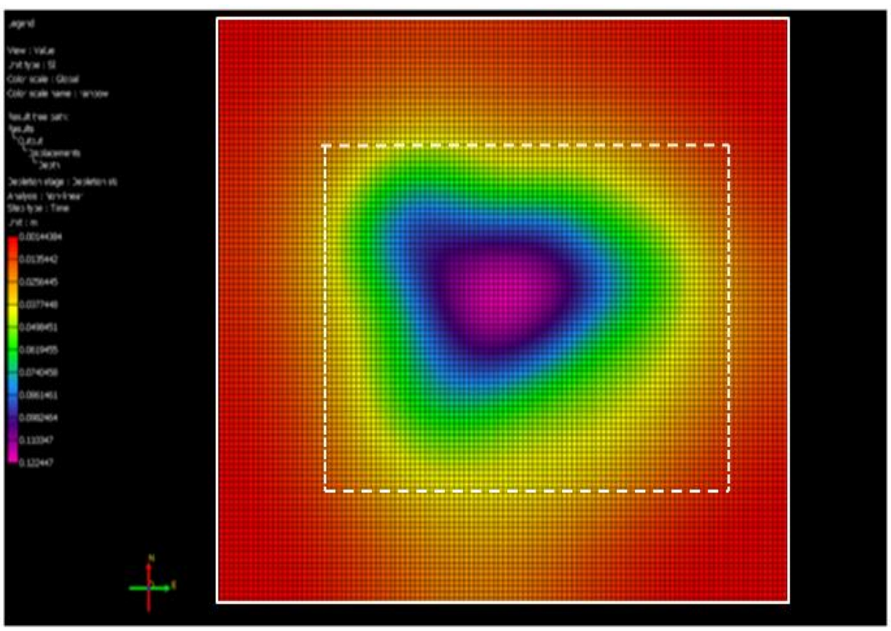

Figure 3.4: Subsidence bowl (0-12 cm) resulting from salt dissolution and salt creep leaving zero brine volume in the salt. Dashed white rectangle indicates the scale of Figures 3.2 and 3.3.
Easting: 251738-263336 / Northing: 490558-500658

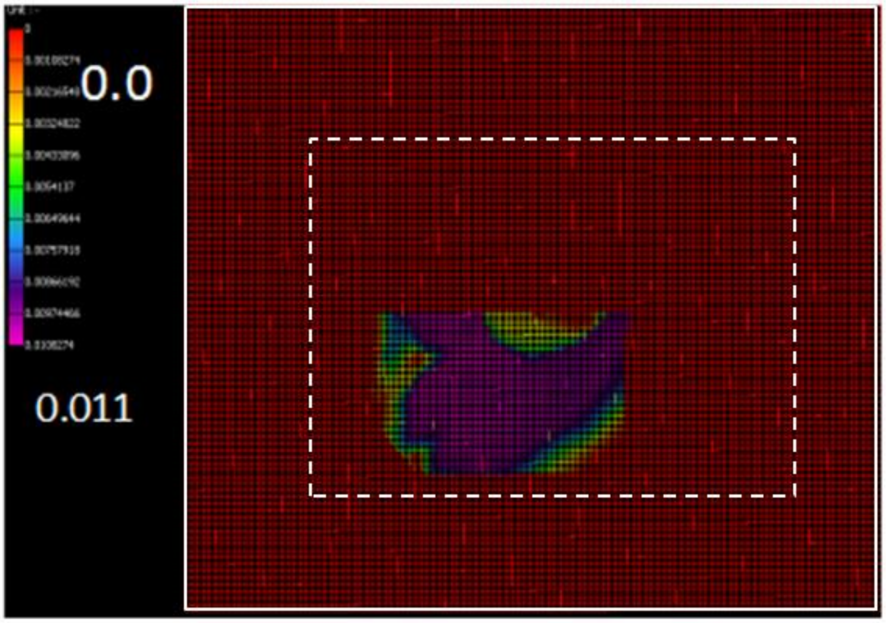

Figure 3.5: Concentrated salt dissolution (shrinkage strain) for the same total amount (painted on mesh). Dashed white rectangle indicates the scale of Figures 3.2 and 3.3.
Easting 251738-263336; Northing 490558-500658

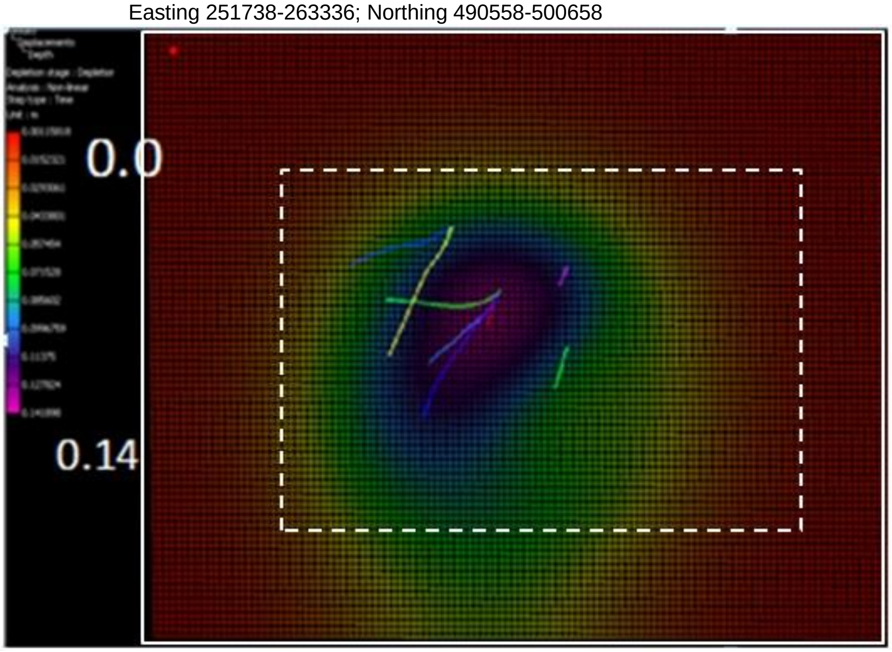

Figure 3.6: Subsidence bowl (0-14 cm) resulting from concentrated dissolution, also showing some well paths. Dashed white rectangle indicates the scale of Figures 3.2 and 3.3.
Easting 251738-263336; Northing 490558-500658