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Report on Coulomb Failure Stress models of the Slochteren Sandstone, Delft Sandstone and Dinantian Limestone for KEM-15 ("Cooling induced seismicity")

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1. Introduction

In this report we describe the results of the Coulomb Failure Stress (CFS) change models of the Slochteren, Delft and Dinantian formations that were performed within the KEM-15 project. The Slip Tendency (ST) model results of all three formations are reported in **Appendix 6**.

2. Methodology and model setup

The models analysed in this report are the same models as described in **Appendix 4**. The CFS results for the Slochteren Sandstone are described in detail in **Appendix 9**. The CFS results of Delft Sandstone and Dinantian Limestone scenarios are only shown in this report. The difference between the ST model and the CFS model is only the postprocessing of the results. For the complete model setups, we refer to **Appendix 6 and 9**. The ST methodology is described in **Appendix 5 and 6** and the CFS methodology is described in **Appendix 8 and 9**. Unless otherwise stated, we use a Seismogenic index of -7 and a Gutenberg-Richter b-value of 1 for all CFS scenarios in the Slochteren, Delft and Dinantian reservoir models as well.

3. Results and discussion

3.1. Slochteren sandstone

We analysed the seismic response of all Slochteren Sandstone Scenarios according to the CFS model. We show the influence of the Seismogenic index on the magnitude-frequency distribution and the probability density function of the simulated seismicity (Figure 1). The probability density function describes the likelihood of seismic events with a certain magnitude to occur.

Natural and induced seismicity can be expressed in a magnitude-frequency distribution (Gutenberg-Richter plot), which can be described by the Gutenberg-Richter a- and b-values. The Seismogenic Index (SI) is equivalent to the a-value of the naturally occurring seismicity at a specific site. With the CFS model we calculate the change in the a-value resulting from stress changes induced by geothermal operations (temperature and pressure changes and resulting stress changes).

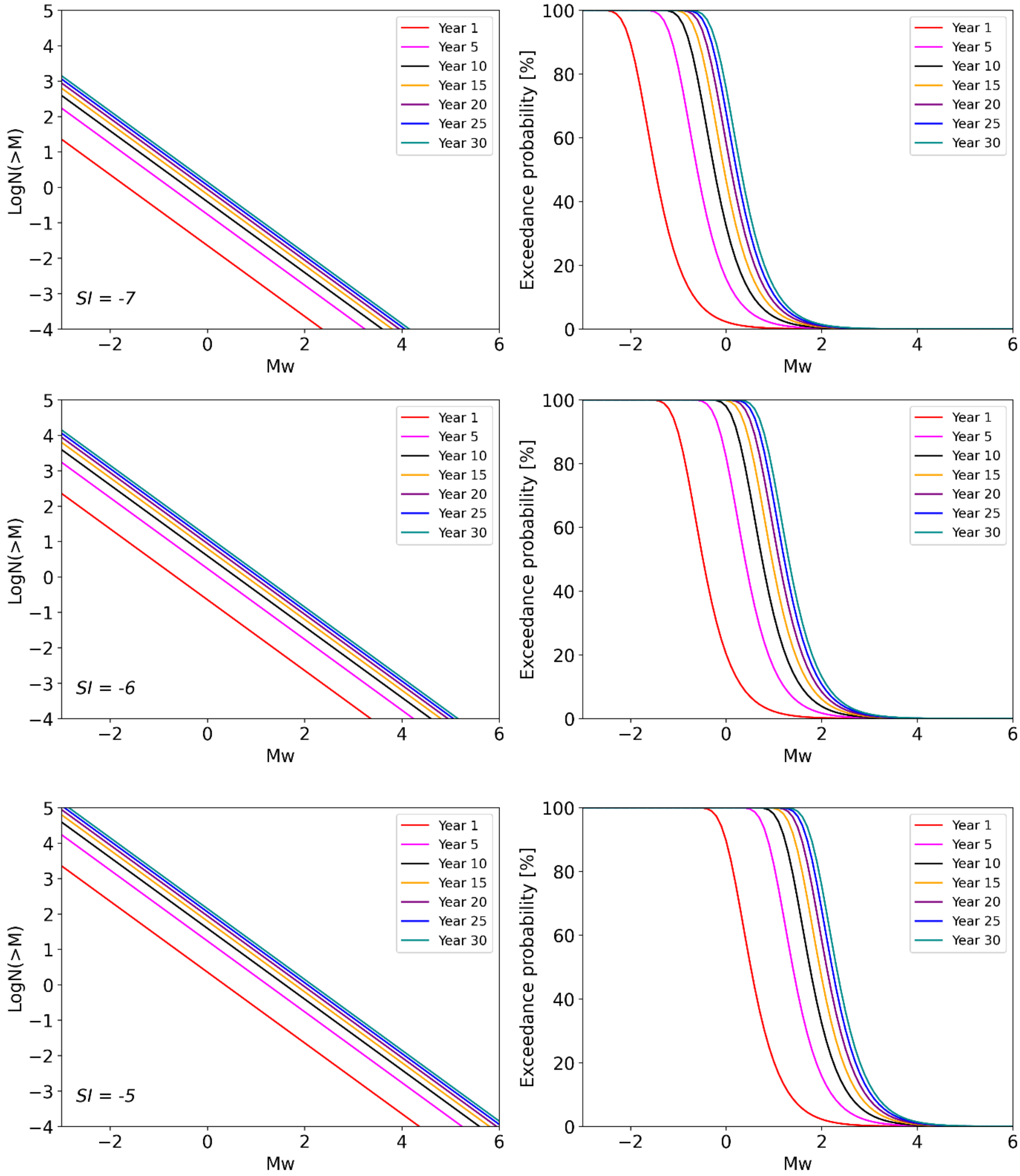

Figure 1: Influence of Seismogenic Index (top row (base case): SI=-7, middle row: SI=-6, bottom row: SI=-5) on magnitude-frequency distribution (left) and probability density function (right) for the Slochteren base case model.

As seen in Figure 1, a higher Seismogenic Index (here -5) leads to more and larger seismic events while a lower Seismogenic index (here -7) leads to less and lower magnitude seismic events. This implies, that in areas with higher natural seismic hazard, also the induced seismic hazard will be higher and in areas with low natural seismic hazard, also the induced seismic hazard will be lower.

For seismic risk assessment we chose a SI of -7 to ensure that our results are consistent with the case study review of Buijze et al.(2019), which suggests a low probability for a seismic event of M > 2.0 in any of the sandstone reservoirs in the Netherlands induced by geothermal operations.

Additionally, we compare the magnitude-frequency distribution of the base case Slochteren model with the naturally occurring seismicity in Figure 2. It can be seen that naturally, no seismicity is to be expected and that the operation of the well-doublet significantly increases the number and magnitude of induced seismic events (even though induced maximum magnitudes are still low).

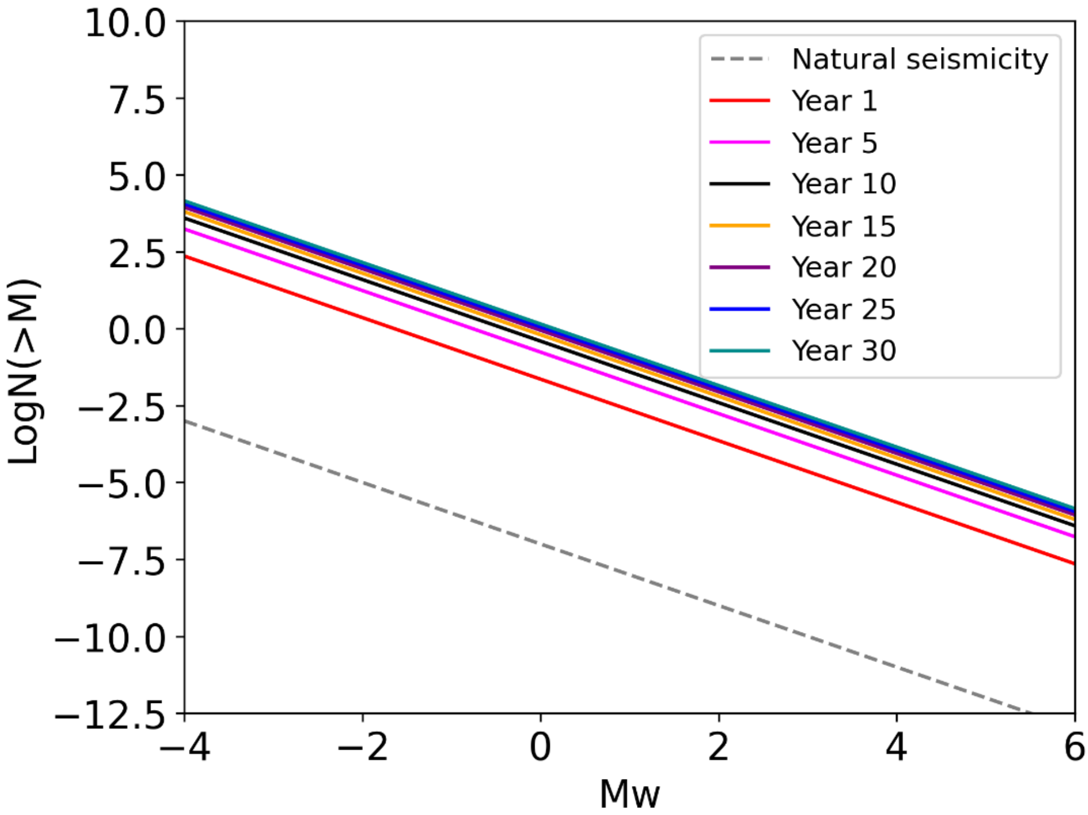

Figure 2: Comparison of naturally occurring seismicity (dashed line) with induced seismicity after 1-25 years of cold-water injection simulated for the Slochteren base case model.

The results of the sensitivity analysis of all Slochteren Sandstone models is shown in Figure 3 and Figure 4, where the moment magnitudes that occur with 10% probability (P10) and with 90% probability (P90) are displayed. Compared to the slip tendency analysis, where individual parameters have a strong influence of the tendency of an individual fault to slip (**Appendix 5 and 6**), in the CFS most of the investigated parameters did not significantly change the simulated induced seismicity. The maximum change in P10 and P90 moment magnitudes is less than 1. The minimum P90 moment magnitude is -0.5 and the maximum P10 moment magnitude is 1.5. The base case values for P90 and P10 are -0.2 and 1.1, respectively.

The main difference between the two models is that in the CFS model even small stress changes lead to seismic slip of statistically distributed critically stressed fractures and faults, while in the ST model stresses need to overcome the friction of one specific fault with a specific orientation in the stress field. Nevertheless, both models were able to match the seismicity induced by hydraulic stimulation treatments in Groß Schönebeck (see Blöcher et al., 2018 and **Appendix 8**).

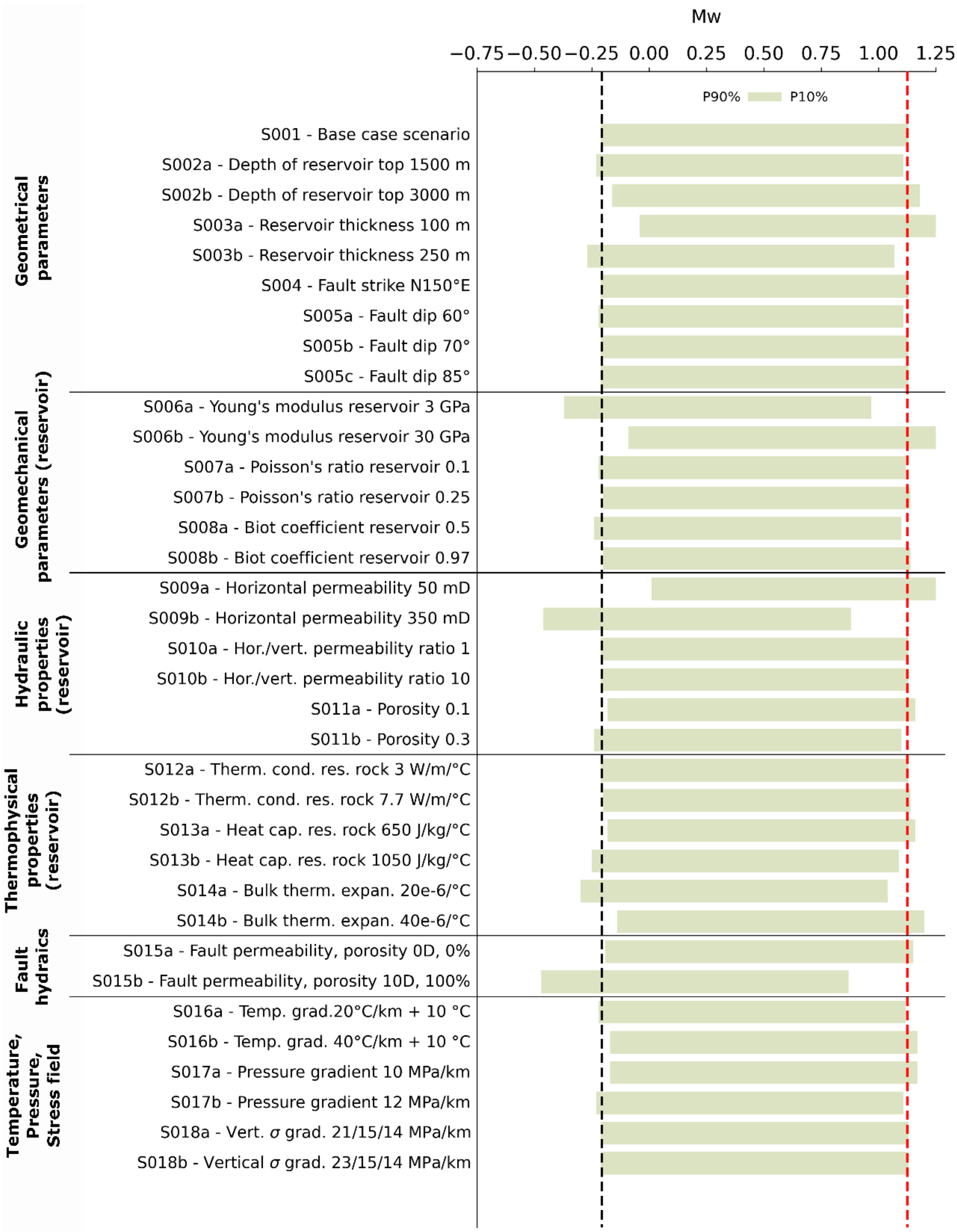

Figure 3: Sensitivity analysis showing the influence of individual model parameters on the probability of earthquake occurrence. P90% and P10% mean a probability of 90% and 10%, respectively, that a seismic event of the specified magnitude will be induced (Scenarios S001-S018b). Black and red dashed lines mark the P90% and P10% values of the base case model,

respectively.

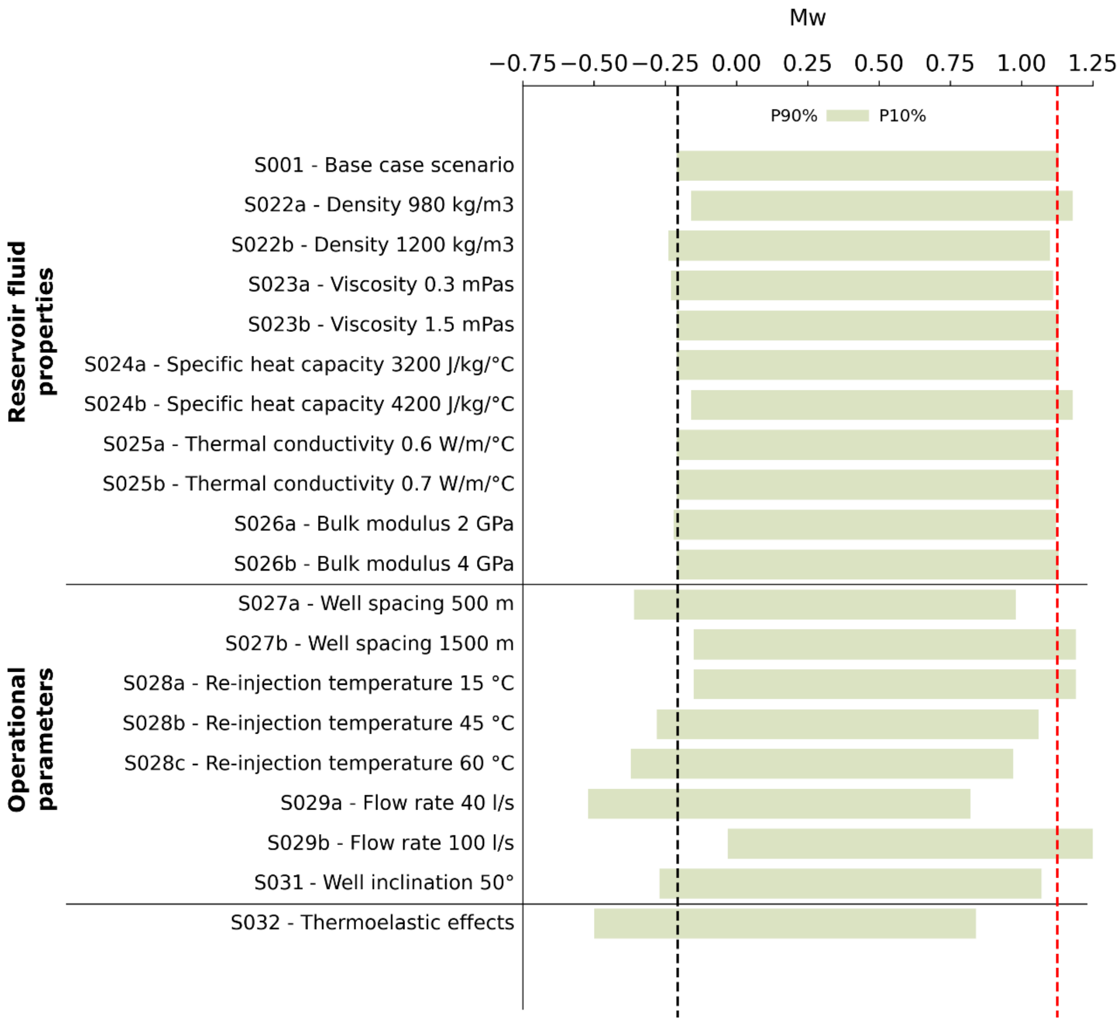

Figure 4: Sensitivity analysis showing the influence of individual model parameters on the probability of earthquake occurrence. P90% and P10% mean a probability of 90% and 10%, respectively, that a seismic event of the specified magnitude will be induced (scenarios S022-S032). Black and red dashed lines mark the P90% and P10% values of the base case model, respectively.

3.2. Delft sandstone

Despite the fact that the slip tendency model indicates that the investigated fault is more prone to slip in the Delft base case model as compared to the Slochteren base case model (**Appendix 6**), the CFS results of Slochteren Sandstone (Figure 1) and Delft Sandstone (Figure 5) model are similar, although the seismic hazard is slightly lower in the Delft sandstone reservoir, which is most visible in the first year of the operation.

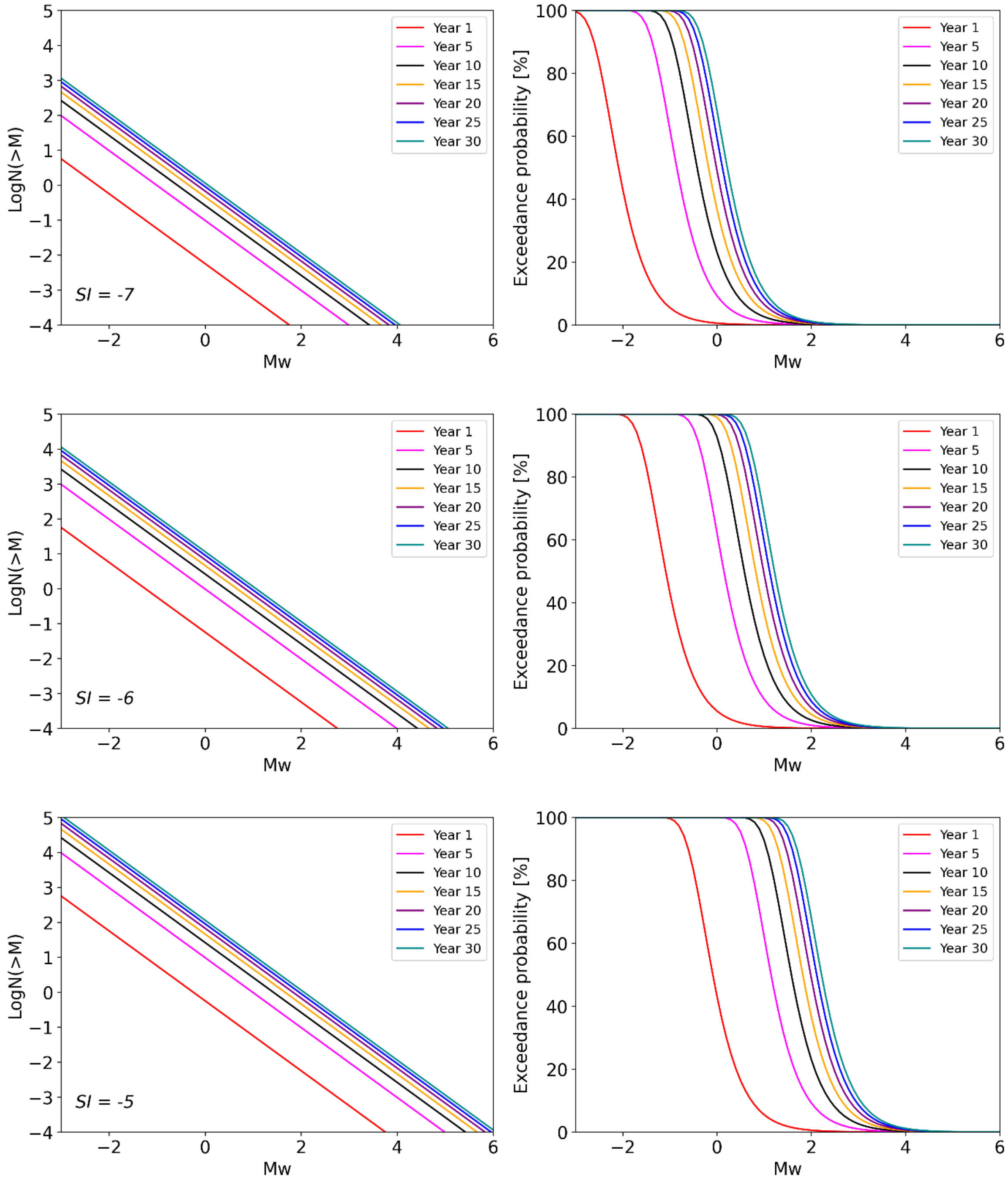

Figure 5: Influence of Seismogenic Index (top: SI=-7 (base case), middle: SI=-6, bottom: SI=-5) on magnitude-frequency distribution (left) and probability density function (right) for the Delft base case model.

Figure 8 shows the influence of the SI in the case of the Delft base model. The effect is the same as in the Slochteren sandstone model; the higher the SI, the higher the induced seismic hazard.

The comparison of the influence of reinjection temperature on the probability of earthquake occurrence in case of the Slochteren and Delft sandstone reservoir models is shown in Figure 6, represented by the P10 and P90 parameters. The Delft sandstone model results show a slightly lower seismic hazard compared to the Slochteren Sandstone base model. The minimum P90 moment magnitude is -0.5 and the maximum P10 moment magnitude is 1.2. The Delft base case values for P90 and P10 are -0.3 and 1, respectively.

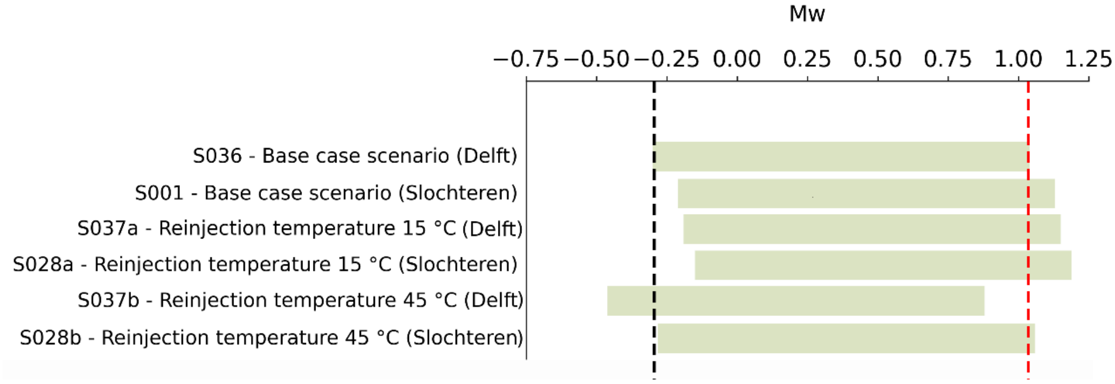

Figure 6: Comparison of influence of reinjection temperature on probability of earthquake occurrence in case of Slochteren and Delft sandstone reservoir models. P90% and P10% mean a probability of 90% and 10%, that a seismic event of the specified magnitude will be induced. Black and red dashed lines mark the P90% and P10% values of the Delft base case model, respectively.

3.3. Dinantian limestone

Figure 7 shows the simulated induced seismic hazard for the Dinantian modelling scenarios (with SI = -7) compared to the Slochteren and Delft base scenarios. The P90 and P10 values for the Dinantian base model are magnitude 0.21 and 1.55, respectively. Based on our modelling results, the Dinantian reservoir has a higher induced seismic hazard potential compared to the sandstone reservoirs, however, the maximum induced seismicity (occurring when the cold fluid is injected directly into the fault damage zone) is still below the detection level (M>2). This is because we used the same SI here. However, a higher natural seismic hazard and thus a different SI is likely.

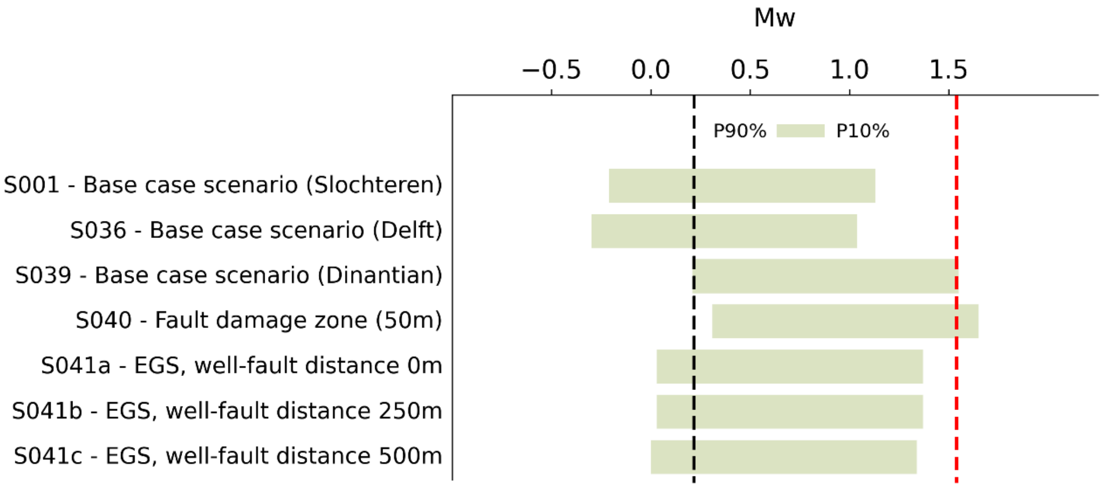

Figure 7: Comparison of the results of the Dinantian modelling scenarios with the Slochteren and Delft base models in terms of seismic hazard. P90% and P10% mean a probability of 90% and 10%, respectively, that a seismic event of the specified magnitude will be induced.

References

Blöcher, G., Cacace, M., Jacquey, A.B., Zang, A., Heidbach, O., Hofmann, H., Kluge, C. & Zimmermann, G., 2018. Evaluating micro-seismic events triggered by reservoir operations at the geothermal site of Groß Schönebeck (Germany). Rock Mechanics and Rock Engineering **51**(10): 3265–3279.

Buijze, L., van Bijsterveldt, L., Cremer, H., Paap, B., Veldkamp, H., Wassing, B.B., Van Wees, J.-D., van Yperen, G.C., ter Heege, J.H. & Jaarsma, B., 2019. Review of induced seismicity in geothermal systems worldwide and implications for geothermal systems in the Netherlands. Netherlands Journal of Geosciences **98**.