Influence of the heat flow anomaly above a salt dome on shallow water temperature in the Drentsche Aa

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Abstract

The aim of this project is to evaluate how a salt dome influences the shallow water temperature. To see what happens in the subsurface on top of a salt dome, a numerical simulator program is needed. The research will be done with the finite element modeling program TOUGH. The graphical user interface for TOUGH is PetraSim. The specific area that the upper part of the model is based on is the Drentsche Aa, where two parts of the river merge. The model is built based on the open source data of TNO.

After the model is built, it will run until it is in steady state. There are 3 spots where salt water and fresh water were injected, respectively. In the model, the water flowed for 1,000 years, and after that the temperature distribution was viewed.

The difference between salt and fresh water was negligible, and the water flew upwards to the surface.

The temperature on top of the salt dome is higher than the temperatures that are on the sides of the model. The reason for this is that the thermal conductivity of salt is much higher than the other materials and therefore conducts heat better than the surrounding. The shallow ground water temperature is therefore higher than when there is no salt dome. In the heat peaks, where the heat accumulates, the temperature increase varies between 0.3°C and 1.0°C.

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Introduction

Geothermal energy is heat that comes from the inner part of the Earth. The dominant source of geothermal energy is radioactive decay inside the Earth. Since the beginning of planet Earth, many geological periods have taken place. The different geological periods formed many different earth layers, such as salt, clay and sand. These ground layers are not always flat, mostly because of plate tectonics, difference in pressure and other stresses. All of the ground materials have their own material properties. All different layers combined with the different material properties provide the variation in temperature in the shallow water per location.

Currently, it is not clear how the presence of the Anloo salt dome influences the shallow water temperature in the Drentsche Aa. The exercise is to examine if the shallow water temperature is affected by the salt dome, therefore water will be injected in a modeling excercise to simulate a flow. The flow represents the ground water that is flowing in the subsurface. Salt and fresh water will be injected separately to determine whether there is a different flow due to the different water compositions. This will be done with the finite element modeling program TOUGH2. The graphical user interface for TOUGH is PetraSim.

The exact location where the upper part of the model is based on is the Drentsche Aa where two parts of the Drentsche Aa merge. A detailed map of the area and subsurface is given in Figure 1 and Figure 2. [Dinoloket, 2015]

Figure 1: Map of the study area

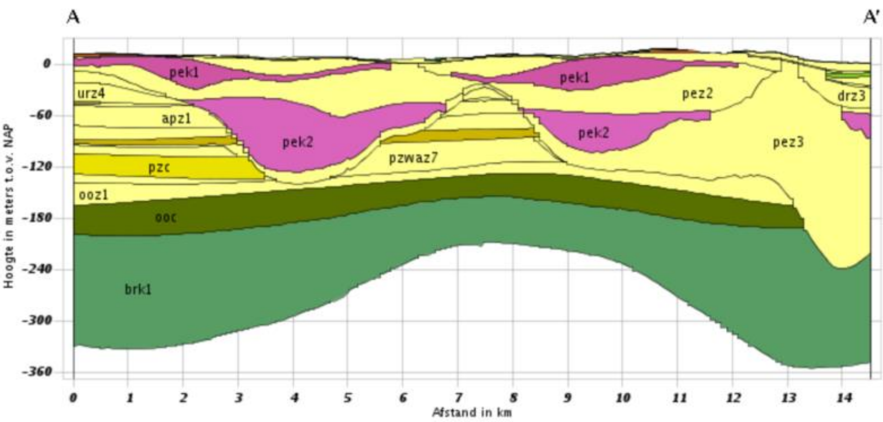

Figure 2: The subsurface of the study area (vertical exaggeration 19:1)

Methodology

The subsurface model of the Netherlands is made by TNO, which is open source. To find the subsurface model of the specified region, the cross section of the model area gives the output as shown in Figure 2. The depth of the cross section is around 300 meters. The width of the cross section can be determined by the user. The given subsurface is only available in 2D and is made by REGIS II, a modeling program that is made for the hydro geological structure and permeability of the subsurface.

Model setup

The selected subsurface map is taken from TNO. The subsurface is simplified in the model, because the calculation time of TOUGH increases rapidly with adding layers. The reason to omit some layers is that these layers are small and do not differ much from the surrounding layers. These layers only cause trouble for TOUGH and generate numerical errors, while the benefit of adding these layers is negligible. The omitted layers have the same rock density as the layers as where they are merged with. The permeability of the omitted layer is also in the range of 10% with the merged layer. The coordinates of the TNO data are taken and copied to the TOUGH model. The upper and the lower locations of the layers are copied, so the two layers enclose a subsurface layer. Each layer has specific material properties. (Which are given in Table 1)

In PetraSim there are two different ways to build a model. The first one is to add different layers, where each layer has its own material and mesh. This way of building a model doesn't work for this geometry. This is because the layers are too complex for PetraSim. The layers converge to the eastern side of the model. Due to steep slopes between the cells, the large difference between the vertical and the horizontal component and the associated differences between the material properties in the cells will cause numerical errors and therefore the model will crash.

This problem can be solved by the second method to build a model. The second option is to create a rectangle with a small grid size. The corresponding layers can be added in the rectangle by using it as an internal boundary. This way ensures that the cell sizes are all the same. When two layers share a cell, the cell will get the properties of the layer which has the highest share of that cell. The drawback is that there is no mesh refinement around layer boundaries.

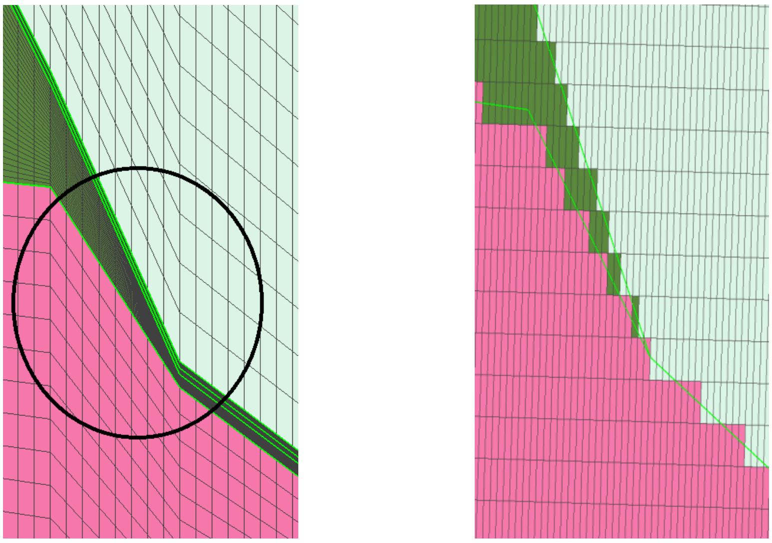

Figure 3: Two different mesh types (left: method 1, right: method 2)

The upper 300 meters of the model are the objective and also the most varying part, so the cell size of the upper 300 meter was chosen to be smaller than the lower 3200 meters.

The cell size in the top 300 meter is 20 meter width and 5.5 meter height. In the lower part of the model, all cells have a height of 15 meters and a width of 20 meter. The large size differences between neighboring cells and high ratios between height and width of a cell may cause numerical problems. This is the reason why the first method of building a model causes a crash in TOUGH. In this model, the factor for the upper and lower part is respectively 3.6 and 1.3. This factor is the height of the cell divided by the width. This factor should not be higher than 10, because of the numerical problems. These values are considered appropriate for the model, since it ran without errors. The benefit of building a model this way is that it is easier to implement the finite element method. Another benefit of building the model this way is that the layers converge on the sides of the model, while there is no material present in that location. An example is given in Figure 4

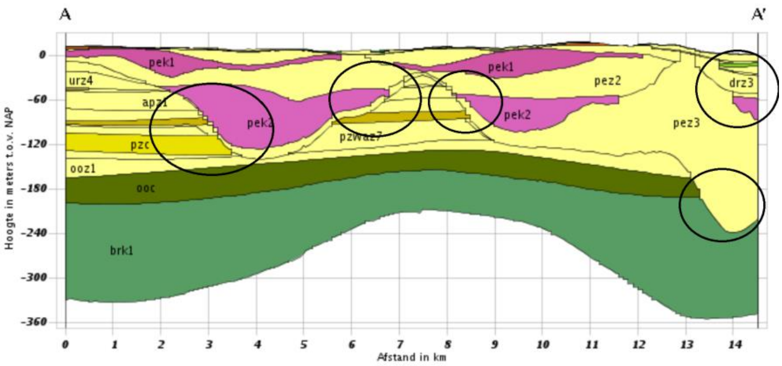

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Figure 4: The difficult spots of the model, vertical exaggeration 19:1

When the first method is used, the cells on the converged lines will be infinitely small. The effect of these cells is negligible while the cells still have to be calculated. The effect of the meaningless cells is that the calculation time increases and the model will eventually crash. The second method sees that the share of the meaningless cells is small and the cell will be assigned to the layer with the largest share. This means that the boundary problems disappear. Therefore the calculation time will decrease and the model won't crash. Another benefit is that the mesh can be more detailed in other places, because the omitted cells can be used elsewhere.

The disadvantage of this model is that the layers are not smooth anymore, because the cells are not infinitely small. This problem can be solved by a smaller mesh size. The problem with a smaller mesh is that the calculation time increases rapidly. The flow of the injected water can be seen in this mesh. The benefits of a bigger mesh do not outweigh the disadvantage of the huge additional calculation time for the purpose of this research. A study of the temperatures in the upper 10 or 20 meter of the model will need a higher resolution of the mesh.

After finishing the subsurface model, some initial conditions have to be given. The temperature and pressure of the surface and Rotliegend area are set to be fixed. The model runs until it is in steady state.

Lithologies

Each layer has its own lithology, with specific density, porosity, horizontal and vertical permeability, wet heat conductivity and specific heat. All the layers with their name are given in Figure 5. The related values and properties of the different lithologies can be found in Table 1.

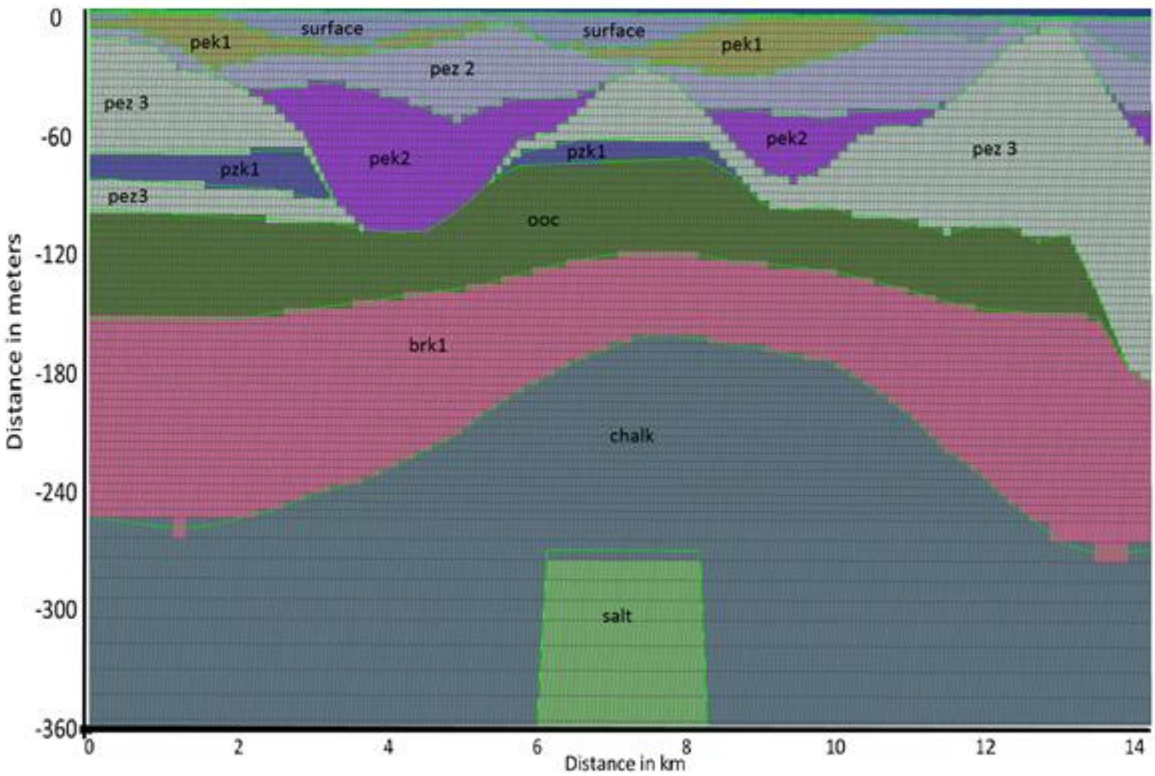

Figure 5: All the layers with their names (vertical exaggeration 14:1)

Name	Lithology	Density [kg/m3]	Porosity	Horizontal permeability [m2]	Vertical permeability [m2]	Wet heat conductivity W/[m*K]	Specific heat J/[kg*K]	Source
Surface	Sand	2500	0.1	1.48E-11	1.48E-11	3.0	1061	A, B,
pez2	Sand	2640	0.3	6.34E-11	6.34E-11	3.0	1061	A, B, D
pez3	Sand	2640	0.3	3.18E-11	3.18E-11	3.0	1061	A, B, D
pek1	Clay	1780	0.4	1.06E-14	1.06E-14	2.0	869	A, C
pek2	Clay	1780	0.4	4.22E-15	4.22E-15	2.0	869	A, C
pzk1	Clay	1780	0.4	2.32E-14	2.32E-14	2.0	869	A, C
brk1	Clay	1780	0.2	1.06E-13	1.06E-14	2.0	869	A, C
ooc	Sand	2640	0.2	1.06E-12	1.06E-13	3.0	1061	A, B, D
Salt	Salt	2170	0.01	0	0	5.5	880	A, E
Chalk	Chalk	1200	0.26	6.58E-17	1.32E-18	2.0	900	A, E
Rotliegend	Sand	2640	0.1	6.0E-15	6.0E-15	3.0	1061	A, B, D

A: Magri, 2011. B: Botor, 2002. C: Smoltczyk, 2003. D: Dezayes et al., 2008. E: Waples et al., 2004.,

Table 1: All the rock properties

Name	Description
pez2	Second sand unit from Peelo
pez3	Third sand unit from Peelo
pek1	First clay unit from Peelo
pek2	Second clay unit from Peelo
pzk1	First clay unit from Peize
brk1	First clay unit from Breda
ooc	Complex unit from Oosterhout

Table 2: Nomenclature of the lithoformations

Initial conditions

To solve the differential equations initial and boundary conditions are needed. The initial condition for temperature is the geothermal gradient. The geothermal gradient is around 25°C per kilometer depth. In the Rotliegend, there is a uniform temperature. There is a borehole (ANLOO-1) in the studied area, where a temperature log is made. The temperature around 3500 meter depth is around 100°C and is fixed. Also the surface temperature is in a fixed state. The average surface temperature in the Netherlands is around 10°C, so the fixed surface temperature is 10°C. Also a fixed surface temperature of 0 and 20°C has been tested.

The initial condition for pressure is the hydrostatic pressure gradient. The pressure gradient is 87.65 bar per kilometer. This gradient is taken because the pressure at 3300 meter depth is 307 bar. The pressure gradient of fresh water in the subsurface is 97.3 bar/km.[Nelson, 2003] Because the model runs after this initial condition, this value is only used for the pressure at 3300 meter depth. This depth corresponds to the Rotliegend. The pressure at the surface is atmospheric and is stated fixed at 1 bar.

Steady state

When a model is in steady state, the model output doesn't change in time. This means that the model is in balance. TOUGH interprets a model to be in steady state after the whole model doesn´t change during 10 time steps in a row. A time step can be set fixed or can be automatically adjusted by TOUGH. TOUGH increases the time step when the solutions converge.
The steady state of this complex model is hard to reach. After about 20,000 years, the model is practically stable. Because of the complexity of the model, some cells will remain instable for a long time. The importance of this couple of cells is negligible, but to reach the steady state these cells cause delay.
The input of the model only consists of the temperature and pressure gradient, while the Rotliegend and surface properties are fixed. The result of this model is used as initial conditions for the dynamic model.

Injection of groundwater

The steady state situation of the model was used for the injection of water. The temperature and pressure distributions of the steady state will be loaded in the new models where water will be injected. To inject water, there are two options possible. The first option is to build a well, which can be used to inject water. The completion depth of the well can be chosen and the well is able to inject water and steam or to inject a tracer. The second option is to choose a cell which is a starting point for a flow. In both options, the injection of water is determined by the rate and the enthalpy. The second option has the advantage with respect to the first option that instead of a constant rate the rate can specified as a constant flux rate. Because the groundwater flow of the selected area is 0.1 meter/day, it is necessary to use a constant flux rate. This is the reason why a well injection doesn't work in this model. Consequently, the only option in this model to inject water is put water with a certain pressure and flow rate in a cell. The water that is injected will simulate a groundwater flow. This water should have the same pressure and temperature as the surrounding, so the pressure and temperature of the steady state provide the enthalpy input value. The injected water provides an increasing pressure, and therefore the water will flow.

The enthalpy input value is calculated by the following formula:

$$H = U + pV \tag{1.1}$$

Where H is the enthalpy [Joule], U is the internal energy [Joule], p is the pressure [Pascal] and V is the volume [m³]. To inject water into the system, PetraSim needs an enthalpy in units J/kg. Therefore, the specific enthalpy has to be calculated. The specific enthalpy is calculated by the formula:

$$h = H/m \tag{1.2}$$

In this formula, h is the specific enthalpy [J/kg], H is the enthalpy [J] and m is the mass of the cell. The mass of the cell is specified by the volume of the cell and density of the material. The specific enthalpy of the injected water is calculated by using the pressure and temperature of the exact location where the water will be injected. Figure 8 is a P-h diagram, where the enthalpy, temperature and pressure are given.

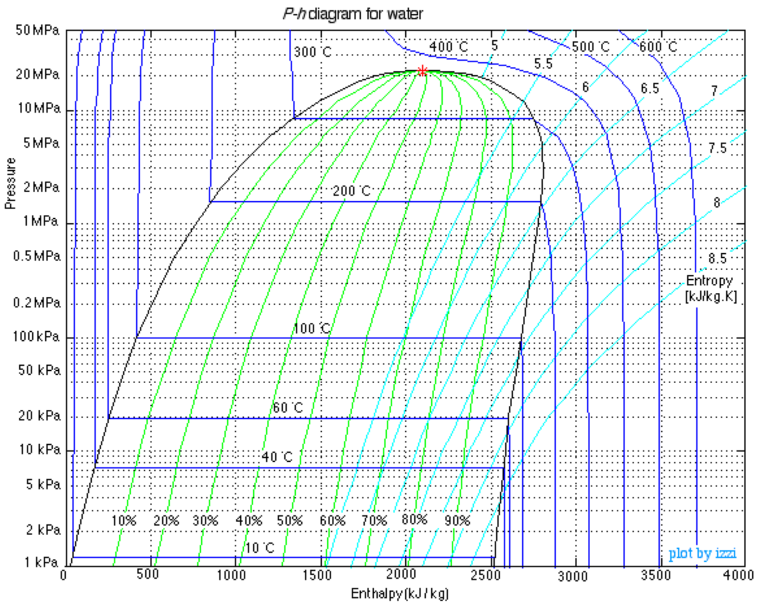

Figure 8: A P-h diagram for fresh water. [NIST Chemistry workbook]

The flux rate of the water injection can be calculated by using the densities of fresh and salt water. The flux rate ϕ [kg/(s·m²)] can be calculated by dividing the constant ground flow rate φ , 0.1 meter/day, by the density of the specified water. In Table 3 the injected values are shown. The flux rate is thus calculated by the formula:

$$\phi = \varphi/\rho \tag{1.3}$$

Where ϕ is the flux rate, φ is the groundwater flow rate and ρ is the density of water.

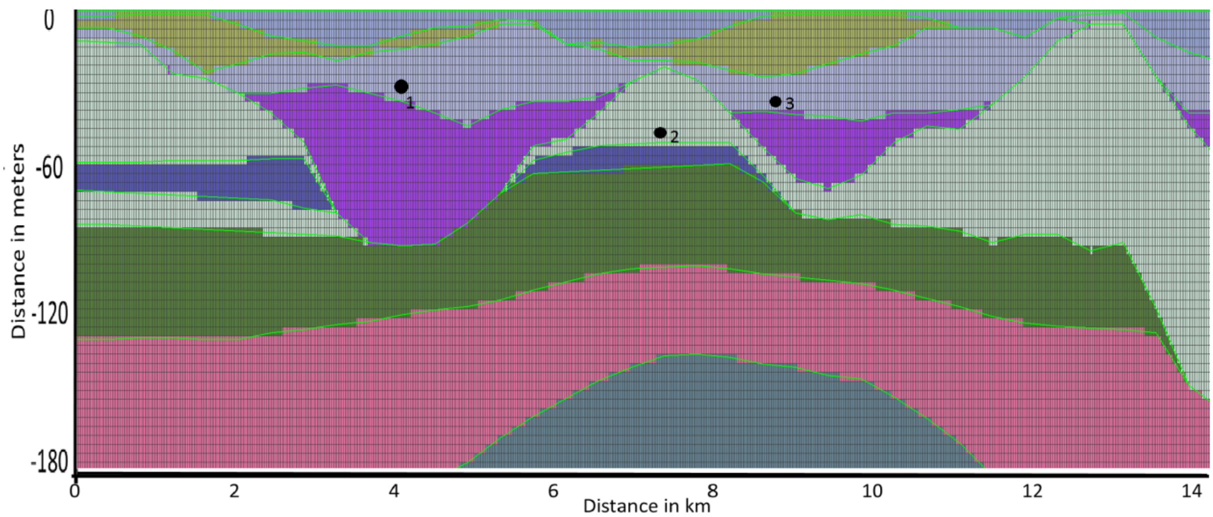

Figure 6: The injection points in the model (vertical exaggeration 14:1)

Spot	Fresh/salt water	Specific Enthalpy [J/kg]	Constant rate [kg/(s m²)]
1	Fresh	4.70E4	1.16E-3
1	Salt	4.70E4	1.19E-3
2	Fresh	5.52E4	1.16E-3
2	Salt	5.52E4	1.19E-3
3	Fresh	5.06E4	1.16E-3
3	Salt	5.06E4	1.19E-3

Table 3: The injection values with their spots

Injection points

The hypothesis is that the flow is going along the clay layers. Therefore the water should be injected in a sand layer between clay layers.

Output and solution control

The goal of this research is to investigate how the shallow ground water temperature is influenced by the salt dome. Water is injected to see how the water flows through the subsurface. The results of this model are shown in images of the model over time. In these images of the temperature (or pressure) the values of the whole model can be checked. In the case of the water injection, the time steps are set to be fixed. Because PetraSim sees a model as in steady state when no cell in a model changes in 10 time steps, the time step should be high enough. When the changes in time are too small, PetraSim labels a model as in steady state while this does not have to be the case.

TOUGH/PetraSim

This model is made by the finite modeling program TOUGH ("Transport Of Unsaturated Groundwater and Heat"). A finite modeling program uses the finite element method, a numerical technique for finding approximate solutions for boundary value problems for partial differential equations. There are a several versions of TOUGH, like TOUGH2, T2VOC, TMVOC, TOUGH2-MP, TOUGHREACT and TOUGH+. Each TOUGH version has its own features, such as the number of phases that can be used, the different kinds of mixtures that can be injected and other aspects that differ from each other. Within each TOUGH version, an 'Equation of State' (EOS) should be chosen.

In this study TOUGH2 is being used. TOUGH2 is a basic simulator for non-isothermal multiphase flow in fractured porous media, which is made to solve the heat flow problems. The TOUGH2 simulator TOUGH2 is primarily designed for geothermal reservoir studies, but is also very useful for calculating the heat flow. To calculate the heat flow, fluid flow and convection, TOUGH2 uses Darcy's law and gravity, pressure and viscous forces. The thermal conduction of the materials provides the heat transport between the different layers. The simulator also accounts for multiphase transitions in terms of relative permeability.

There are different Equations of States that can be chosen. In this model, EOS1 is chosen. The reason for this is that EOS1 is made for water injection research. The water injection properties that are needed for EOS 1 are water flux rate and enthalpy. The reason is that only the properties of water are needed, while other components as for example CO2 are not.

TOUGH2 is a numerical simulator to calculate the temperature, pressure and other fluid or gas properties in different cells. The interface of the TOUGH modeling program is PetraSim. PetraSim is a graphical interface program that integrates the TOUGH codes. The advantage of PetraSim is that the user can focus on the model and that the user doesn't have to do all the calculations.

The only option in this model is to vary the vertical cell size. The upper part of the model has more different layers and materials than die lower part of the material. Therefore, the grid size in the upper part should be much smaller than in the lower part. In PetraSim, only the horizontal lines may differ from one another. Therefore, the lower part of the model takes too much cells. This is at the expense of the grid size in the upper part of the model. A better way of defining a mesh would be if the mesh would be easier to customize. This is the other disadvantage of PetraSim.

By injecting water into the ground, an enthalpy has to be given. The problem with enthalpy is that both pressure and temperature are variables. When the input value for enthalpy is varied, PetraSim varies the temperature, while the pressure is stated fixed. A better way of injecting water should be that the pressure and the temperature can be given, so that you can vary both variables independent from each other.

Results

The salt dome has an influence on the temperature distribution in the steady state. As shown in Figure 9, the temperature on top of the salt dome is higher than the surrounding at the same depth level. This is a result of the salt dome, because the heat conductivity of the salt dome is much higher than the surrounding materials. The temperature above a salt dome is therefore higher than if no salt dome is present.

After injecting fresh and salt water into the model at the same temperature as that the cell is in steady sate, it turned out that the difference between the injection of salt and fresh water was negligible. Therefore, the results are extracted from the fresh water injection. On the eastern side of the model, a strange temperature distortion is formed. This is due to the exaggeration of the model. In reality this deformed shape is really small. The point of interest is the middle of the model, so the right deformed shape is ignored. In Figure 10, Figure 15 and Figure 20 the temperature distributions for the western, central and eastern injection are given after 1,000 years. The black dot marks the place where the water is injected. In the appendix the temperature distributions of the three models are given with smaller time steps. These pictures show how the temperature in the model is distributed over time.
The temperature scale for all the pictures is given as in Figure 9. In Figure 9, the steady state of the upper part of the model is given. The temperature varies between 10°C and 15°C in the images, because the interesting temperature changes lie in that temperature range.

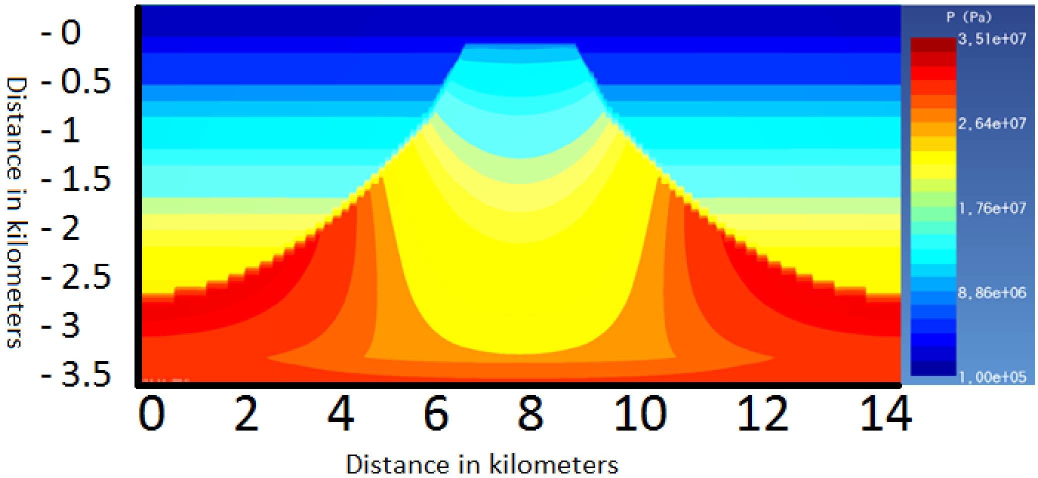

Figure 7: The pressure steady state of the model. Vertical exaggeration 20:1

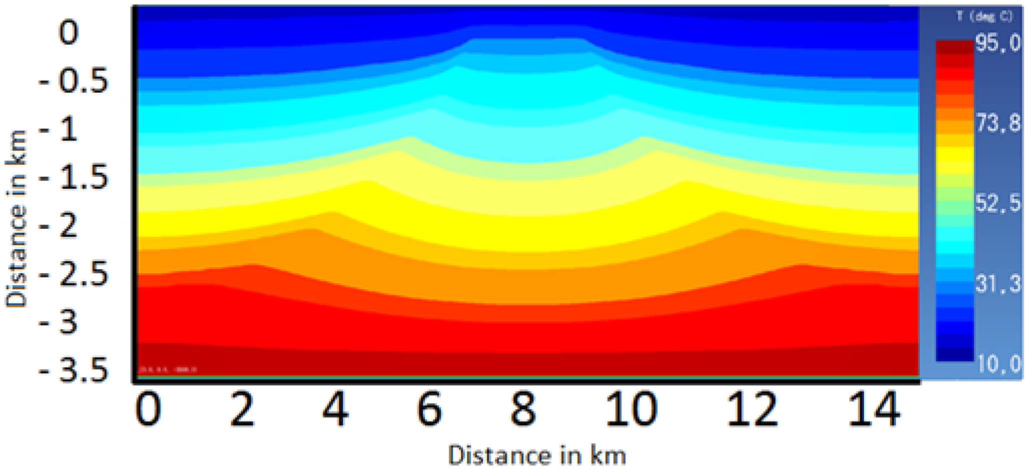

Figure 8: The temperature steady state of the model. Vertical exaggeration 20:1

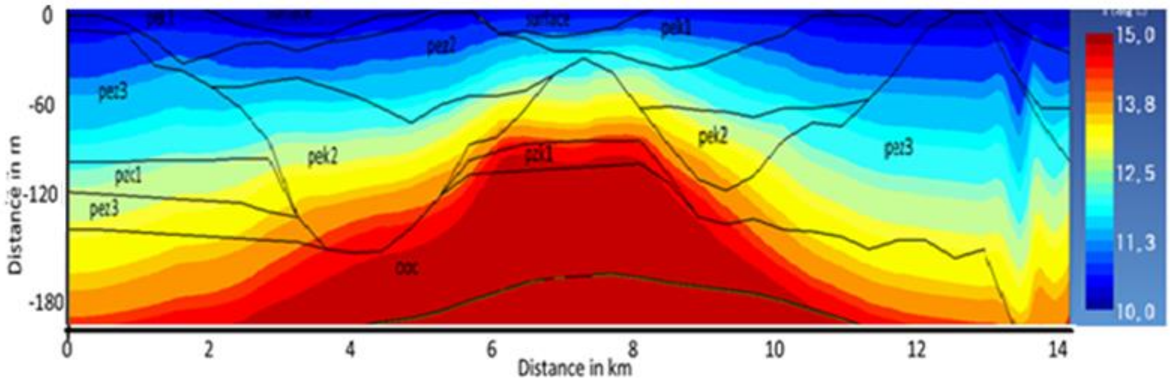

Figure 9: The model in steady state with max temperature 15°C. (vertical exaggeration 14:1)

Injecting water at the left spot

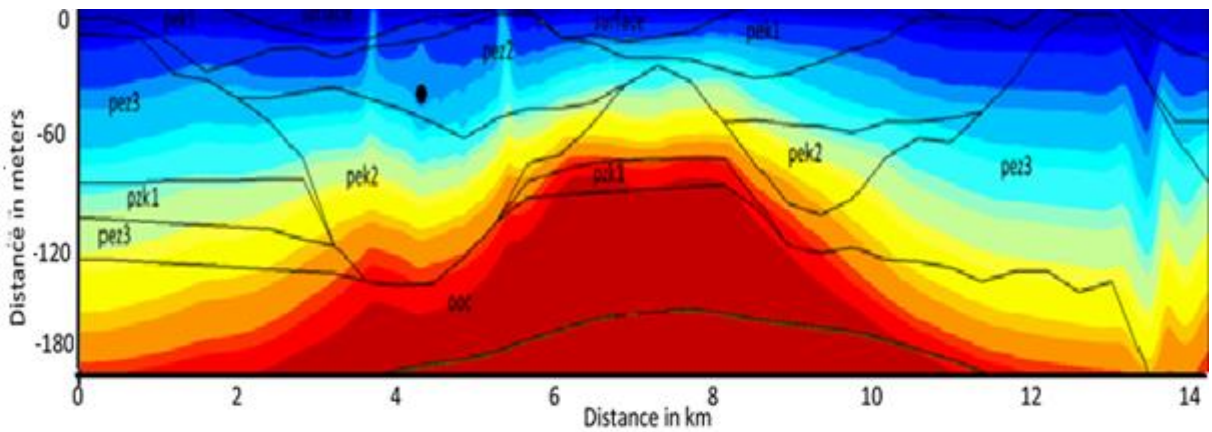

Figure 10: The temperature distribution after 1,000 years when water is injected at the left spot. The temperature scale is the same as in Figure 9. (vertical exaggeration 14:1)

According to the hypothesis, the injected water at the left spot will flow upward. Figure 10 shows that this is the case. The temperature difference is shown better in Figure 13, where there is zoomed in on the temperature distribution. The temperature difference between the steady state and the model after 1,000 years in the left peak is at most 0.3°C. This is shown in Figure 11. The temperature difference in the right peak is at most 0.4°C. This is shown in Figure 12. It looks like that the temperature increases instantaneously, but this is because of the big time step. The steady state is reached in about 160 years.

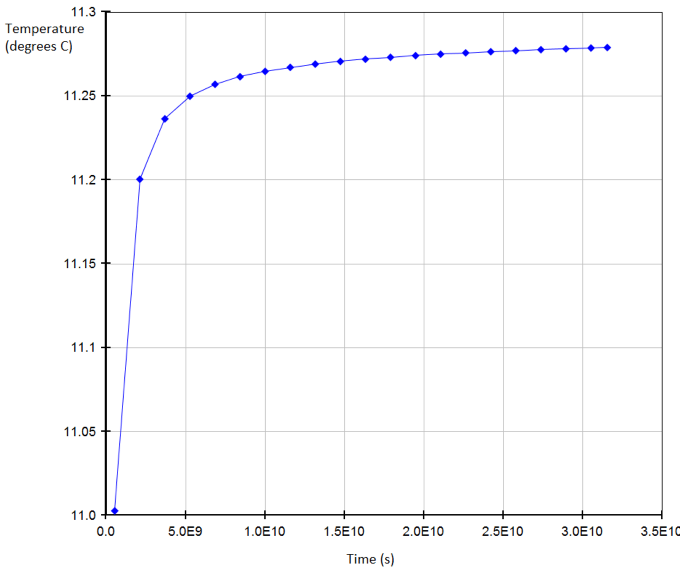

Figure 11: Temperature of the left peak over time

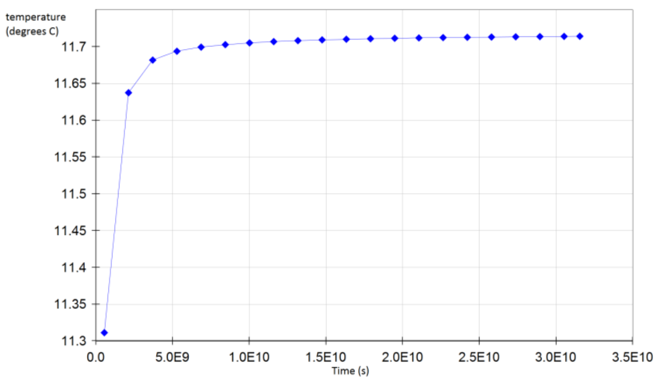

Figure 12: Temperature of the right peak over time

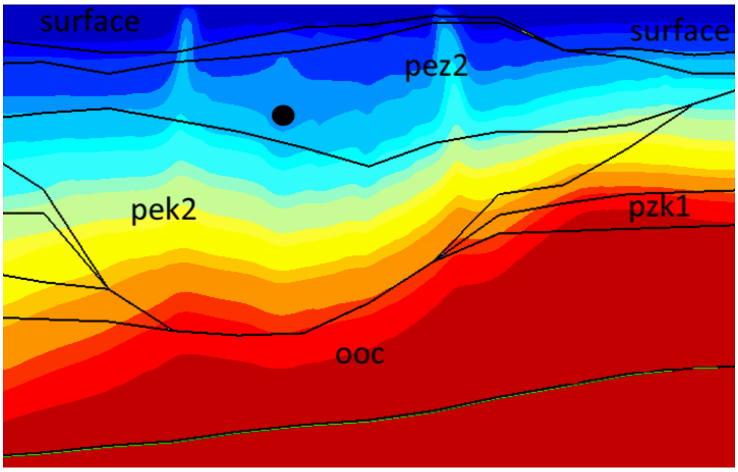

Figure 13: The left spot injection after 1,000 years zoomed in. The temperature scale is the same as in Figure 9

Injecting water at the middle spot

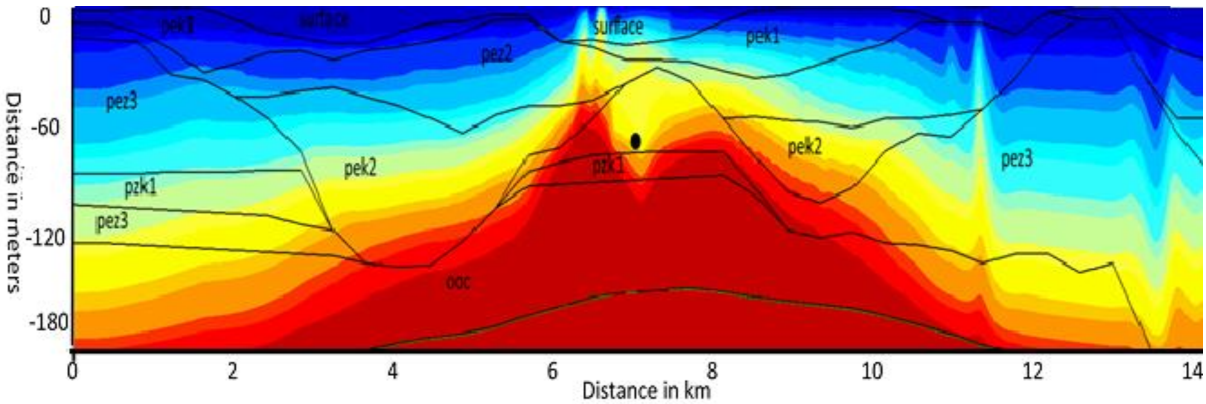

Figure 14: The temperature distribution after 1,000 years when water is injected at the middle spot (vertical exaggeration 14:1)

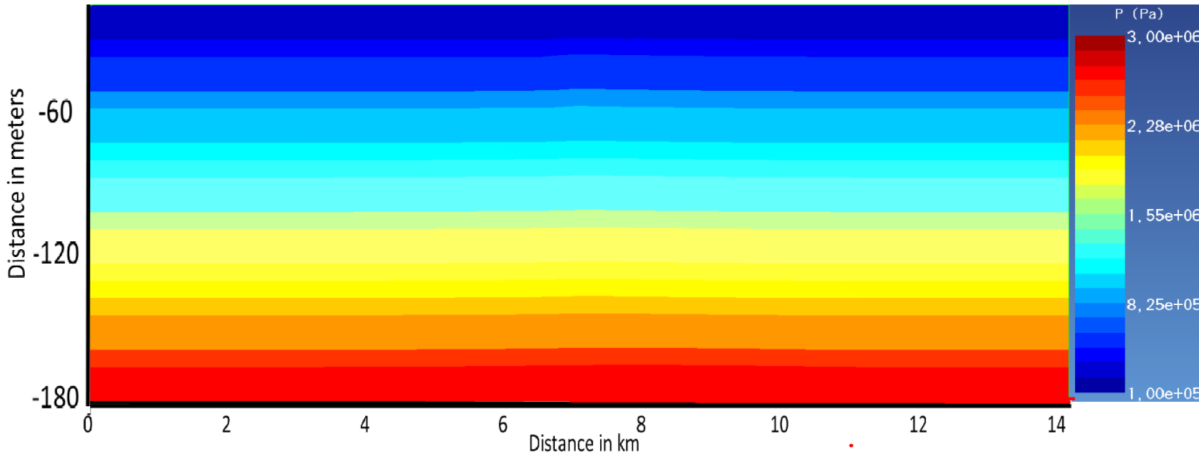

Figure 15: Pressure distribution after 1,000 years (vertical exaggeration 20:1)

When the water is injected in the middle spot, the water will flow upward along the clay layers. The hypothesis that the water flows upward through sand layers instead of clay layers is also confirmed. Figure 17 is a zoomed in picture of the interesting area.

The temperature difference between the steady state and 1,000 years in the left peak is 0.8°C, as can be seen in Figure 16.

The temperature difference between the steady state and 1,000 years in the right peak is 0.7°C, as can be seen in Figure 17.

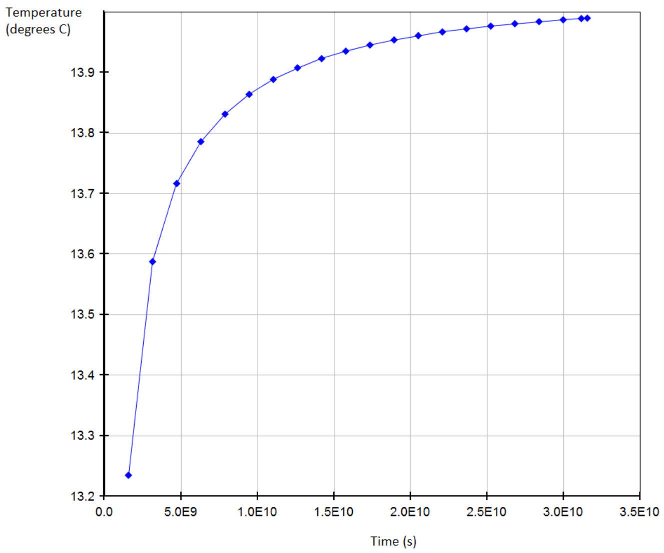

Figure 16: The temperature in the left peak over time

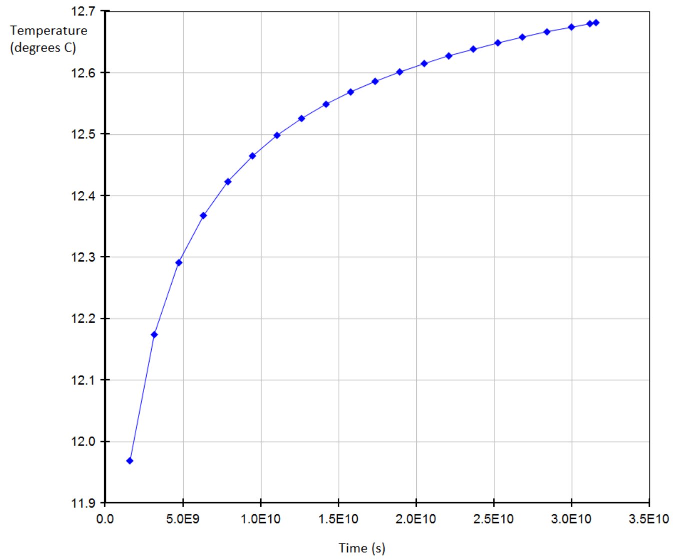

Figure 17: The temperature in the right peak over time

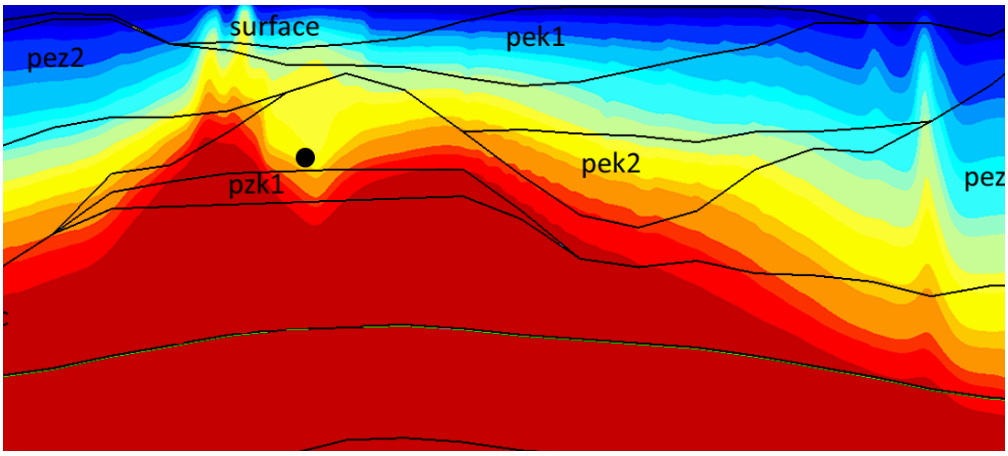

Figure 18: The middle spot injection after 1,000 years zoomed in. The temperature scale is the same as in Figure 9.

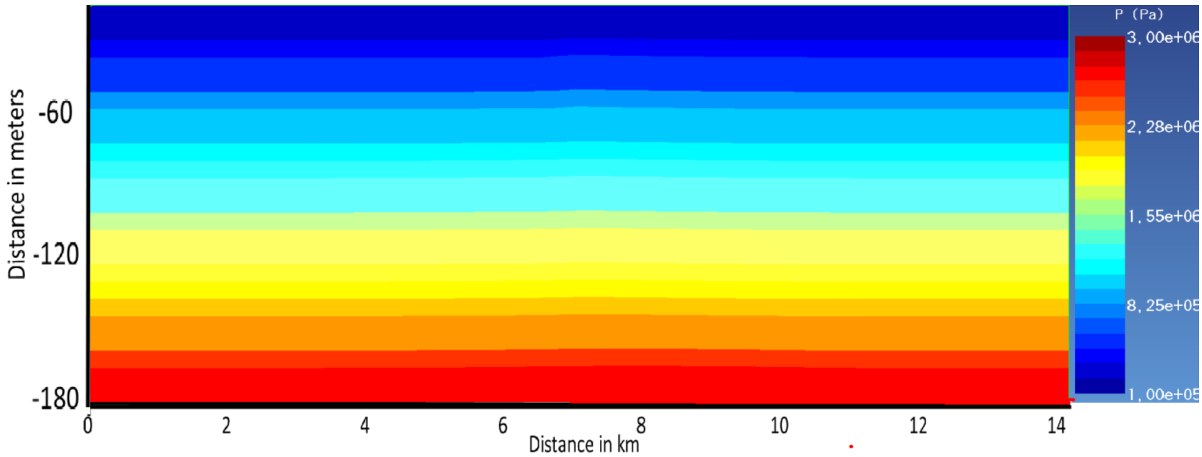

Figure 19: Pressure distribution after 1,000 years (vertical exaggeration 20:1)

Injecting water at the right spot

When the water is injected in the right spot, the water will flow to right and the left between the clay layers. The hypothesis that the water flows upward through sand layers instead of clay layers is also confirmed. Figure 23 is a zoomed in picture of the interesting area.

The temperature difference between the steady state and 1,000 years in the left peak is 0.8°C, as can be seen in Figure 21.

The temperature difference between the steady state and 1,000 years in the right peak is 1.0°C, as can be seen in Figure 22.

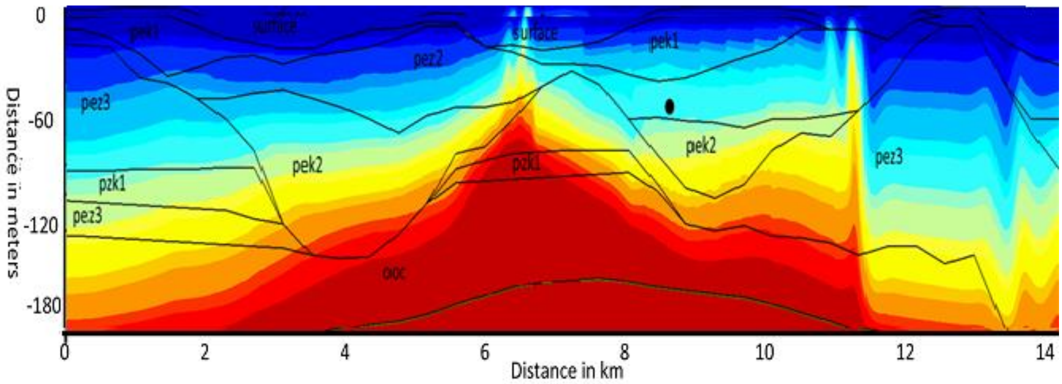

Figure 20: The temperature distribution after 1,000 years when water is injected at the right spot

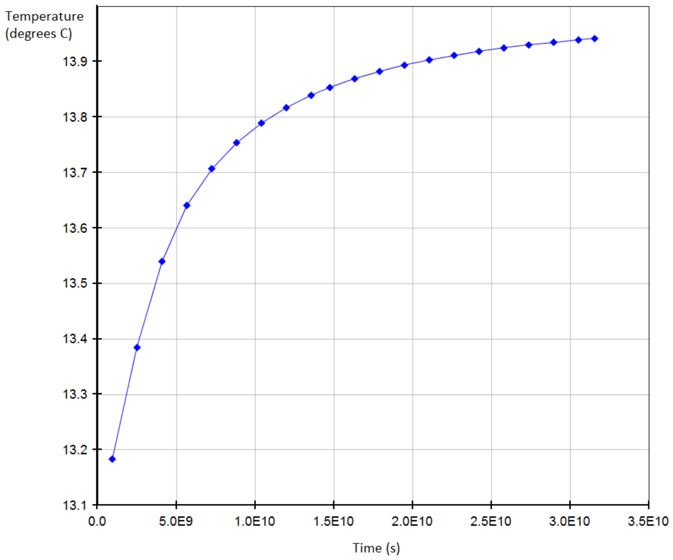

Figure 21: Temperature at the left peak over time

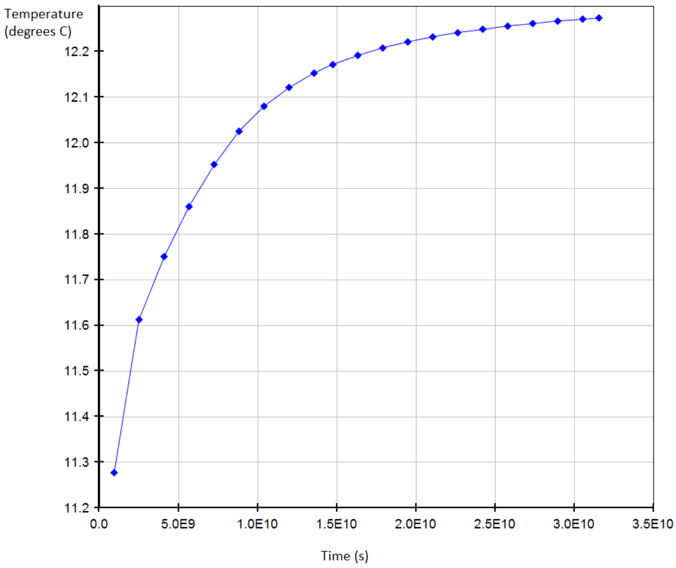

Figure 22: Temperature at the right peak over time

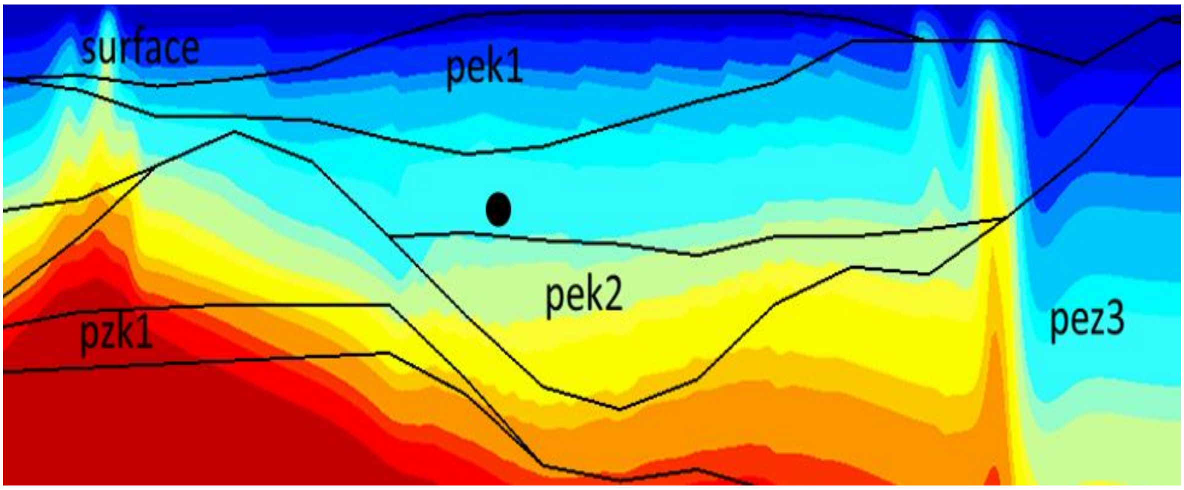

Figure 23: The right spot injection after 1,000 years zoomed in. The temperature scale is the same as in Figure 9

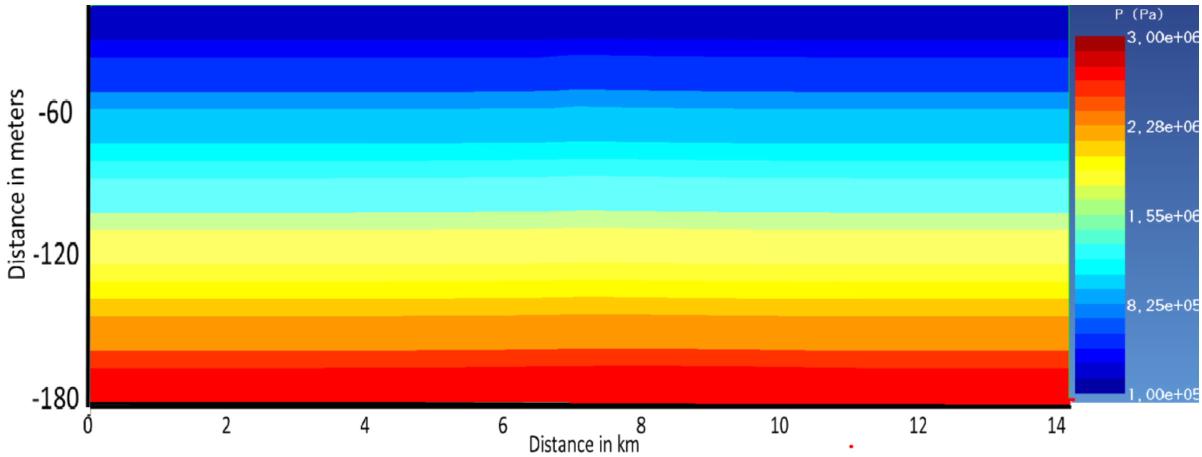

Figure 24: Pressure distribution after 1,000 years (vertical exaggeration 20:1)

Discussion

After the injection of water at the injection spot, the pressure in that point increases. Therefore, the water will flow to places with a lower pressure. Because of the hydrostatic pressure gradient, pressure increases with depth, and therefore the injected water will flow upwards.

Left peak injection

The water is injected in a sand layer between two clay layers, to see how the temperature would distribute. The clay layers have a lower permeability than the sand layers, so the water will flow through a sand layer upward. Because the pressure and temperature of the water below the upcoming flow are higher than the pressure and temperature of the water that flows upward, the temperature below the peaks will also increase. This is due to the rising temperature in the upper layers, which pulls up the lower layers. During this reaction, the temperature below the temperature peak will also rise. At the left side of the injection spot, the water flows through a clay layer. This is a fault of the model, because of the limited mesh. The clay layer is in reality really thin, so the share of the clay layer was too small in some cells. PetraSim used the cell as sand instead of clay. Therefore the water was not actually flowing through the clay, but through the sand.

Middle peak injection

The reason that the flow goes through the sand layers is exactly the same as in the previous injection. The permeability of the clay is lower than the permeability of sand, so the water flows through the sand layers upwards. The left peak is very easy to explain. The water flows upwards through a sand layer and goes along the clay layer to the surface. The right peak is a result of the two clay layers on the right side of the injection spot. The water flows between these layers to the surface. The water flows underneath the lower clay layer, where the pressure will increase. At the most eastern point, a pressure drop arises and the temperature starts to go up. The pressure drop provides that the temperature in the lower layer also increases.

Right peak injection

The reason that the flow goes through the sand layers is exactly the same as in the previous injections. The permeability of the clay is lower than the permeability of sand, so the water flows through the sand layers upwards. Both the right and the left peak are easily explainable. The water flows along the clay layer to the top, where a peak will be formed. The same thing happens as in the middle peak injection. The pressure under the eastern clay layer will increase and at the most eastern point where the clay layer ends, the water will flow upward and a pressure drop arises. Therefore, the temperature peak is formed. The temperature underneath the temperature peak will also rise, due to the pressure drop in the peak.

Error analysis

The mesh of the upper part of the model is not accurate enough. Due to this, the layers are not equal to reality. The problem is that the mesh in PetraSim is not manually adaptable. This could be done better by improving the whole mesh, but at the same time the calculation time would increase dramatically.

Some of the layers are taken together to simplify the model. The reason is that the calculation time would decrease. This is only done with layers that have the same density, wet heat conductivity, porosity, specific heat and a permeability within a range of 10%.

The salt dome that was used in the beginning was not a real dome. Therefore, the choice is made to make an own more realistic dome which can be used in the model. Due to this modification, the model is not comparable to the specified area anymore.
Because the water flows in two directions, in each injection model there arise two temperature peaks.

On the right side of the temperature model, a strange shape is formed. This is because of the exaggeration of the model and in reality this shape is not that dominant. It is possible that this shape is an effect of numerical errors in the model.

Conclusion

The temperature on top of the salt dome is higher than the temperatures that are on the sides of the model. The reason is that the thermal conductivity of salt is much higher than the other materials and therefore conducts heat better than the surrounding. The shallow ground water temperature is therefore higher than without the salt dome present. In the heat peaks, where the heat accumulates, the temperature increase varies between 0.3°C and 1.0°C. This means that the temperature increases by 0.3°C to 1.0°C at places where there is a hole in the shale layer. The temperature difference between the shallow layers of the surrounding areas and the shallow layers of the salt dome area for the steady state model is around 2.5°C. This temperature difference occurs at 120 meter depth. Therefore not all of the extra thermal heat is going into the peaks.

The difference in temperature distribution inside the Earth due to the different surface temperatures is negligible.

The flow is dependent on the litohologies in the upper subsurface. This is because of the different permeability values. Clay has a much lower permeability than sand so water will flow through the sand layer and not through the clay layer.

According to the hypothesis, the results are good. The water flows through the sand layers upwards till a certain level and the water flows along the clay layers. The water flows to the surface and therefore some peaks arise with different temperatures. This is what was expected from the hypothesis.

After the injection of salt respectively fresh water, the temperature distribution was the same. Also the pressure gradient was comparable. Therefore the difference between the injection of salt and fresh water is negligible.

Due to the mesh size, the water does flow through a clay layer in the left injection model. This could have been helped when the mesh size was smaller, but the problem is that the calculation time would be too high.

Further research is possible using a smaller grid size, so the results will be more precise. This requires more time, because the calculation time will increase enormous.

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APPENDIX I

Injection at the left spot

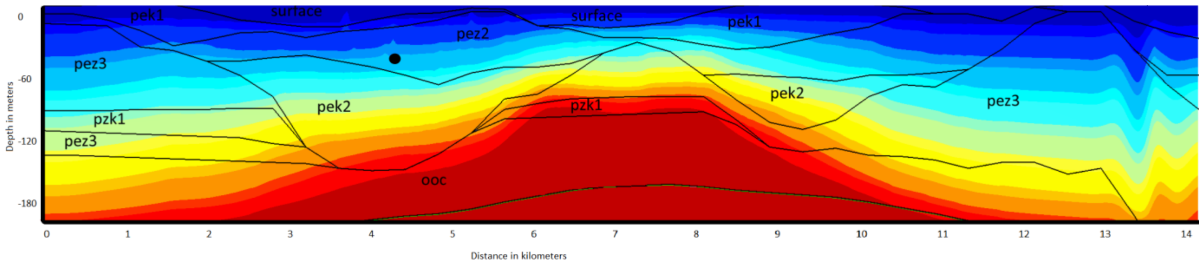

Figure 25: The temperature distribution after 5 months (vertical exaggeration 14:1)

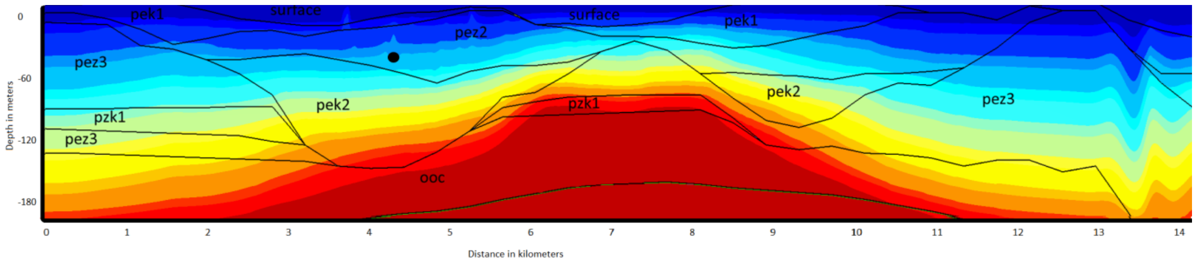

Figure 26: The temperature distribution after 10 months (vertical exaggeration 14:1)

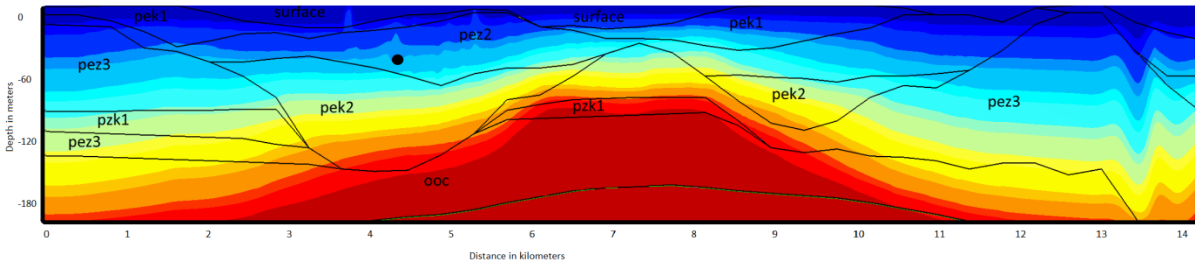

Figure 27: The temperature distribution after 20 months (vertical exaggeration 14:1)

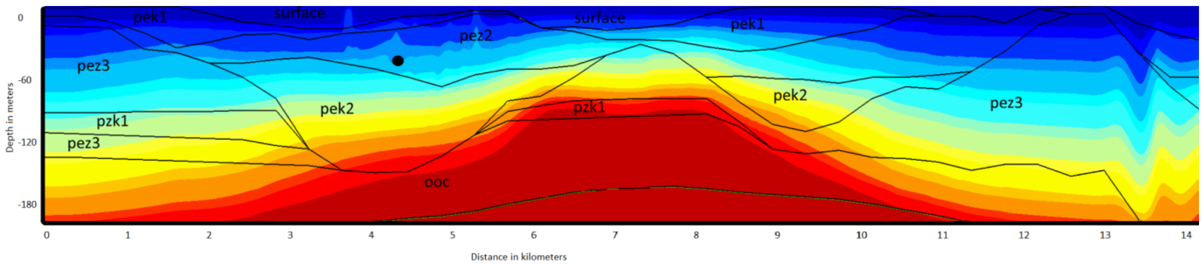

Figure 28: The temperature distribution after 30 months (vertical exaggeration 14:1)

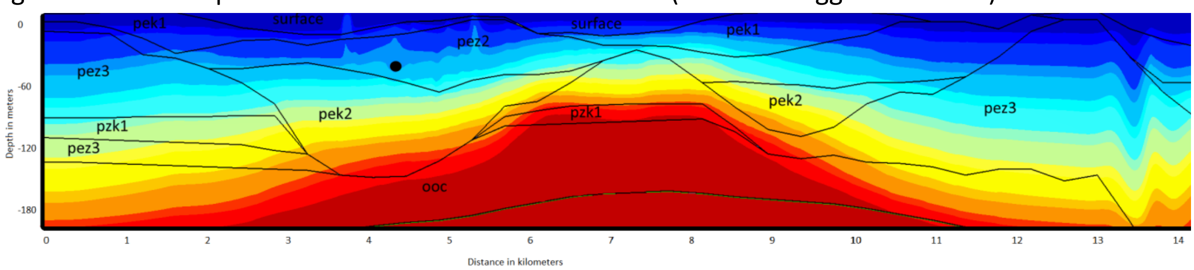

Figure 29: The temperature distribution after 50 months (vertical exaggeration 14:1)

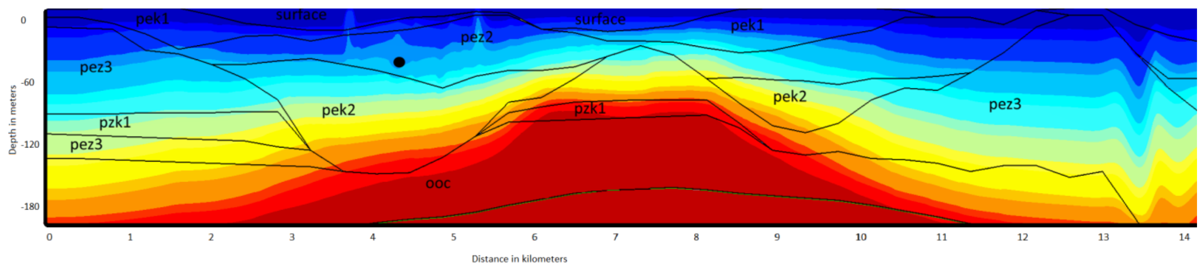

Figure 30: The temperature distribution after 70 months (vertical exaggeration 14:1)

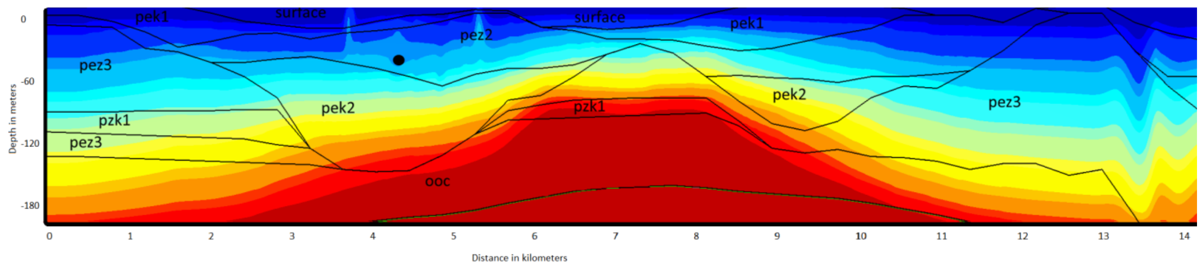

Figure 31: The temperature distribution after 100 months (vertical exaggeration 14:1)

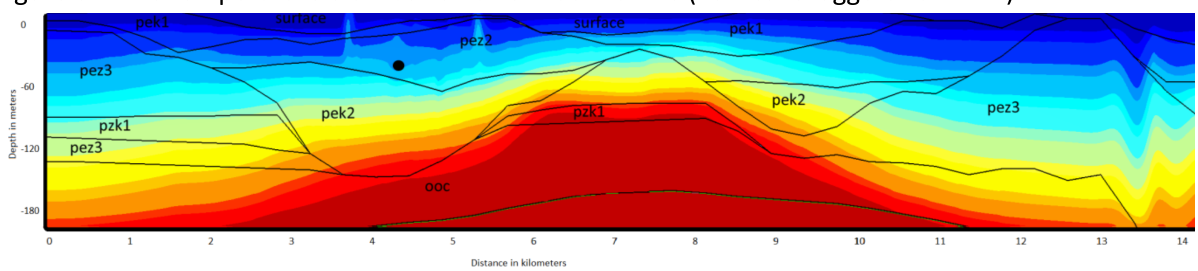

Figure 32: The temperature distribution after 10 year (vertical exaggeration 14:1)

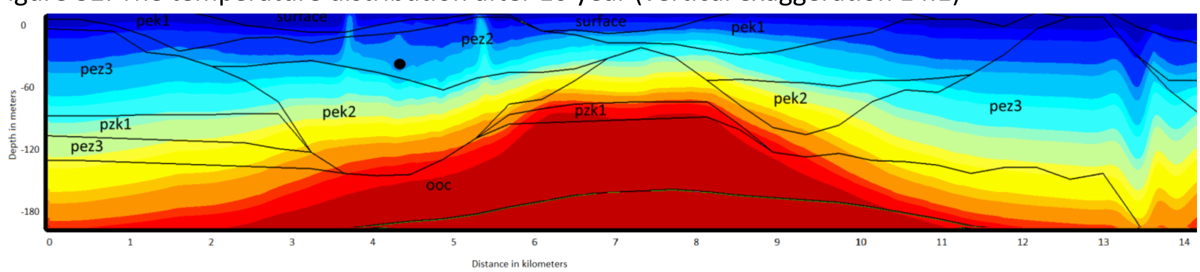

Figure 33: The temperature distribution after 50 year (vertical exaggeration 14:1)

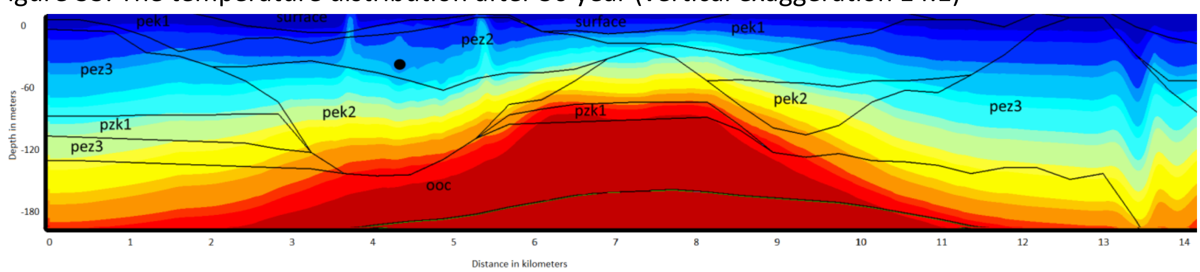

Figure 34: The temperature distribution after 100 year (vertical exaggeration 14:1)

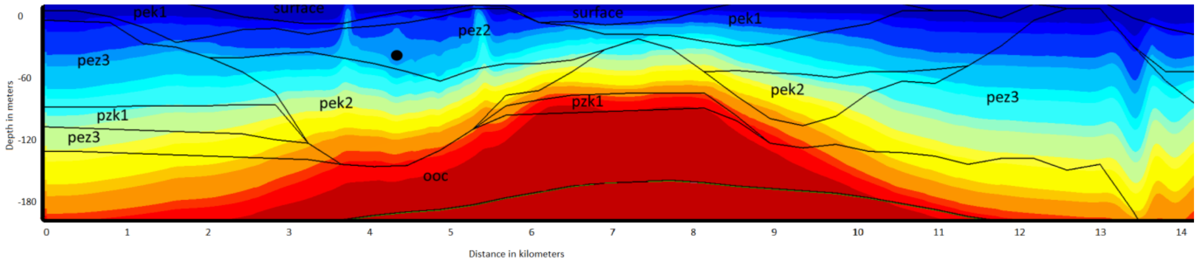

Figure 35: The temperature distribution after 250 year (vertical exaggeration 14:1)

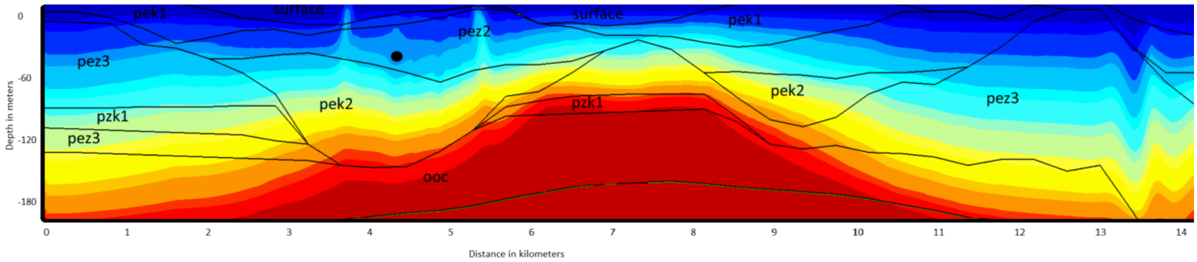

Figure 36: The temperature distribution after 500 year (vertical exaggeration 14:1)

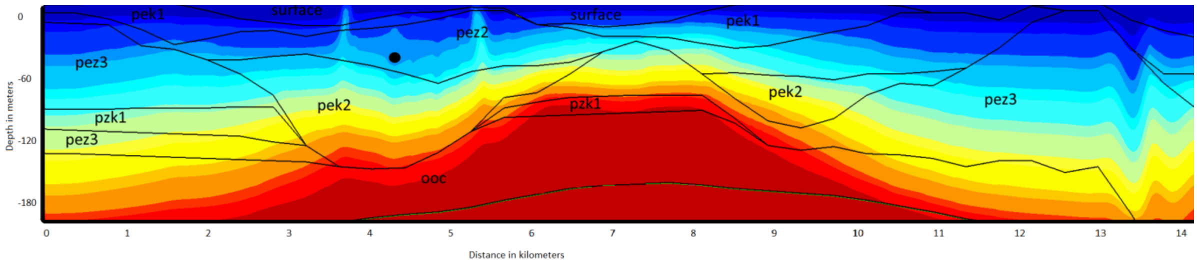

Figure 37: The temperature distribution after 1000 years (vertical exaggeration 14:1)

APPENDIX II

Injection at the middle spot

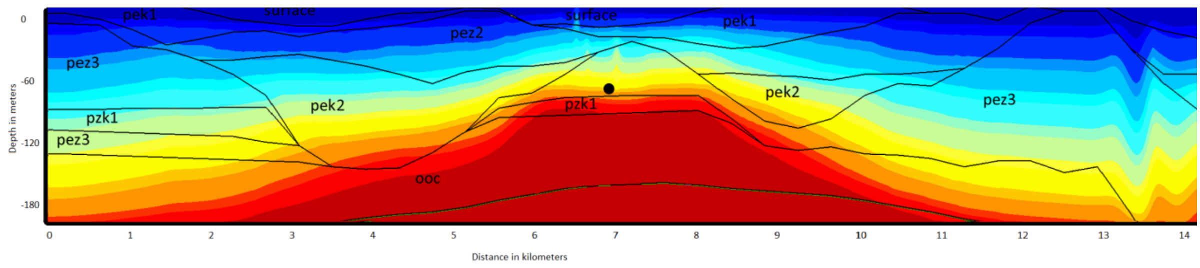

Figure 38: The temperature distribution after 5 months (vertical exaggeration 14:1)

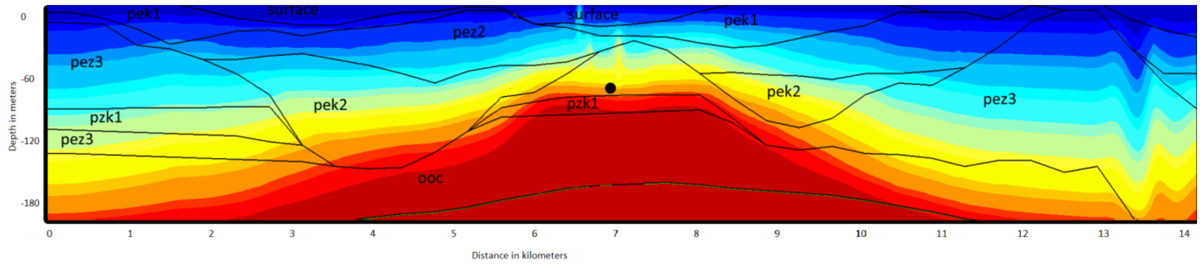

Figure 39: The temperature distribution after 10 months (vertical exaggeration 14:1)

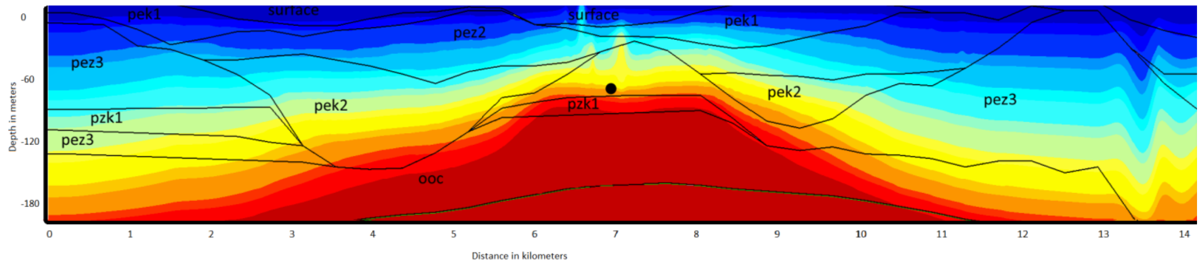

Figure 40: The temperature distribution after 20 months (vertical exaggeration 14:1)

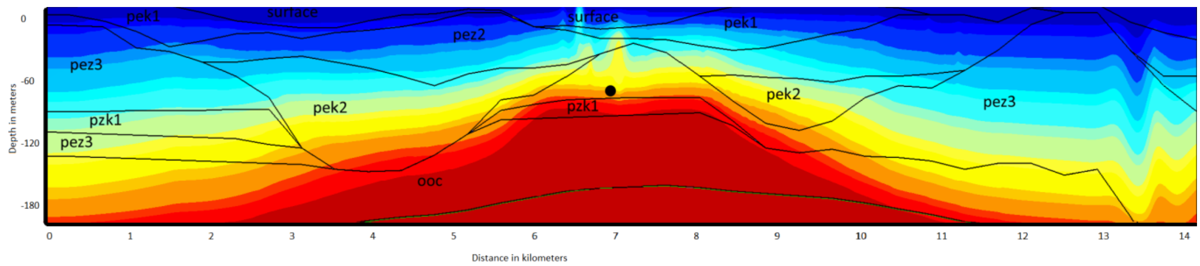

Figure 41: The temperature distribution after 30 months (vertical exaggeration 14:1)

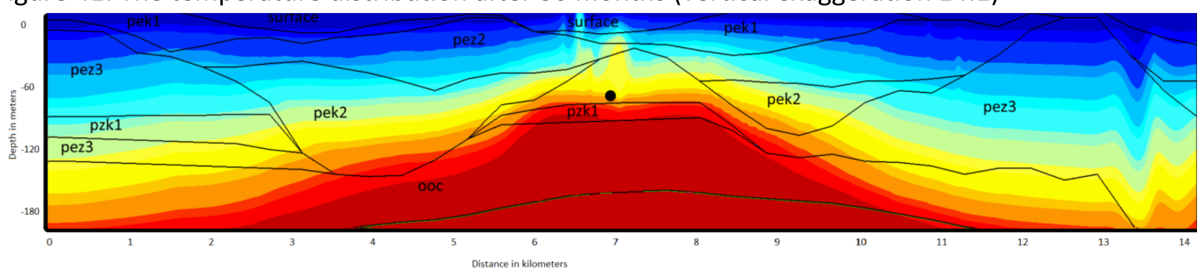

Figure 42: The temperature distribution after 50 months (vertical exaggeration 14:1)

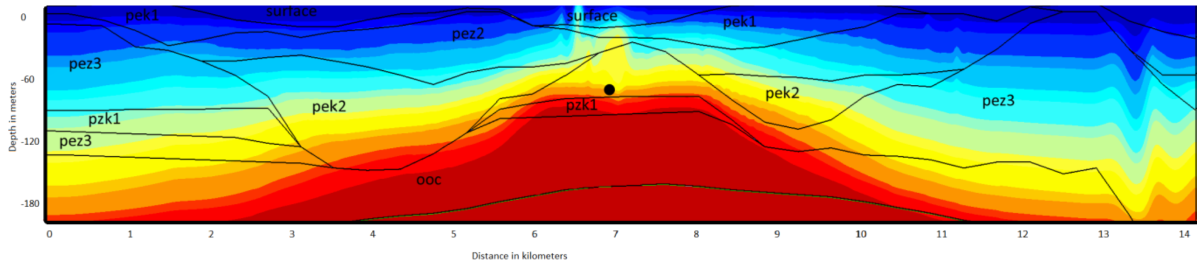

Figure 43: The temperature distribution after 70 months (vertical exaggeration 14:1)

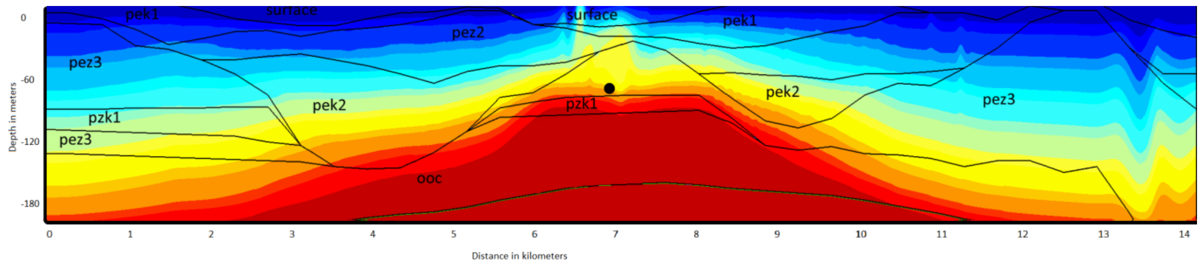

Figure 44: The temperature distribution after 100 months (vertical exaggeration 14:1)

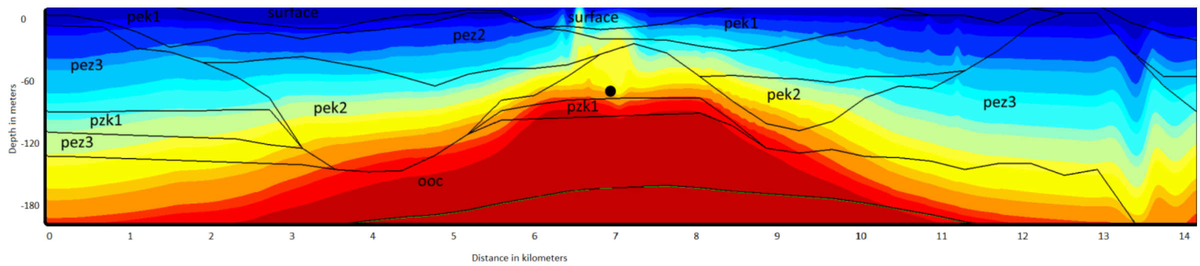

Figure 45: The temperature distribution after 10 years (vertical exaggeration 14:1)

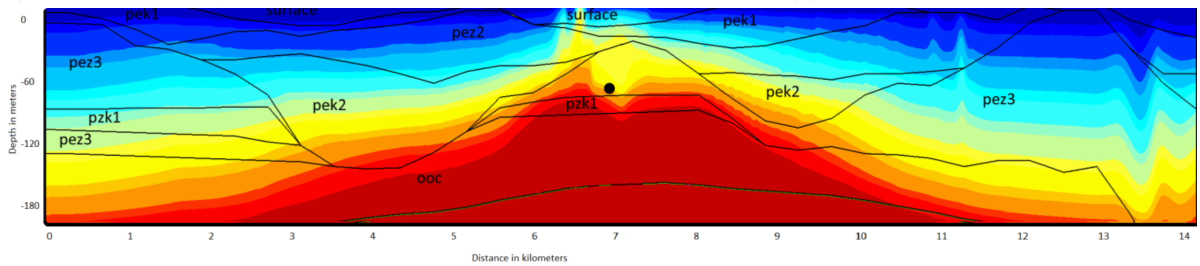

Figure 46: The temperature distribution after 50 years (vertical exaggeration 14:1)

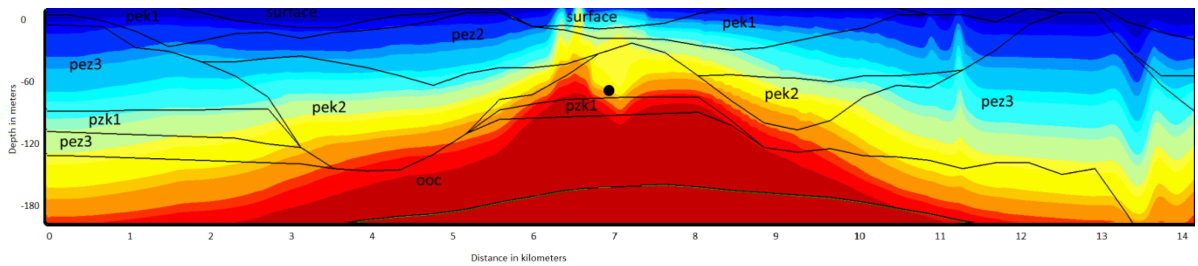

Figure 47: The temperature distribution after 100 years (vertical exaggeration 14:1)

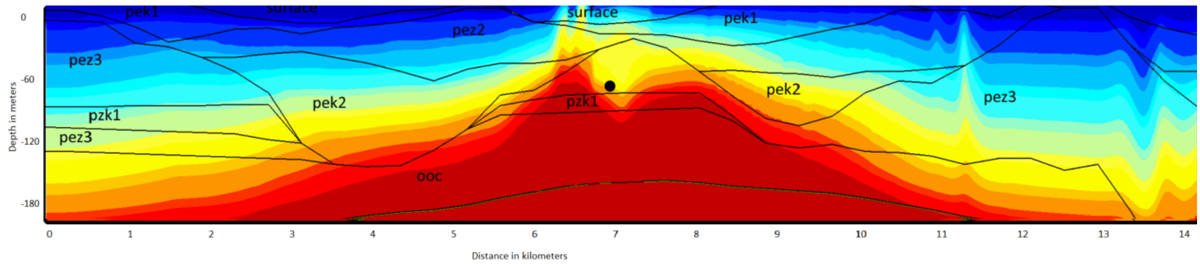

Figure 48: The temperature distribution after 250 years (vertical exaggeration 14:1)

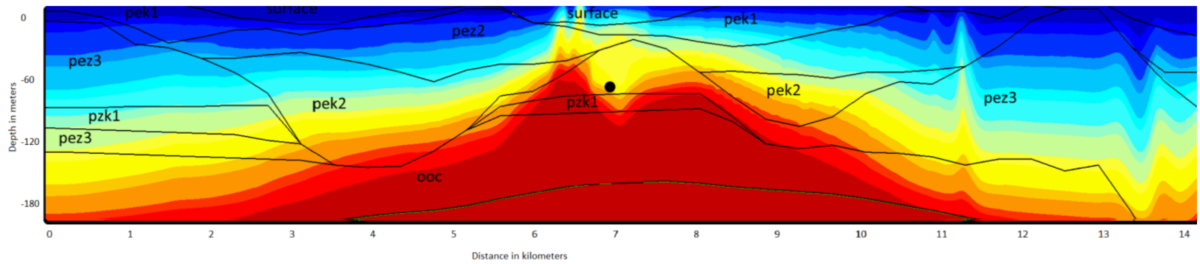

Figure 49: The temperature distribution after 500 years (vertical exaggeration 14:1)

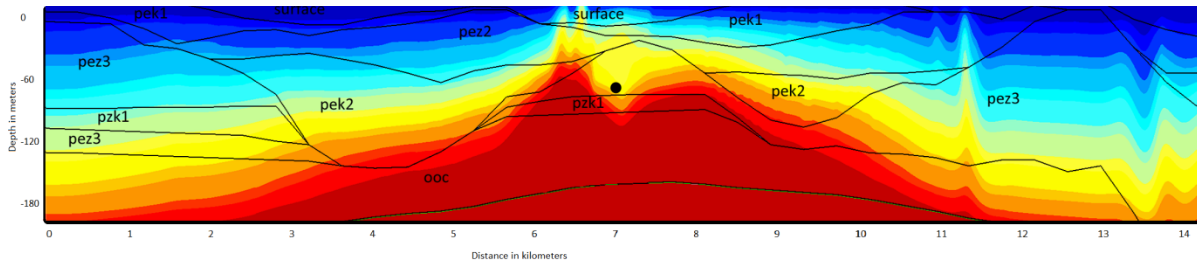

Figure 50: The temperature distribution after 1000 years (vertical exaggeration 14:1)

APPENDIX III

Injection at the right spot

At the Figures below, the horizontal axis is 14 kilometers while the vertical axis is 200 meters.

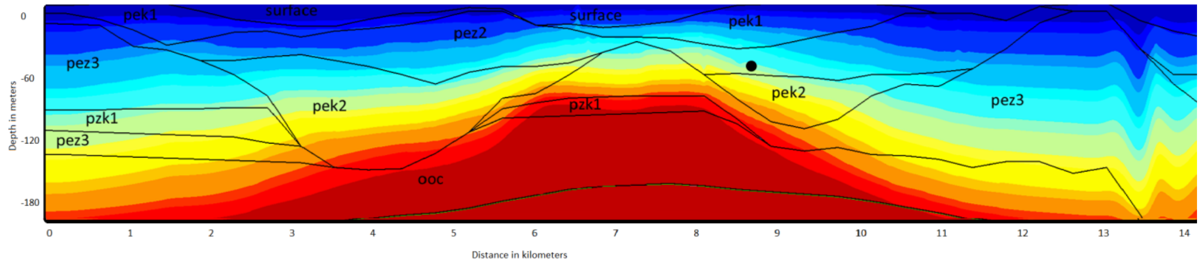

Figure 51: The temperature distribution after 5 months (vertical exaggeration 14:1)

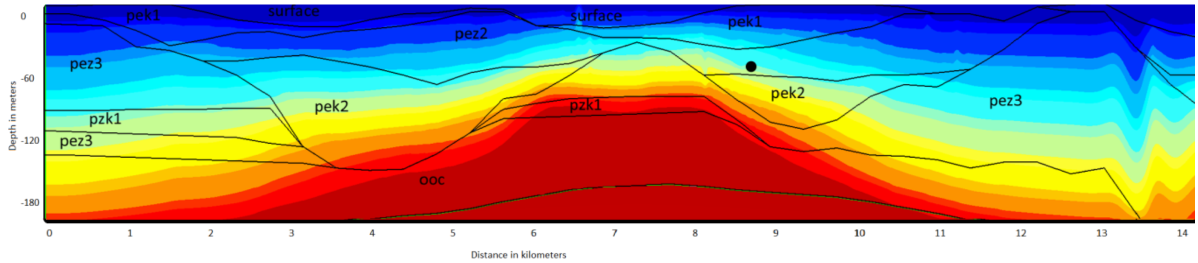

Figure 52: The temperature distribution after 10 months (vertical exaggeration 14:1)

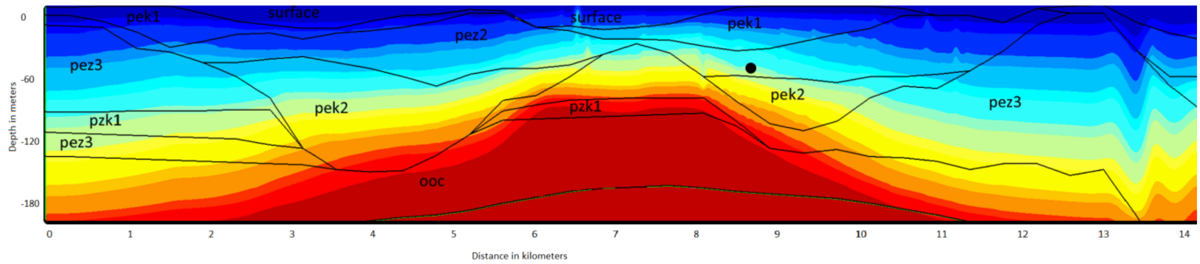

Figure 53: The temperature distribution after 20 months (vertical exaggeration 14:1)

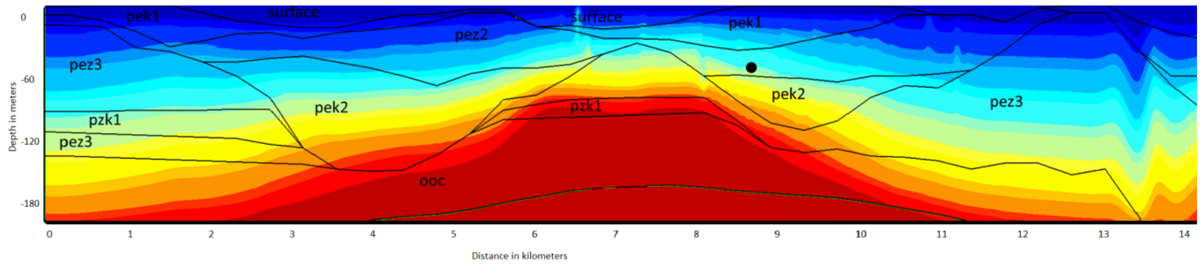

Figure 54: The temperature distribution after 30 months (vertical exaggeration 14:1)

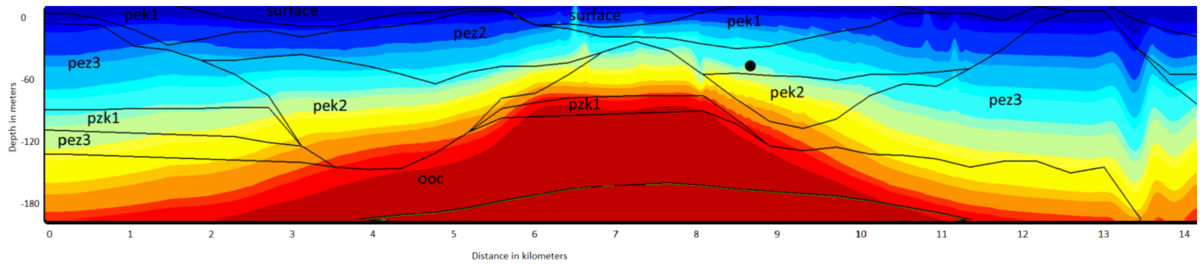

Figure 55: The temperature distribution after 50 months (vertical exaggeration 14:1)

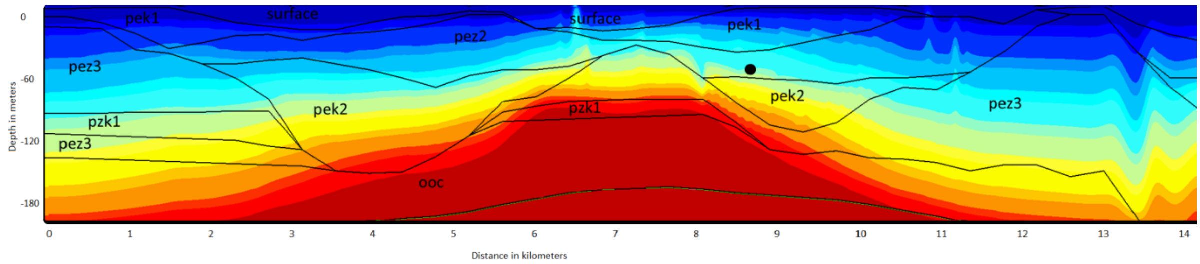

Figure 56: The temperature distribution after 70 months (vertical exaggeration 14:1)

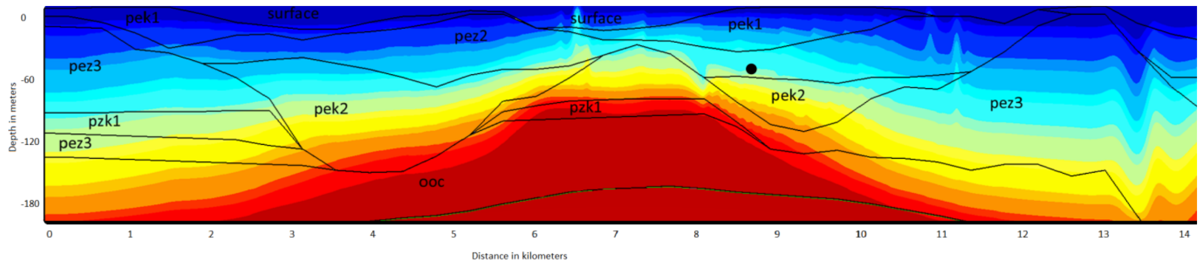

Figure 57: The temperature distribution after 100 months (vertical exaggeration 14:1)

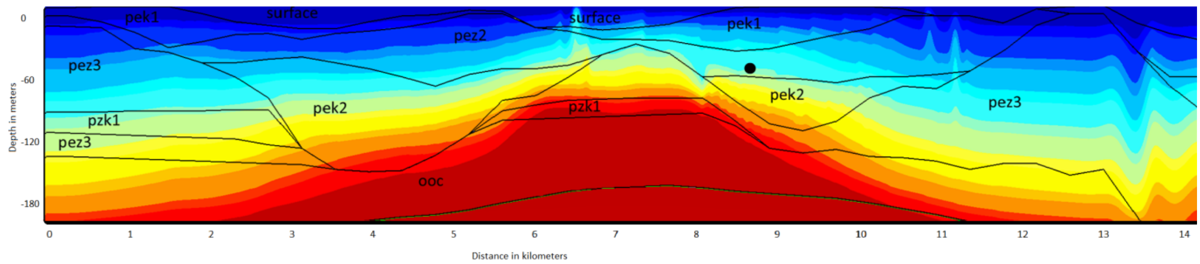

Figure 58: The temperature distribution after 10 years (vertical exaggeration 14:1)

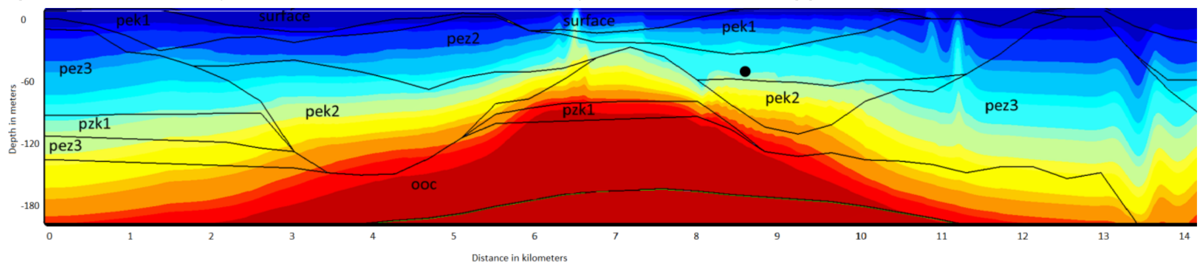

Figure 59: The temperature distribution after 50 years (vertical exaggeration 14:1)

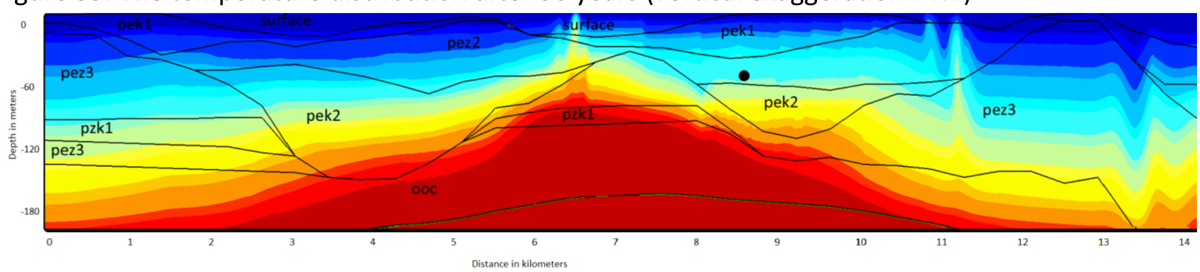

Figure 60: The temperature distribution after 100 years (vertical exaggeration 14:1)

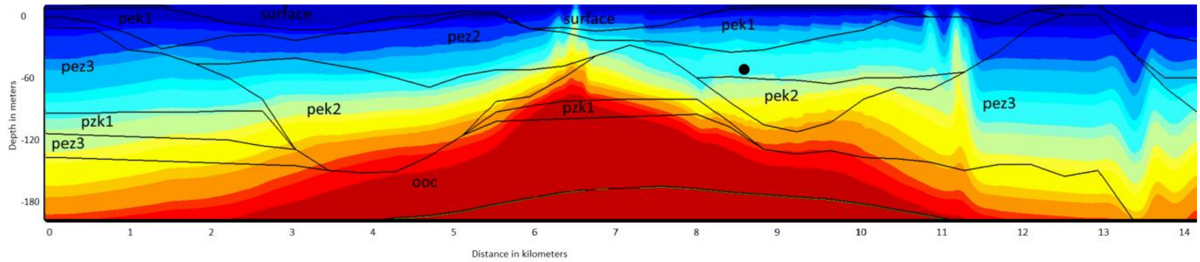

Figure 61: The temperature distribution after 250 years (vertical exaggeration 14:1)

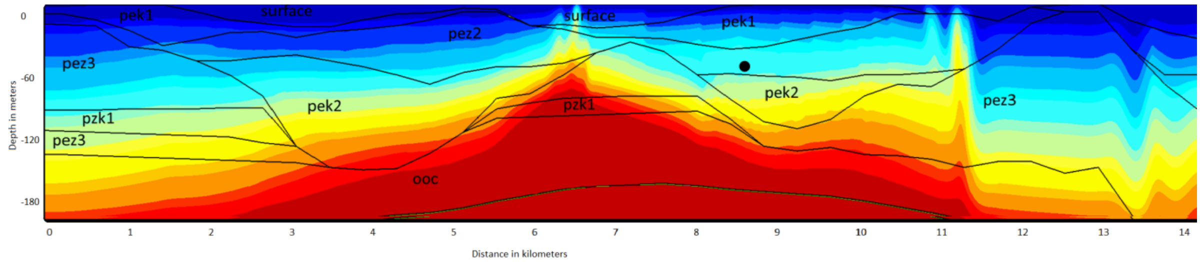

Figure 62: The temperature distribution after 500 years (vertical exaggeration 14:1)

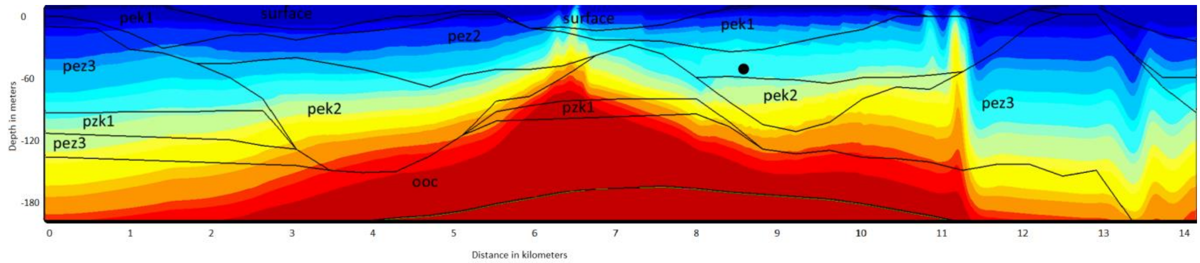

Figure 63: The temperature distribution after 1000 years (vertical exaggeration 14:1)