COMPUTER METHODS AND MODELING IN GEOLOGY
TEMPERATURE PROFILES IN PERMAFROST

Permafrost is perennially frozen ground that exists at high latitudes. In order for ground to be considered permafrost, its temperature has to have remained at or below 0 °C for a period of at least 2 years. The fact that water in permafrost is frozen and does not circulate means that the only way for heat to be transmitted through it is via conduction. Conduction refers to the process by which kinetic energy from fast moving molecules is transferred to slower moving molecules through collision. Transfer of heat in this manner can be described by Fourier's Law, which relates the flux of heat through a substance to the temperature difference across it and to its thermal conductivity, an inherent material property. Since Earth's internal temperature is higher than its surface temperature, heat is continuously being conducted toward the surface. The temperature difference leads to the "geothermal" gradient, which measures roughly 30 °C / km depth.

In the mid-1980's Arthur Lachenbruch and Vaughn Marshall realized that they could use inflections in the geothermal gradient of permafrost to search for evidence of climatic change. Their reasoning was thus: if mean annual temperature remains constant over a long period of time, the geothermal gradient is fairly constant with depth (barring changes in the thermal conductivity of the rocks and soil that the heat has to move through). However, if the mean annual temperature changes, either to become warmer or to become cooler, the gradient has to adjust itself to the new surface temperature. Because the movement of heat through a medium is not instantaneous, but rather takes time, the surface layers of soil and rock respond to the change well before the deeper layers. This variation in the time of response creates a "kink" in the geothermal gradient with depth.

To demonstrate this phenomenon, Lachenbruch and Marshall used thermistors dropped into exploratory holes drilled into Alaska's North Slope area by oil companies. In many instances, the thermistors registered anomalously high temperatures near Earth's surface, which they interpreted as evidence of a warming of 2-4 °C over the last several decades. We're going to create a model of heatflow in permafrost to see if we can replicate some of their findings. I want you to answer all of the questions below. Open up Microsoft Word at the same time that you have STELLA running. You can write the answers to your questions as you go along. You can also paste any graphs you would like to use to answer your questions into your Word document to hand in to me.

Readings

Turcotte, D.L., and Schubert, G., 2000, Geodynamics, 2nd ed., Cambridge, U.K.: Cambridge University Press, p. 132-143, 150-152.

Lachenbruch, A.H., and Marshall, B.V., 1986, Changing climate: geothermal evidence from permafrost in the Alaskan Arctic, Science, v. 234, p. 689-696.

Exercises

1) Create a model of heat flow through a 1000-m thick chunk of ground. I would recommend that you do this in 100-m thick layers, so that you don't have to work with too many reservoirs and fluxes. As you do this, consider what the reservoirs are, what quantity they contain, what the fluxes are, and how they are related to the reservoirs. For this exercise, do not consider the contribution of radioactive decay to heating of the ground.

   Note: you will want to consult the STELLA help --> Chp. 4, Map/Model level building blocks --> Flows section about uniflows versus biflows when creating your model.

   Once you have created your model, use the information in Turcotte and Schubert (pg. 135) to determine your model inputs (use an average value for conductivity, and the continental value for heat flow). Be very aware of your units - you may need to do some conversions. Since we're in permafrost terrain, start with an air temperature of -5 °C (again, check your units!), and run your model with an annual timestep.

2) Starting with initially empty reservoirs (initial value=0), run your model for as long as it takes to achieve a steady state condition. What is the geothermal gradient you eventually achieve? Paste in a graph to help explain your answer.

3) What happens if you change the thermal conductivity to the value Turcotte and Schubert give for salt? Do you achieve the same geothermal gradient? Why or why not?

4) Using Fourier's law, explain why the gradient changed the way it did.

5) Now do the same thing for the shale conductivity. Did the gradient change the way you expected it to?

6) Go back to your original value of average conductivity, and this time change the heat flow into the model to that in oceanic rock. What is your result? Is it as you expected?

7) Go back to the continental value for heat flow, and now run some experiments with changing the atmospheric temperature. If you raise or lower the air temperature, what is the impact on the geothermal gradient? Why? Hint: you may want to use a little calculus to answer this question.

8) What we're going to do now is see what kind of impact a climatic change would have on the geothermal gradient. Change your model so that you have a step change of +5 °C about a third of the way through your run. Describe what you see. Do all the layers change their temperature at the same time? Why or why not? How long does it take for them to achieve their new temperatures?

9) What impact would a change in the thermal conductivity have on the time it takes for the profile to equilibrate to the new conditions?

10) Now let's experiment with some climate oscillations. Modify the air temperature input so that it oscillates between -10 and 0 °C with a period of 1000 years. What is the equation you need to write in the air temperature converter?

11) Run the model. Describe and explain what you see. How far down into the ground is the perturbation felt? How does the amplitude of the perturbation vary with depth? Is the perturbation in each depth level in phase? Why or why not?

12) Experiment with changing the period of oscillation. If you make the period shorter, what happens and why?

13) What if you make the period longer?

14) Going back to your initial period of 1000 years, run the model and then export the values to Kaleidagraph. Toward the end of your run, select a row of data every 100 yrs for 1000 years so you can see the entire temperature cycle.

As you select the data, copy and paste them into a new Kaleidagraph spreadsheet.

15) Once you've got your 10 lines pasted in, go to Edit > Select All, and then go to Functions > Transpose to take the values and rotate them 90 degrees. After the rotation, each column of numbers represents one time slice, and each row represents a different depth.

Highlight the A column, and then go to Data > Insert Column. This will put a blank column in front of your 10 time slice columns. Put the depth of each reservoir in this column from 0 m down to 1000 m. Double click on the column heads to give them names, and then go to Gallery > Linear > Line to plot your values. Choose the depth column as X, and the temperature columns as Y's. Once your graph is made, double click on either of the axes and then hit Exchange X and Y on the dialog box that appears. You want your graph to have depth as the Y axis and temperature as the X in the end, and you want the depth to be increasing downward just as it does on Earth. Paste your final graph in here.

16) Do the same kind of thing for a shorter period run. Comment on what you see.