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Extrapolating geothermal reservoir quality from wells in inverted basins: the importance of taking into account maximum burial

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1 Introduction and summary

Geothermal energy is considered a major renewable energy source in the Netherlands. Its economic potential depends strongly on reservoir temperature and flow rates which can be achieved in a geothermal production system.

Temperature increases with depth as a function of the geothermal gradient. Consequently it is attractive to target relatively deep reservoirs. However achievable flow rates of clastic reservoirs in the Netherlands tend to decrease with depth larger than 1.5-2 km as a function of compaction of the pores and associated reduction of permeability (e.g. Van Wees et al., 2012). In addition pores at larger depth and temperature can become cemented and can clog fluid path ways resulting in very low permeability. Furthermore porosity-depth and porosity-permeability relationships vary considerably for reservoir lithologies (Pluymaekers et al., 2012).

In this report, we argue that relatively shallow reservoir data obtained from wells drilled at anticlinal structures, formed during basin inversion, can be representative for reservoir conditions deeper on the flanks up to depths of past maximum burial. This is often overlooked, as hydrocarbon industry have preferentially targeted structural highs, and as burial anomalies are difficult to estimate and require basin modelling approaches, including palinspastic restoration and/or backstripping.

In order to take the effects of burial anomalies effectively into account in such settings, we present a simple analysis methodology for anticlinal structures, and demonstrate its use for the Rotliegendes reservoir in the Jutphaas Anticline in the Utrecht region. Adopting the proposed method, it can be demonstrated for the JUT-01 well that the top Rotliegendes in the JUT-01 well encountered at 1659 mAH depth (1648 mTV), had been buried ca 1150 m deeper in Cretaceous times (ca 2800 m). Deep burial levels of 2500 m or more have been experienced up to ca 70 My (from ca 145-75 Ma), most likely at similar geothermal gradient as observed today (Nelskamp and Verweij, 2012). This long time interval suggests that the reservoir quality deeper in the flank may very well have been preserved the last 65 My after inversion.

The findings of the simplified method match very well with independent estimates from earlier studies (Nelskamp and Verweij, 2012), the abnormally low porosity values of the JUT-01 Rotliegendes reservoir, compared to porosity-depth trends for similar facies in non-inverted basin areas (Grötsch, 2011) and the high seismic velocities encountered in the anticlinal structure (Vijverberg, 2019).

2 Burial anomalies in inverted basins in the Netherlands

The clastic reservoirs in the Netherlands have experienced a burial history with gradual burial over geological times over tens to hundreds of millions of years (Ma). In some (inverted) regions the burial of reservoirs may have been considerably deeper in the geological history than present day burial. For the Netherlands, many studies have proven that this is the case in inverted basins. This is evidenced by maturity data, sonic velocities and palinspastic reconstruction and/or backstrip analysis and basin modelling (e.g. Van Balen et al., 2000; Nelskamp and Verweij, 2012; Van Wees et al., 2009; Worum and Van Wees, 2017; Figure 1).

In case of a burial anomaly, the present-day burial depth may show a relatively poor reservoir quality in terms of porosity and permeability with respect to its present-day depth. In particular wells on anticlinal structural highs, including JUT-01 and EVD-01 in the Utrecht region, have been identified to be marked by significant burial anomalies in excess of more than 1000 m by past basin modelling studies (Figure 2).

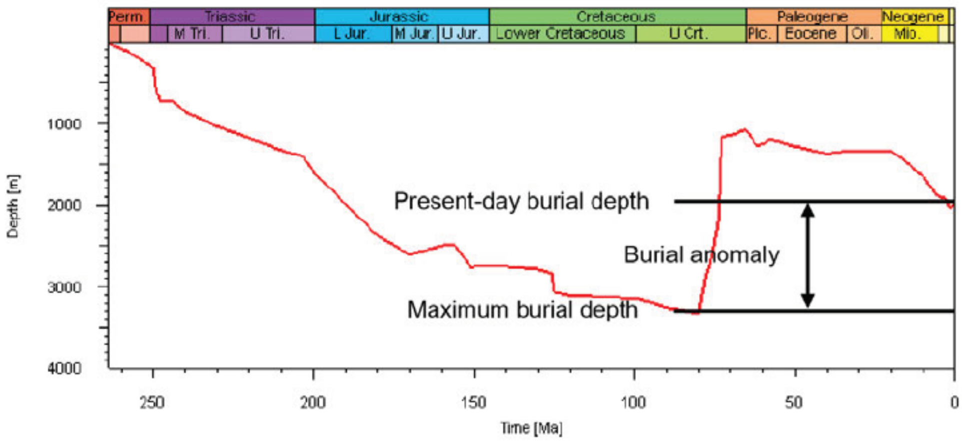

Figure 1 Quantitative assessment of bwurial anomaly from reconstructing the burial history of a well in the West Netherlands Basin (source: fig. 35 from Nelskamp and Verweij, 2012).

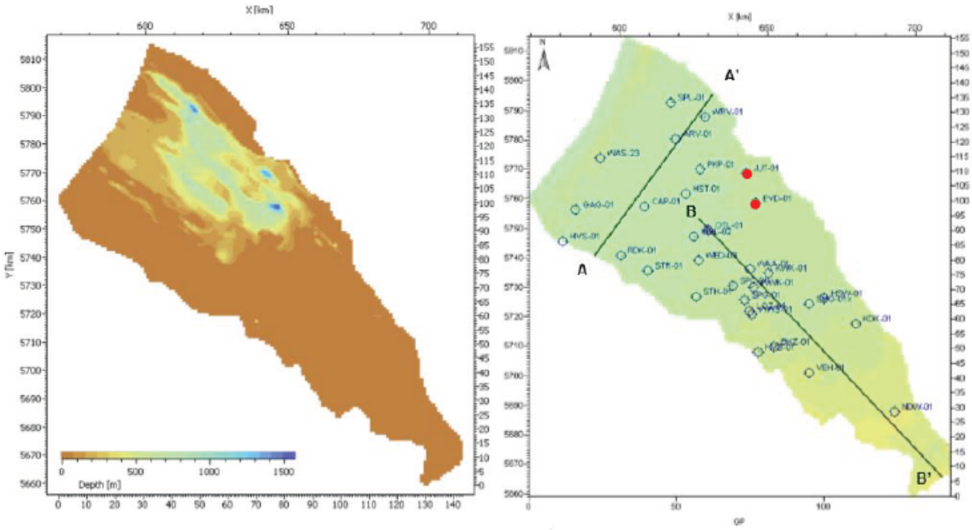

Figure 2 Left: Map view pattern of burial anomalies in the West Netherlands Basin and Roer Valley Graben of the Late Cretaceous, calculated as difference between Late Cretaceous burial and present day. Right: Location of wells used including JUT-01 and EVD-01 (in red) (source: Nelskamp and Verweij, 2012)

3 Simplified method for constructing burial anomaly of an anticlinal crest

The method we propose here uses a simplified backstripping approach (Figure 3). It reconstructs the original sediment thickness at the start of the inversion (h_p) from the thickness the sediments have today at the deeper flank buried below the erosional unconformity (present day thickness h_{pd}). It is argued that this deeper flank has been marked by the same depositional history (thickness of sediments) as the anticlinal crest prior to the onset of inversion.

Estimation of the burial anomaly related to an anticlinal structure involves the following steps:

1 Backstrip the preserved thickness to the thickness it had prior to inversion (h_p). To this end, calculate the solid thickness (h_s) of the preserved thickness by subtracting the pore fraction integrated over the present-day depth range (h_{φ_pd}):

$$h_s = h_{pd} - h_{\varphi_{pd}}\ ,\ h_{\varphi_{pd}} = \left\lfloor -k\ \varphi_0\ e^{-\frac{z}{k}} \right\rfloor_{zmin}^{zmax} \quad \text{(eq. 1)}$$

And solve for h_p:

$$h_p = h_s + h_{\varphi},\ h_{\varphi} = \left\lfloor -k\ \varphi_0\ e^{-z/k} \right\rfloor_0^{h_p} \quad \text{(eq. 2)}$$

2 Add additional eroded thickness on the flank (h_e) to the total pre-inversion thickness:

$$h_{p\_total} = h_p + h_e \quad \text{(eq.3)}$$

3 Determine the burial anomaly as

$$BA = h_{p\_total} - z_{crest} \quad \text{(eq. 4)}$$

The integrals in eqs. 1 and 2 assume an exponential porosity (porosity φ as fraction) -depth (z- meter) trend of the form:

$$\varphi = \varphi_0\ e^{-\frac{z}{k}} \quad \text{(eq. 5)}$$

Where φ_0 is surface porosity and *k* is constant. The porosity depth curves vary significantly for different lithologies (e.g. Van Wees et al., 2009; Nelskamp and Verweij, 2012). Here we adopt a porosity depth curve with $\varphi_0 = 0.55$ and k=2000.

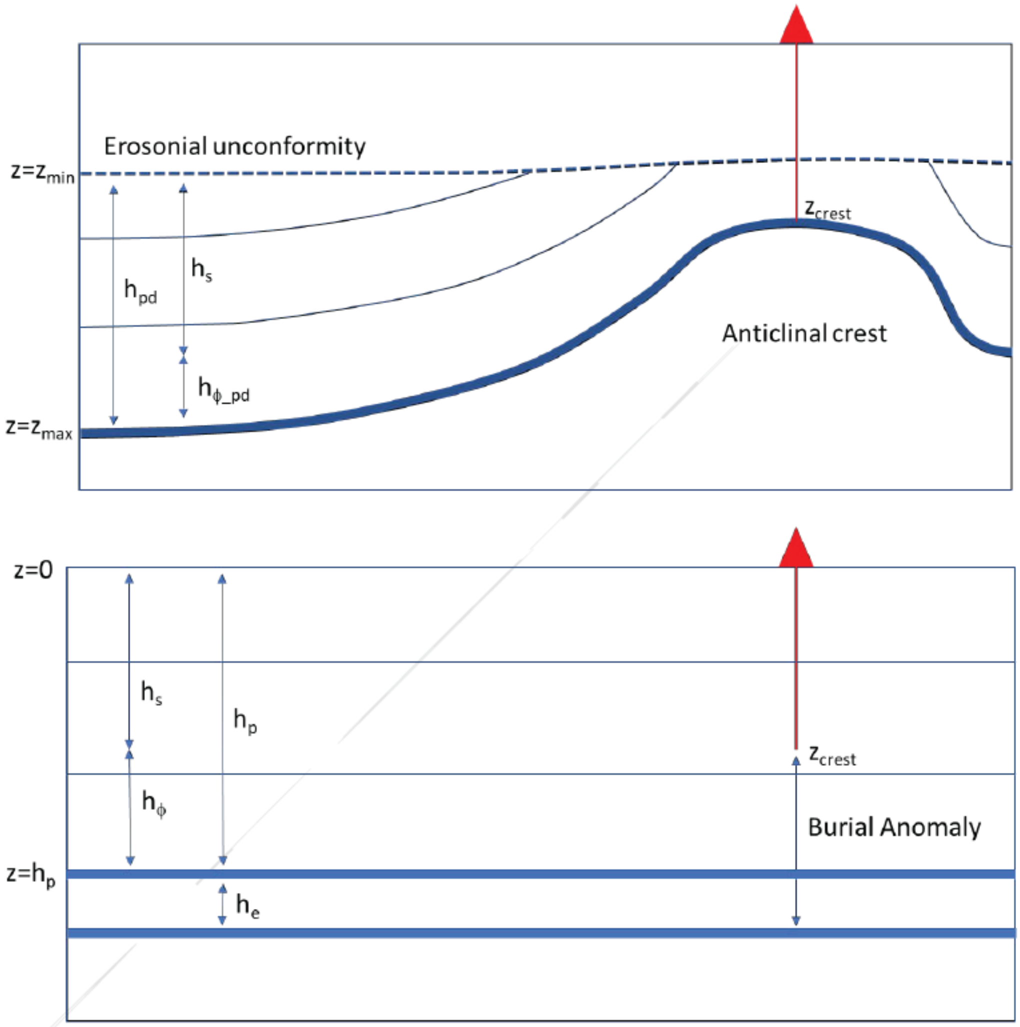

Figure 3 Schematic cross section illustrating the reconstruction of sediment thickness from present-day (top) to pre-inversion stage (bottom). The thick line denotes the geothermal reservoir drilled in the past by the hydrocarbon industry in the anticlinal crest (denoted by the red triangle and line).

4 Results for JUT-01

The JUT-01 well is located at an anticlinal crest (Figure 4), formed during the Late Cretaceous inversion. The targeted Rotliegendes geothermal reservoir is encountered at relatively shallow depth in JUT-01, with the top Rotliegend at only 1648 m depth.

The seismic section over the crest clearly shows a folding structure, with relatively continuous strata from the crestal anticline deeper down the southern flank of the anticline (Figure 5)

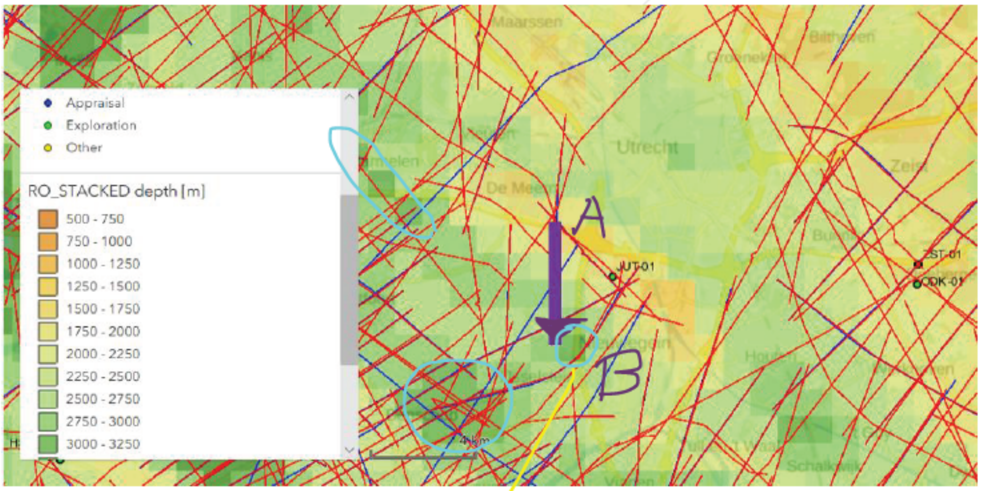

Figure 4 Snapshot from ThermoGIS of top Rotliegendes depth map in the Utrecht region. In red location of seismic lines, in purple location of seismic line MZ85-14 (partially shown in Figure 5) and section of DGM model v4.0 (Figure 6)

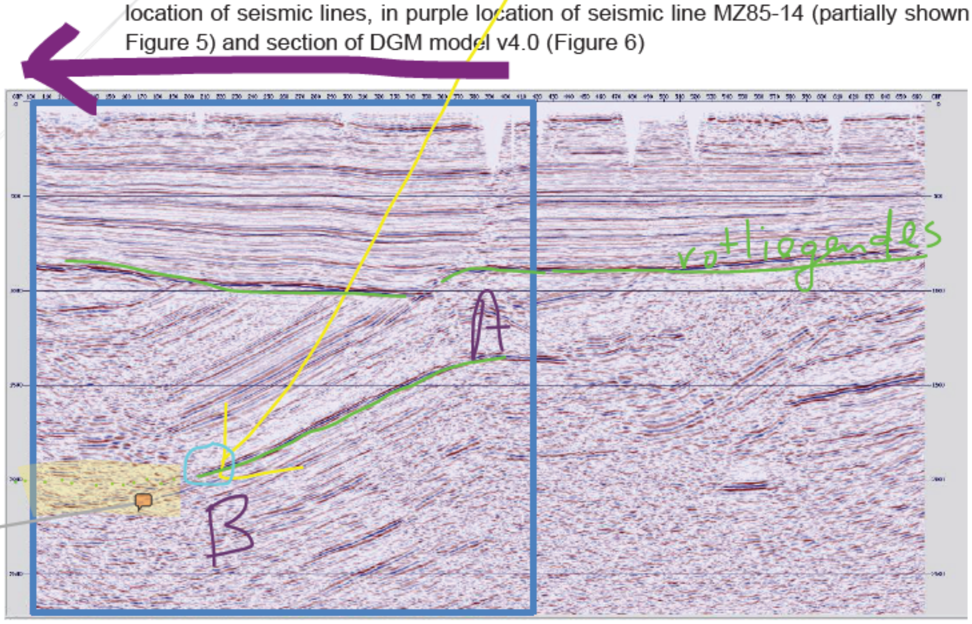

Figure 5 Seismic line MZ85-14. The left part of the line, in the blue box, approximately corresponds to the purple section line in Figure 4 (source Vijverberg, 2019).

Figure 6 shows the depth converted interpretation of the geological structure over southern flank of the anticline. It clearly highlights the erosion of Jurassic strata at the crest, in accordance with the seismic line in Figure 5.

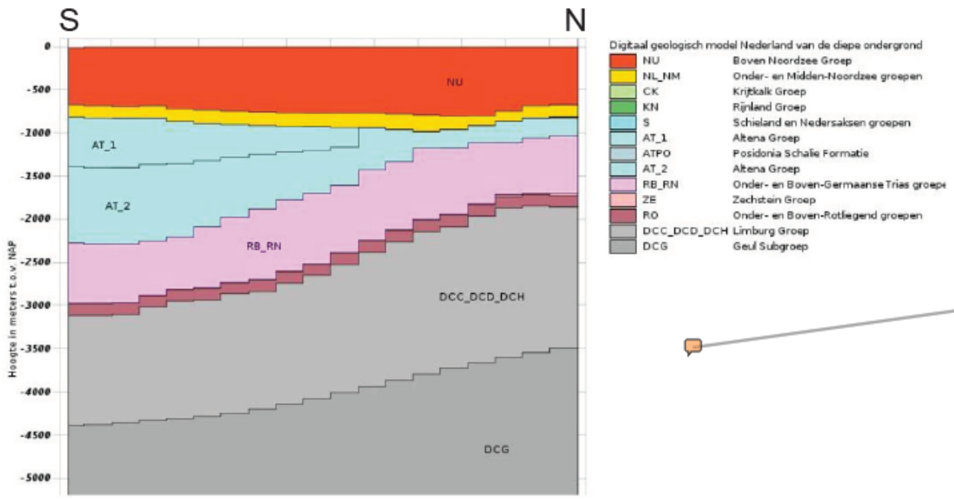

Figure 6 Cross section of DGM v4.0 (from https://www.dinoloket.nl/ondergrondmodellen) at the location shown in purple in Figure 4.

In order to reconstruct the pre-inversion thickness of the Jurassic and Triassic sediments we first determine z_{max} = 3000 m (approximate deepest present day depth of top Rotliegendes), Z_{min}= 800 m (approximate depth of post-inversion Base North Sea Group). This results in h_{pd}=2200m.

Application of eq. 1 and 2 results in a pre-inversion backstripped thickness of h_p= 2491 m. This can be found by a goal seek for h_p for eq. 2 (for instance implemented in an Excel environment), substituting h_s=1708m obtained from eq. 1.

Furthermore, we can assume that additional late Jurassic and Cretaceous sediments have been deposited prior to erosion. Adopting h_e= 300 m, results in an estimated pre-inversion burial of ca 2800 m.

The burial of at least ca 2500 m (rounded value from h_p= 2491 m) has lasted from the end Jurassic (ca. 145 Ma) until the onset of inversion estimated at ca 80-70 Ma (e.g. Figure 1; Nelskamp and Verweij, 2012). The reservoir quality at the anticlinal crest evidences that geologically long residence times of tens of millions of years at burial depths of 2500-2800 m did not affect negatively the reservoir quality. Since heat flow and thermal conditions did not significantly change over the last 100 My in this area (e.g. Nelskamp and Verweij, 2012), it is likely that the last 65 My after inversion did not significantly modify the reservoir quality at these depth conditions.

The estimated maximum burial up to ca 2800 m for the top Rotliegendes in JUT-01 results in a burial anomaly of ca 1150 m. This number is a conservative value compared to the burial anomaly of 1300 m estimated by Nelskamp and Verweij (2012)

Our findings are further supported by two independent observations. The first is the fact that the measured porosity values in JUT-01 are relatively low for the aeolian dune reservoir facies (described in the NAM well report, Nachtegaal, 1969) compared to the full spectrum of aeolian dune core plug measurements of porosities in the Netherlands, which have mostly been measured at significantly larger depth (Grötsch et al., 2011). In other words, the encountered porosity of the Rotliegend in JUT-01 is expected at a deeper depth.

The other observation is the detailed seismic velocity structure of the seismic line MZ85-14, which has been obtained from reprocessing of the seismic line (Vijverberg, 2019; Figure 7). It can be clearly seen that relatively high interval velocities are encountered at the anticlinal crest, which appear to follow the dip structure of the anticline. The strong horizontal extrapolation of interval velocity control points locally obscures this trend on the southern flank of the anticline.

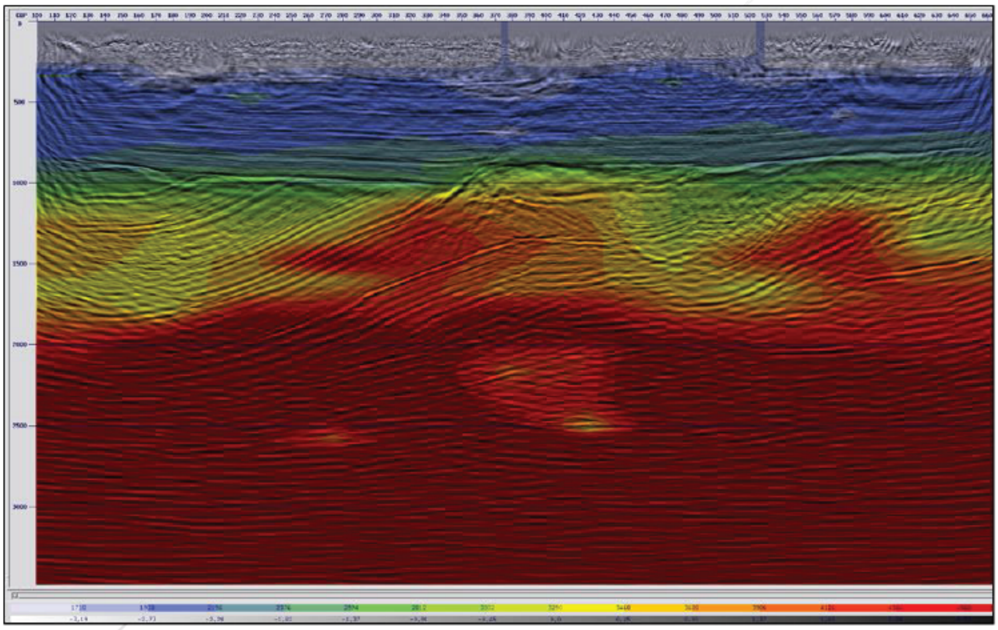

Figure 7 Interval velocity model of MZ85-14 (colours), with the re-processed seismic line of MZ85-14 overlain (source Vijverberg, 2019).

5 Conclusions

We have presented a simple methodology to estimate maximum burial depth and demonstrated that burial anomalies can have large implications for extrapolation of reservoir condition measured at locations with large burial anomaly to deeper depths. In particular reservoir data obtained from wells drilled at anticlinal structures, formed during basin inversion, can be representative for reservoir conditions deeper on the flanks up to depths of past maximum burial. This is often overlooked, as hydrocarbon industry have preferentially targeted structural highs, and as burial anomalies are difficult to estimate and require basin modelling approaches, including palinspastic restoration and/or backstripping.

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Mijn conclusie mbt tot het doelgebeid voor winning en tot de beoogde winningsput voor aansluiting op het WOS

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Notes

1-1 A gemene opmerk ng over de stud e:
Desk study, re-mode ng and mathemat ca ca cu at ons on o d se sm c data by a sma nner c rc e of Dutch experts. No add t ona recent se sm c data from more ocat ons n th s heaven y fractured area have been captured to ncrease re ab ty od the outcome on a sma er more deta ed sca e, nor any rev ew on the outcome has been made by experts outs de th s nner c rc e of Dutch experts.

4-1 Betekent toch ook dat er extreme breukv akken z tten rond N euwege n waardoor de r s co's b j bor ngen en w nn ngen op ca ama te ten toenemen.

8-1 In f guur 5 gt de top op gem dde d 900 m

8-16 De d epte van het Rot egendes waar op gem kt wordt houdt vo gens deze jn op b j 2000 m b edt daarmee een te ger nge warmtetemperatuur voor het warmtenet. Dat s n et ge jk met de nk eur ng n de h eru t afge e de f guur 4 waar een d epte van 2700 m wordt gesuggereerd.

8-18 In d t gedee te s de Rot egendes aag n et meer z chtbaar.

9-1 Deze afge e de f guur corresponeert ook n et met de se smo og sche bas s nformat e u t f guur 5

11-7 M jn conc us es z jn:
Het d epste dee van de nvers e van het Rot egendes strekt z ch u t op een jn over Harme en tot aan N euwege n-Zu d en para e daaraan s ook nog een verge jkbare d epte n een jn d e over Benschop oopt. De d eptes versch en nog we wat b nnen deze jn. Het d epste punt n de jn Harme en gt aan de andere kant van de A2 onder IJsse ste n. D t betekent dat de d chtsb jz jnde gesch kte p aast voor de w nn ngsput op ca 2-3 km afstand van het WOS gt n ZW r cht ng.