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Do salt diapirs promote the geothermal energy potential of shallow aquifers?

Beekman F[1]*, Veldkamp JG[2], Seelen M[1,2], Van den Berg M[1,2] and Van Wees JD[1,2]
[1]Utrecht University, Dept of Earth Sciences, Netherlands; [2]TNO-Geological Survey of the Netherlands
Corresponding author: fred.beekman@uu.nl

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INTRODUCTION

Anomalous geological structures, such as salt domes, can locally enhance subsurface temperatures in overlying shallow aquifers through increased heat flow caused by the large thermal conductivity of halite-rich formations. This 'chimney effect' (Fig. 1) allows heat from deeper strata to be conducted upward more efficiently, potentially resulting in elevated temperatures near and above the crest of salt structures (Daniilidis & Herber 2017; Raymond et al., 2022). The Onstwedde salt dome in NE Netherlands (TNO-GDN, 2014) is a prime candidate for evaluating shallow geothermal potential due to its proximity to the surface. It was expected that this structure could provide direct heat for local applications such as swimming pool heating and residential systems. However, borehole temperature measurements (Kombrink, 2022) yielded a temperature of only 15.7 °C at 295 m depth—significantly lower than expected (25–35 °C). This result necessitated a reinterpretation of seismic data and the performance of numerical modeling studies in which the effect of stratigraphic heterogeneity, variations in thermal rock properties and the influence of groundwater flow on the temperature of the aquifer were assessed.

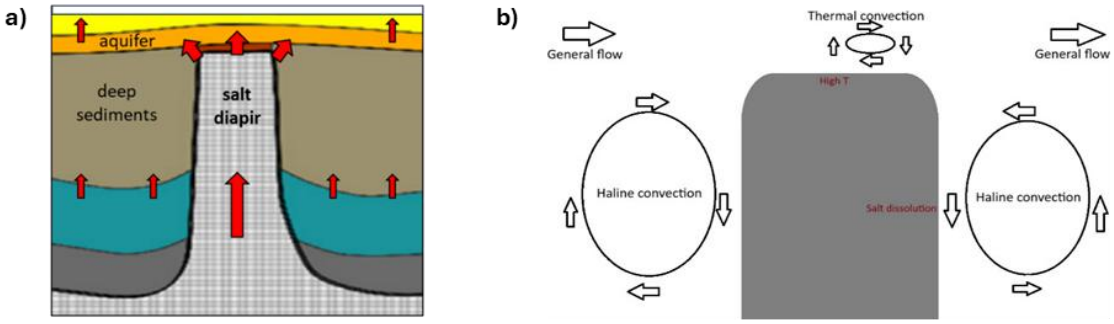


Figure 1. (a) Conceptual model of heat flow (red arrows) in and around a salt dome (after Raymond et al., 2022). (b) Schematic groundwater flow around a salt dome: (1) regional/general flow with constant direction; (2) small-scale thermal convection induced by temperature changes near the top of a dome; (3) haline convection due to dissolution of salt in groundwater.

1 GEOLOGICAL BACKGROUND

The Onstwedde salt dome, located in the NE Netherlands (Fig. 2), comprises Zechstein evaporitic salts deposited during the Late Permian (TNO-GDN, 2014). Through halokinetic processes, the salt has intruded overlying Triassic and Jurassic sediments to form a near-cylindrical diapir. The dome base lies between 3550–4000 m, and the crest rises to approximately 215 m below surface (Fig. 2b). Overlying formations include mostly Tertiary Upper North Sea Group sediments, and Quaternary deposits of the Peelo Formation. A pronounced glacial incision valley (Fig. 2d) cuts directly over the dome and is filled with Peelo Formation coarse sand and gravel at its base, capped by clay (Kluiving et al., 2003).

Rock salt has a high thermal conductivity of around 6 $Wm^{-1}K^{-1}$, with the exact value dependent on pressure and temperature (Hsieh, 2021) compared to 1-4 $Wm^{-1}K^{-1}$ for sandstone and shale, dependent on pressure, temperature, porosity and mineralogy (Abdulagatova et al., 2009; Gabova et al.,2020; Sun et al., 2017). Water, present in the pores of the rock, has a thermal conductivity of less than 1 $Wm^{-1}K^{-1}$. The thermal conductivity of rock salt (halite) is known to vary significantly with temperature, decreasing from approximately 9.9 $Wm^{-1}K^{-1}$at −75 °C to below 3 $Wm^{-1}K^{-1}$ at 300 °C (Urquhart & Bauer, 2015). This reduction in conductivity at higher temperatures affects the internal heat transfer within salt domes, resulting in lower predicted temperature anomalies at their crests. Consequently, temperature-dependent thermal conductivity must be incorporated into numerical models to achieve realistic predictions.

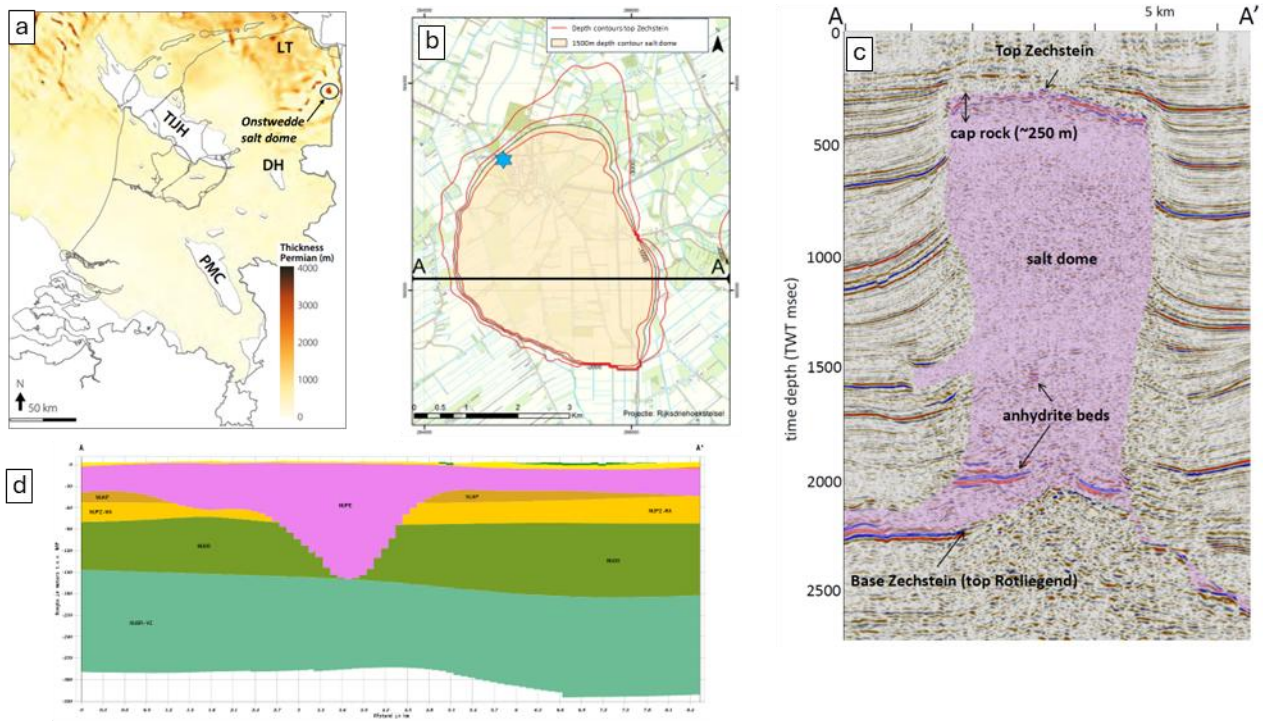


Figure 2. a) Permian thickness map of onshore Netherlands with location of Onstwedde salt dome (Ten Veen et al., 2025). b) Shape of the Onstwedde salt dome (TNO, 2014). Red lines are depth contours to top of Zechstein salt; the 1500 m depth contour is yellow color filled. Blue star is location of Onstwedde borehole. c) Seismic section A-A' through the Onstwedde salt dome. d) Geological section showing the presence of a glacial incision valley with Quaternary sands and gravels (Peelo formation, NUPE) above the salt dome.

2 METHODS

Three methods were employed: (1) seismic interpretation and 3D geological modelling using Petrel[1]; (2) steady-state thermal modelling using TNO's in-house developed Basin3D software (Bonté et al., 2012, Bekesi et al., 2020); and (3) coupled groundwater flow-heat transport modelling using the reservoir simulator Eclipse[1].

Using the Dutch national geological model DGM-Deep4 as a starting point, regional 3D seismic data was reinterpreted by Van den Berg (2023) to obtain a more detailed 3D geological model of the Onstwedde salt dome and surrounding areas (Fig. 3a). The VelMod-4 velocity model (TNO, 2020) was used to convert the 3D stratigraphic model from time to depth. Data from several nearby boreholes was used for calibrating the depth of the stratigraphic horizons.

The new geological model was used by Van den Berg (2023) to build an initial Basin3D thermal model with 12 lithostratigraphic layers. The thermal boundary conditions for the top and bottom of the model were constant temperatures of 10 °C and 120 °C, respectively. The rock properties of the layers were based on Hantschel and Kauerauf (2009). Changes in porosity and density with depth due to compaction were accounted for. The base model assumed a constant thermal conductivity of 6.5 W/m/K for salt and 1.6-4.0 W/m/K for shale and sandstone. Additional Basin3D model calculations by Van den Berg (2023) investigated the influence of temperature-dependent thermal conductivity and the presence of the glacial incision valley porosity. Sensitivity tests were performed to evaluate the impact of varying thermal properties in the upper layer. The conductivity of the Peelo Formation, the Upper North Sea Group, and the Chalk Group was varied by ±30% relative to the baseline values of Hantschel & Kauerauf (2009) to assess how lithological uncertainty influences surface temperature predictions.

Seelen (2024), using more detailed Basin3D models with 31 stratigraphic layers and improved horizontal and vertical grid resolutions (Fig. 3b), investigated paleotemperature corrections (Gies et al., 2021) and the presence of a gypsum salt dome cap. Seelen also probed the use of lithological data from the Zeerijp borehole, located 40 km northwest of Onstwedde, instead of the rock property data set of Hantschel & Kauerauf (2009).

[1] Petrel and Eclipse are marks of SLB/Schlumberger.

Finally, groundwater flow modeling was used to investigate the influence of regional groundwater flow and local small-scale thermal convection on the temperature above the salt dome. Modelling of haline convection (Fig.1b) was not yet included at this stage. The northwards directed regional groundwater head gradient is 0.4 mm/m. This results when combined with hydraulic conductivities of 10-25 m/day obtained from REGIS (TNO-GDN, 2024) in an estimated flow velocity of 0.5-3 cm/day within the Peelo formation. The horizontal hydraulic conductivity was assumed to be four times greater than the vertical conductivity.

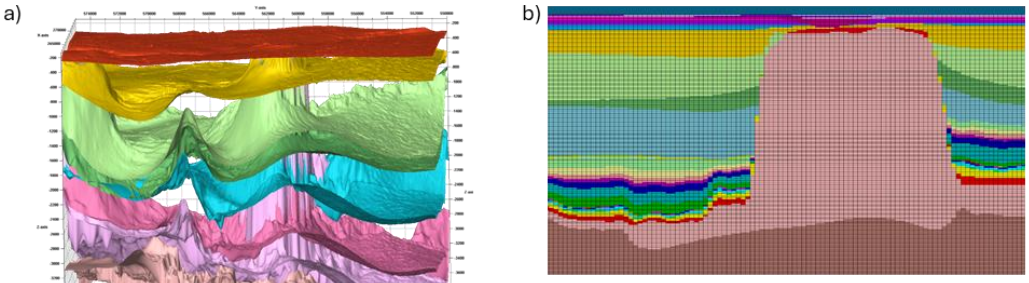


Figure 3. (a) Depth-converted model of the Onstwedde salt dome and surrounding stratigraphic horizons. (b) Refined litho-stratigraphy of the Basin3D thermal model. Horizontal and vertical grid resolutions are 100m and 25m, respectively.

3 RESULTS

The Basin3D simulations by Van den Berg (2023) and Seelen (2024) consistently predict elevated temperatures around the top of the salt dome. For the base model (Fig. 4a), the presence of the salt dome results in a temperature increase of ~20 °C at the top and a decrease of ~3 °C at the base (Fig. 4b). When the temperature-dependent thermal conductivity of halite is introduced, the modeled temperatures at the top decrease by 2-3 °C compared to runs with constant conductivity, while the basal zones of the salt dome become slightly warmer (Fig. 4c). This reflects the lower conduction efficiency of halite at higher temperatures. The lower conductivity sediments of the Peelo Formation filling the glacial incision valley above the Onstwedde salt dome have an insulating effect. Without this valley, crestal temperatures would have been 2–3 °C lower (Fig. 4d).

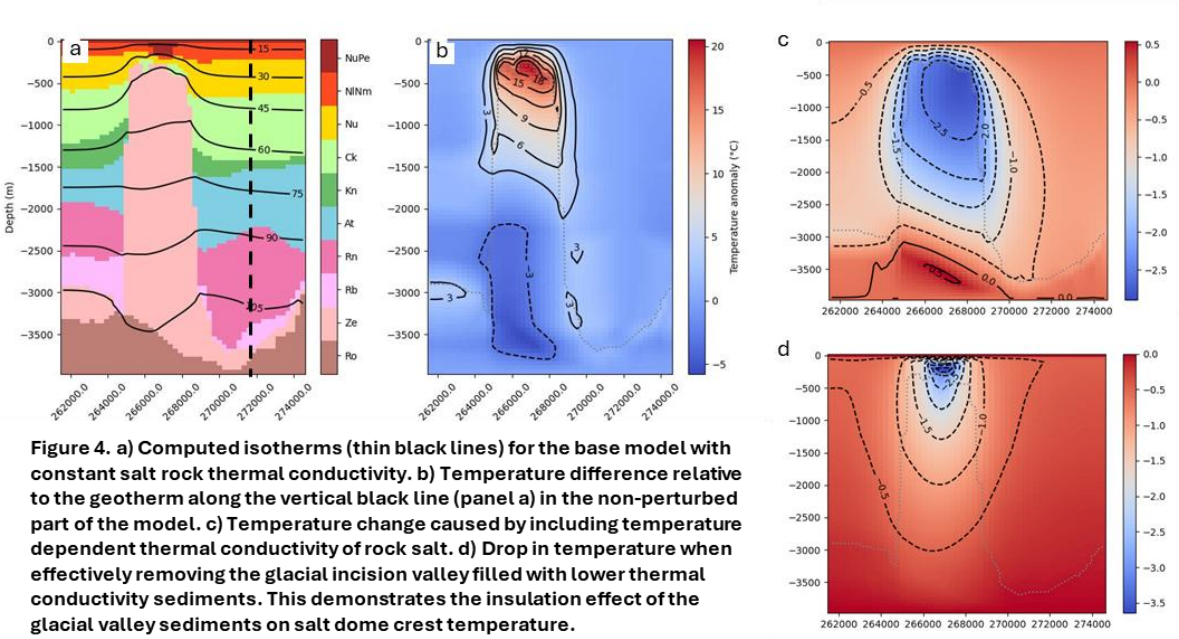


Figure 4. a) Computed isotherms (thin black lines) for the base model with constant salt rock thermal conductivity. b) Temperature difference relative to the geotherm along the vertical black line (panel a) in the non-perturbed part of the model. c) Temperature change caused by including temperature dependent thermal conductivity of rock salt. d) Drop in temperature when effectively removing the glacial incision valley filled with lower thermal conductivity sediments. This demonstrates the insulation effect of the glacial valley sediments on salt dome crest temperature.

Using more detailed stratigraphic layering and a finer grid resolution in the Basin3D models, Seelen (2024) predicted a temperature decrease from 34 to 31 °C in the Onstwedde borehole at a depth of 300 m. The introduction of a 25-50m thick gypsum caprock reduced the temperature at the top by another 1-2 °C, while a correction for the effects of the Saale glaciation (~200-100 ka bp) reduced the modeled temperature by less than 1 °C. The use of presumably more realistic data on the properties of rock from another borehole in the northwestern Netherlands had the greatest effect, reducing the borehole temperature by ~5.5 °C. In summary, after model refinement and parameter calibration and when using regional rock property data, the Basin3D simulations predicted a decrease in borehole temperature from ~34 to ~23 °C.

3.1 Groundwater flow

Eclipse model simulations (Seelen, 2024) show that at a depth of 200 m, significant regional flow occurs only in the incision valley (Fig. 5a), most likely due to the presence of coarse sand with higher hydraulic conductivity. The flow velocity in the valley is ~15-20 mm/d, with a maximum of ~25 mm/d directly above the salt dome. The accelerated transport of heat away from the top of the dome results in a temperature decrease of up to 8 °C at a depth of 200 m above the dome (Fig. 5b). A small temperature increase of ~1 °C is modeled along the flanks of the incision valley immediately north of the dome, where also the Onstwedde borehole is located. This is possibly due to lateral heat flow out of the incision valley.

Simulations of vertical fluid flow (Fig. 5c) show areas with rising and falling groundwater, which may indicate the presence of small thermal convection cells. The areas only reappear within the glacial incision valley and appear to be slightly more pronounced above and north of the dome. Their vertical velocity is approximately one order of magnitude slower than the modeled horizontal flow velocities (Fig. 5a) and their effect on temperature is therefore considered negligible.

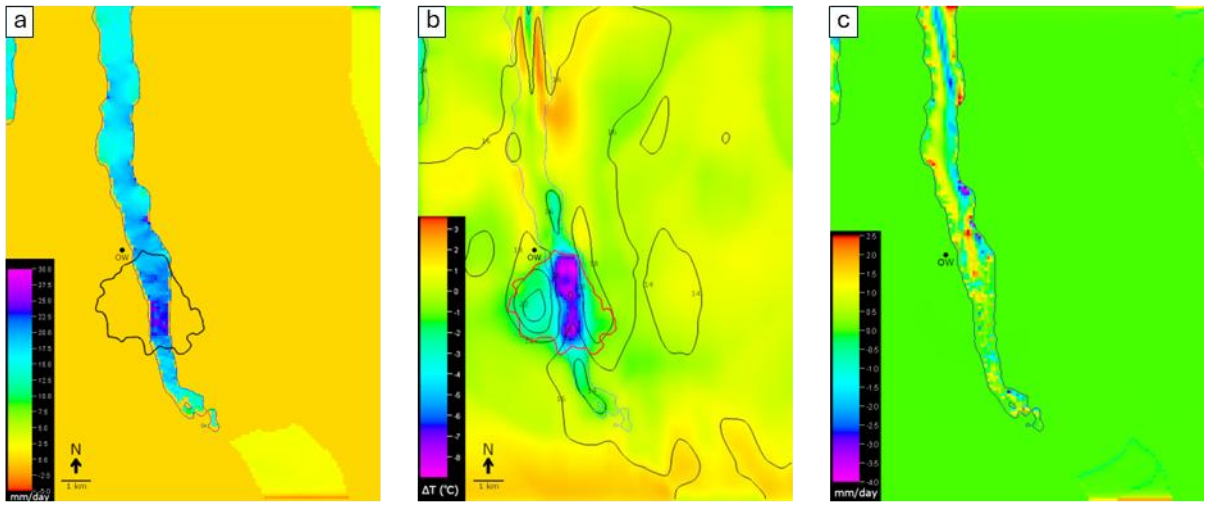


Figure 5. (a) Modelled magnitude of northward horizontal groundwater flow at 200m depth. (b) Groundwater flow induced temperature anomalies at 200m depth. OW: location of the Onstwedde exploration well. (c) Modelled location and magnitude of vertical fluid flow.

4 DISCUSSION

The discrepancy between predicted and measured temperatures in the Onstwedde borehole highlights the complex interplay between stratigraphic heterogeneity, thermal conductivity calibration, and subsurface hydrology. While earlier simplified models overestimated conductive efficiency, the refined models incorporating detailed formation-level layering, paleotemperature corrections and groundwater flow produce more realistic values, reducing the temperature elevation induced by the Onstwedde salt diapir to approximately 4-5 °C in the borehole at 200m depth. However, because the borehole is located at the flank of the Onstwedde salt dome, the temperature elevation in shallow aquifers above the dome center is expected to be larger.

Groundwater flow further modifies the local heat field at Onstwedde. In the Peelo incision valley, regional groundwater flows predominantly from south to north, transporting heat laterally away from the dome. This advective cooling effect reduces the temperature above the dome by an additional 1–3 °C, depending on assumed hydraulic conductivity.

In general, the integrated models suggest that the Onstwedde structure retains a positive but small geothermal anomaly that is only suitable for heat extraction at low temperatures (20-25 °C at a depth of 300 m). However, the remaining difference between the measured (15.7 °C) and predicted (~23 °C) borehole temperature remains unexplained. One possible explanation is that the temperature measured in the borehole was significantly influenced by the drilling process and the circulating borehole fluids (Bonté et al., 2012). Another explanation could be the presence of fractured and fragmented rocks along the flanks and above a diapir, created by the rise of the diapir. The resulting permeability of the fractures could lead to a significant increase in fluid flow and a decrease in temperature around the top of the dome.

5 CONCLUSIONS AND RECOMMENDATIONS

- Combined seismic reinterpretation, 3D thermal modelling, and groundwater flow simulations showed that the temperature distribution of the Onstwedde salt dome (NE Netherlands) exhibits a measurable but smaller-than-expected thermal anomaly.
- This discrepancy is attributed mainly to uncertainties in formation-scale lithological variability, thermal conductivity calibration, the insulating influence of the Peelo glacial valley, and the potential moderating effect of groundwater flow.
- Despite these discrepancies, a positive thermal anomaly of approximately 7–10 °C remains robust.
- The findings indicate that shallow salt structures such as Onstwedde hold potential for low-enthalpy geothermal energy extraction and small-scale, sustainable heating systems, but require additional borehole measurements and refined hydrogeological characterization (i.e. predictive transient groundwater-heat coupling modelling).

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