Exercise 4: Modeling a hydrothermal system

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Deadline: Hand in a version of your python script and a short word document with the four sections as discussed below before or on the 22nd of February (= a bit more than 2 weeks after the exam)

Grading: Each section of you report is graded with a max of 1 point, and a total maximum point count of five. The grading is based on how well you can communicate your results to the reader (me). Try to write in an accessible style so that non-experts can also understand you results.

Introduction

In this exercise we will simulate fluid flow and advective heat transport in a hydrothermal system and we will use the model to answer basic questions on these hydrothermal systems, like how old are these systems? are they in equilibrium or will temperatures or discharge change in the future? From what depths do fluid originate?

For this exercise you can choose between two hydrothermal systems, the Beowawe geyser field in Nevada, or the Aachen hot spring system closer to home. For each system there are a number of unanswered research questions.

We will change parameters such as flow velocity and background temperatures to try to match data on discharge temperature in the hot springs and subsurface temperature from a borehole a close to the hydrothermal system. We will use an existing model code (escript) that uses that solves the heat flow and (optionally) the fluid flow equations using the finite element method. The model is controlled using a jupyter notebook that is located on stud.ip.

The code that we will use in this exercise is a teaching version of the model code Beo (https://github.com/ElcoLuijendijk/beo) that was recently published (Luijendijk 2019). The code was also used to publish a case study of the Beowawe hydrothermal system in the Basin and Range Province (Louis et al. 2019), which you have already heard something about during the lectures.

Objectives

- Learn to simulate transient advective heat flow
- Learn how subsurface temperatures are affected by fluid flow and which parameters are important for this.
- Learn to combine models and geoscience data

Do not hesitate to ask questions if you get stuck anywhere. You can reach me by email at eluijen@gwdg.de or pass by at my office, room 125 in the Structural Geology dept.

Good luck !

Testing escript

We will run the model codes on relatively new and fast laptops that run the Ubuntu linux operating system. Our model code is called Beo, and it uses a separate model code called escript (https://www.auscope.org.au/sam-esys-escript) to do all the heavy computational work, i.e., to solve the partial differential equations that govern heat and fluid flow in the subsurface. Escript is already installed on your system. There is also a example model on stud.ip called `example03a.py` that simulates the conductive cooling of an intrusive. Download this python script, save it somewhere on your computer. Next, start a terminal by clicking on the terminal icon on the left hand side of your screen or opening the search icon on the lower left and searching for the terminal program. The terminal is a window where you can manually type commands. Now navigate to the notebook location on your computer. Use the command `cd /home/user/directory/` to navigate to this directory. Note that you should insert the name of your machine instead of `user`. Now try to run the example model by running the following command: `flatpak run au.edu.uq.esys.escript -i example03a.py`. If all goes well the model should now run and provide some screen output. The model code will also generate a few figure of the modelled temperature field at different timesteps, which will be saved in the same folder. Try to open these figures using the file navigator in the menu on the left-hand side of your screen.

Running the hydrothermal model code

The python script that runs the hydrothermal model is called `exercise4_hydrothermal_model.ipynb` and is located on stud.ip. Download the zip file containing the notebook and place it in a folder in your home directory. Now run this script by typing `jupyter lab exercise4_hydrothermal_model.ipynb`. The notebook will now open in a browser window. The notebook contains detailed instructions on how to use the model and how to change parameters.

Assignments

In contrast to the previous three exercises there are no fixed assignments or questions to answer. There is just one overall goal of this exercise: use the available data and the numerical model to learn something about the hydrothermal system that you chose to work on. Hand in a short word document with the description of your research on this hydrothermal system. Below I list the ingredients that should be present in your report:

1. A cool and informative title.
2. Start with approximately three sentences on why your study is important or interesting.
3. One or two sentences on what piece of knowledge is missing for the hydrothermal system that you chose to study.
4. One sentence with the research question that you are trying to answer. Be very specific here, start the sentence with something like: "The research question that I try to answer is ..."
5. One paragraph that briefly introduce the hydrothermal system that you chose to study, plus one overview figure. Where is it located, what do we know about it, ie. the geological setting (is it hosted in a fault or a permeable formation), etc.. ? Feel free to steal the figure from the handout or the background literature.
6. One paragraph where you describe your methods. What model code did you run? What parameters did you change and why? And which parameters did you not change? Show the equation your model solves. Include a table there with the parameter values for the different model runs, ie. one row per parameter and columns for the range of values that you tried.
7. Your results. A few sentences that describe the results and only the results. Use either bullet points or a numbered list here. Keep any discussion or conclusion for the next section. Add a number of figures here that illustrate your conclusions. The number of figures is up to you, but there should be enough figures to support your discussion and conclusions. Adding a table with one row for each model experiments and columns for the parameters that you changed and the resulting temperature in the boreholes or the spring.
8. Discussion and conclusion. Briefly discuss your findings, ie any results that you think are noteworthy and interesting. And most importantly describe the answer to your objective or research question. Or if this didnt work out describe why you cannot answer the research question yet. Write this section in bullet points or a numbered list.

Some pointers for writing: Keep your document brief and focused on your research questions. One way to make things easier is to write all or most of the text in bullet points. Try to keep your sentences short. DO not combine sentences but try to have one short sentence for each point you are trying to make. And try to write most of your text in active instead of passive voice. For example: I modeled this system using these parameters. Instead of: The system was modeled with these parameters. Writing in active voice is much easier for you and it is often easier to understand for the reader as well.

Research questions

Choose one research questions from the list below, bonus points for two or more research questions.

- What are the fluids sources and flow paths? I.e., where are the permeable formations and faults located that channel heat fluid flow? This is more or less known for the Beowawe system (Howald et al. (2015);Louis et al. (2019)), but is largely unknown for Aachen. However, for the Beowawe system the borehole temperatures show several inflections at shallow depths that hint at a much more complicated flow system than we have modelled so far in Howald et al. (2015) or Louis et al. (2019). Therefore, the strategy would be to try to include additional sources of lateral flow along with upward fluid flow along the main fault zone to try to match the temperatures as best as you can.

- What hydraulic conductivity do we need to explain the hydrothermal system? Hydrothermal systems are actually not that easy to simulate, and need a particular hydrogeological structure to get deep fluid flow paths and rapid upward fluid flow. This question has not been explored at all for Aachen and only to some extent for Beowawe.

- For both the Aachen and the Beowawe system one can try to answer an additional research question on what the age is of hydrothermal activity. For Beowawe this was studied previously by Howald et al. (Howald et al. 2015) and Louis et al. (Louis et al. 2019) who got slightly different results, but both around 3000 years. For Aachen this is unknown. However the temperature data from the geothermal well are too far away from the hot springs to constrain the age of this system, and any age that post-dates the end of the last glaciation (when Aachen was covered in permafrost) gave good results during our first model experiments during the course last year. Therefore this question cannot be the main research question, but you can still refer to this question in your report if you have some new results here.

Note: Bonus points for coming up with an alternative research question as well, talk to your instructor in this case.

Workflow

After you have picked a question to work on start using the model to answer this question. In brief the workflow is to change model parameters in the Jupyter notebook, rerun the model, interpret the model results and compare them to what is known about the system, ie spring temperatures and discharge and borehole temperature data. Keep an excel sheet open on the side where you write down the parameters and results for each model run, and the filenames of the figures that show the model results.

Figuring out the model equation

The code solves the standard escript equation to model heat flow and (optional) steady-state groundwater flow. See the getting started with escript handout for the equation. In the notebook some of the coefficients of this equation are assigned (A, B, C, D, X or Y). Try to figure out where each of these coefficients are changed and what physical model parameters they consists of, ie flux (q), thermal conductivity (K), temperature (T), etc… Note that the coefficients that are not changed in the code can be assumed zero. Now use this information to fill in the parameters in the standard escript equation, and show this equation in the methods section of your report.

Varying the model parameters

The model code simulates advective fluid flux through a steeply dipping normal fault. The model uses a number of parameters, the most important ones are the fluid flux in the fault, the background temperature at the bottom boundary of the model, the width of the fault zone and the duration of fluid flux. Try to find where these parameters are assigned in the notebook and adjust them to find the best fit of your model to the observed temperature data in the borehole next to the fault.

In addition the model contains several sections where a horizontal flux through permeable aquifer can be added or flow through a second fault. You can uncomment these lines to change the model code and test new hypothesis on what kind of fluid flow system drives the hot springs at Beowawe or in Aachen.

If you set the parameter `simulate_gw_flow = False` to True instead, the model code will simulate steady-state groundwater flow. It will then use the calculated groundwater flux in the subsequent simulation of advective and conductive heat flow. The lines below contain the settings for the boundary conditions and the hydraulic conductivity of the model. The upper boundary is controlled by a linear hydraulic head with starting value at the left-hand side of `h0 = 200` and a hydraulic gradient of `h_gradient = -0.02`. You can also specify a recharge rate. The hydraulic conductivity of the subsurface is unknown, so you will need to test different values to get your thermal spring going. Note that you will need a relatively high conductivity for the faults compared to the host rock to generate a deep fluid flow system.

Background information

Below there is some background information on the hot spring systems. The most important parameters for modeling these two systems are summarized in a table below.

Beowawe

The first study area you can choose from is a hydrothermal system around a normal fault that is located in Beowawe, Nevada (Fig 1 and 2). This is a unique hydrothermal system that has generated a large 1 km long and 60 m high terrace of sinter deposits consisting of amorphous silica and calcite (Fig. 1). The system used to host active geysers until geothermal development destroyed the geysers in the 1960s. Fluid flow is most likely driven by topographic gradients, with recharge along a single normal fault, lateral flow through a carbonate formation at 5 km depth and discharge along the Malpais fault zone at Beowawe (Howald et al. 2015; Louis et al. 2019).

Measured temperatures in discharging water are ~95 C, and were obviously higher in the subsurface when the geysers were active. The composition of the discharging water is meteoric, with the exception of very high silica contents. The volume of the sinter terrace likely required 200,000 years of continuous hydrothermal discharge (Rimstidt and Cole 1983). During geothermal development several wells have been drilled near the Malpais fault with detailed temperature records up to several km depth (Fig. 5). We will use temperature data of one of these wells, well 85-18, to constrain models of advective heat transport and to explore the age and characteristics of the hydrothermal system at Beowawe.

For more information on the hydrothermal system see the presentation slides, and also try to look up publications on this system by Howald et al. (2015), Louis et al. (2019) or White (1998) on google scholar.

Aachen hot springs

The second system that you can study is the Aachen hot spring system. The hot springs in Aachen have been in use since Roman times and continue to be important today. The springs are located along two thrust faults at the surface, that join up at depth according to the geological cross-section shown below. There is only one subsurface temperature datapoint available, which was obtained from borehole RWTH-1, which was drilled at the RWTH Aachen campus, but unfortunately something went wrong with the casing of this well and it could not be used for geothermal energy. Nonetheless, the temperature data may help us constrain the system. The well is close to the hot springs, around 500 m from the nearest borehole, and shows that temperatures are undisturbed by hydrothermal activity and follow the regional geothermal gradient of 30 degrees/km. Which means that the system must be relatively young, long hydrothermal activity would have heated up the rocks near the borehole as well. The circulation depth of fluids is unknown. Geological cross-sections show that the thrust faults flatten at ~4 km depth. However, these cross-sections are being updated, and it is by no means certain that the fluid source is at 4 km depth.

For more information on the hot springs the publications by (Herch 2000) and (Dijkshoorn and Clauser 2013) are very useful.

parameter	unit	Beowawe	reference	Aachen springs	reference
average temperature	degr. C	95	Howald et al. (2015)	60	Dijkshoorn & Clauser (2013)
total discharge	m3/sec	0.018	Howald et al. (2015)	4.86E-02	Dijkshoorn & Clauser (2013)
approximate length of hydrothermal system at surface	m	1500	google earth	800	google earth
approx. angle main fault	degrees	65		unknown	
max. depth fluid flow path	m	5000	Howald et al. (2015)	unknown	
max. temperature fluid	degr. C	230	Howald et al. (2015)	115-128	Dijkshoorn & Clauser (2013)
background geothermal gradient	degr. C / m	0.04	Howald et al. (2015)	0.03	Dijkshoorn & Clauser (2013)
average thermal conductivity	W / (m K)	2	Howald et al. (2015)	3.5	Dijkshoorn & Clauser (2013)
average porosity	dimensionless	0.1	Howald et al. (2015)	0.01	Dijkshoorn & Clauser (2013)
groundwater recharge in contributing area	m / yr	0.012	Olmsted and Rush (1987)	0.35	de Graaf et al. (2015)
length of contributing area	m	10000	google earth	20000	Dijkshoorn & Clauser (2013)
temperature data	see csv file			86 C at 2544 m	
distance temperature borehole	m	250		500	google earth

Figure 5. "Beowawe" Geyser erupting from vent 29 to a height of about 8 m on September 22, 1945.

Figure 1: One of the geysers at Beowawe. Source: White (1998)

Figure 4. Malpais fault zone and Beowawe Geysers terrace. View eastward; photograph by G.A. Thompson, taken October 18, 1951.

Figure 2: The Beowawe sinter terrace from the sky. Source: White (1998)

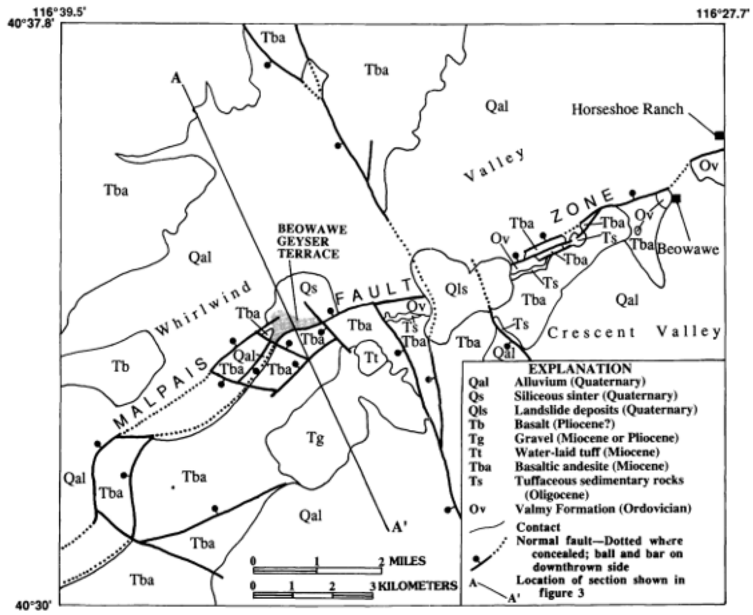

Figure 2. Simplified geologic map of Beowawe Geysers area, north-central Nevada (modified from Zoback, 1979).

Figure 3: Geological map of the hydrothermal system. Source: White (1998)

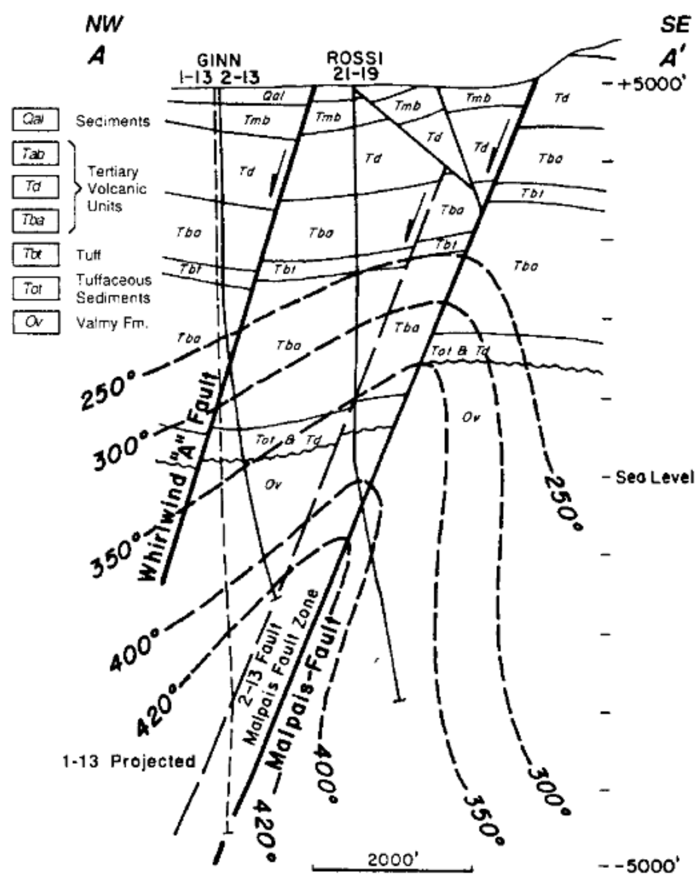

Figure 4. Geologic cross-section A-A'.

Figure 4: Geological cross-section. Source: Hoang (1989)

Figure 3: Pre-Exploitation Temperature Surveys

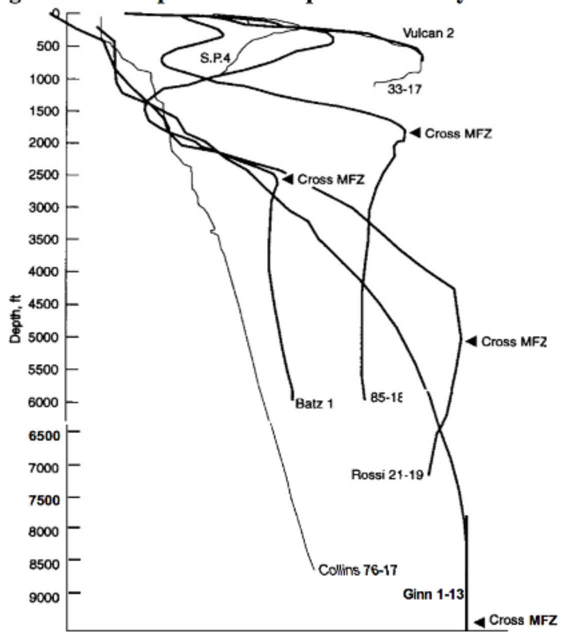

Figure 5: Temperatures near the hydrothermally active Malpais fault. We will try to model the temperature profile of well 85-18. MPZ = Malpais fault zone. Source: Faulder, Johnson, and Benoit (1997)

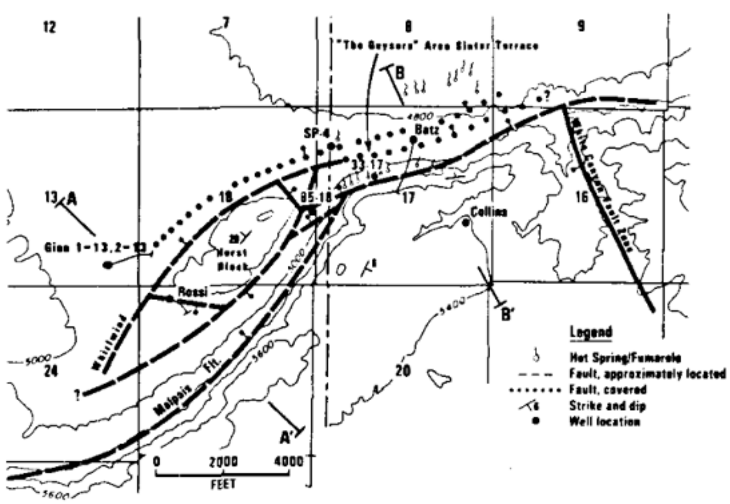

Figure 1. Well locations and surface features.

Figure 6: Location of wells around Beowawe, including well 85-18 from which we use temperature data.

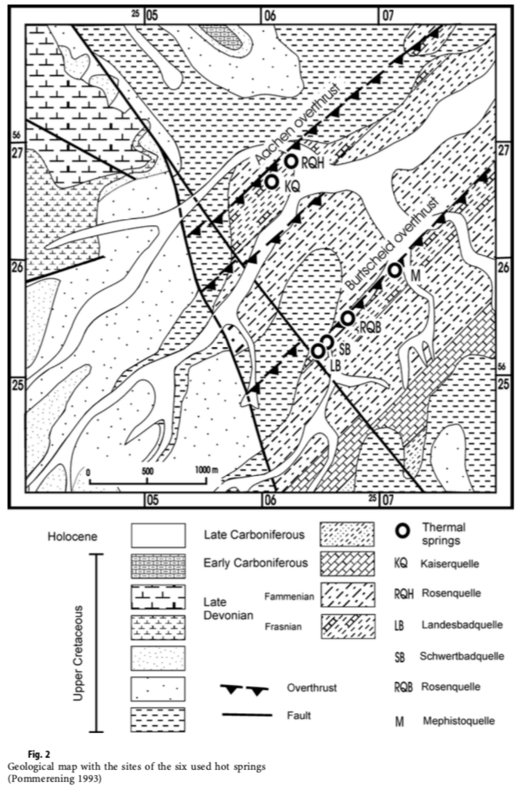

Figure 7: Map of the hot springs at Aachen. Source: Herch (2000)

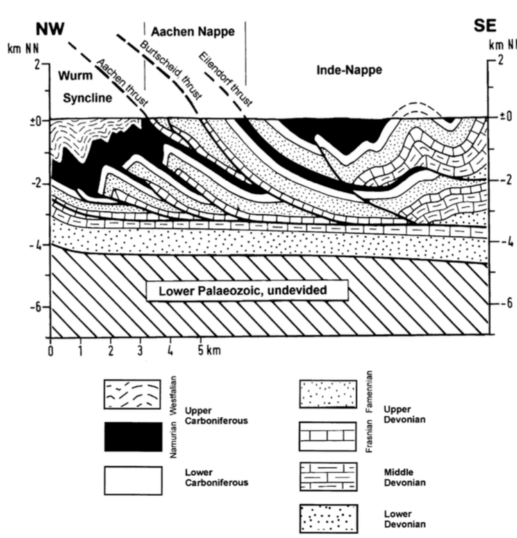

Figure 8: Cross-section of the hot springs at Aachen. Source: Herch (2000)

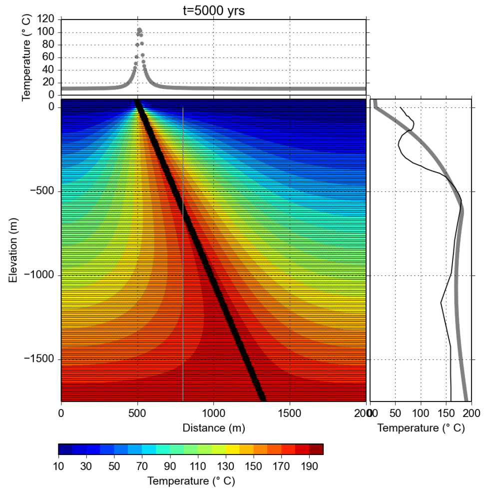

Figure 9: Example of model output using escript and python to model advective heat flow.

References

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