Constraints on Ocean Floor Permeability from Hydrothermal Modelling

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Introduction: In geophysical studies of seafloor spreading processes it is rare to have good quantitative data with which to ground-truth numerical models. An exception is the Atlantis Massif, at 30 ° N just west of the mid-Atlantic Ridge (Fig. 1). A 1415 m deep borehole (IODP Hole 1309D) was drilled into gabbroic rocks in 2005[1], and a temperature profile was measured in 2012[2] (Blackman et al., 2014). The temperature profile in the borehole indicates nearly conductive heatflow with a slow downward advection of seawater in the upper 750 m. 5 km to the south the hydrological regime and hence permeability structure is very different, with the long-lived[3] Lost City Hydrothermal Field venting fluids at 40-90 ° C.

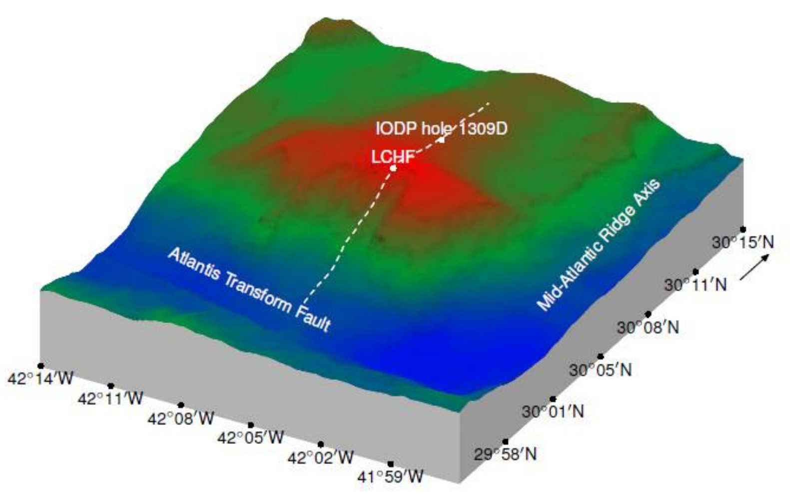

Figure 1. Atlantis massif with borehole and LCHF, and 2-D profile

Computational Methods: To calculate the model we coupled heat transfer in porous media equations with Darcy Flow, using the Heat Transfer and Subsurface Flow Modules in COMSOL Multiphysics®.

$$\begin{cases} \left\{\rho(T)C_{pf}\varepsilon + \rho_p(T)C_{pp}(T)(1-\varepsilon)\right\}\frac{\partial T}{\partial t}(x,y,t) \\ \quad + \rho(T)C_{pf}(T,p)\mathbf{v}\cdot\nabla\mathbf{T}(\mathbf{x},\mathbf{y},\mathbf{t}) = \nabla\cdot((\mathbf{k_p}(\mathbf{T})(\mathbf{1}-\varepsilon)+\mathbf{k_f}\varepsilon)\nabla\mathbf{T}), \\ \varepsilon\frac{\partial\rho}{\partial t}(T,p) = -\nabla\cdot(\mathbf{v}\rho(\mathbf{T})), \\ \mathbf{v} = -\frac{\kappa(\mathbf{T})}{\mu(\mathbf{T})}\Big(\nabla\mathbf{p}(\mathbf{T}) + \rho(\mathbf{T})\mathbf{g}\Big). \end{cases} \qquad (1)$$

We used temperature dependent water and porous material properties (Fig. 2, 3). We used a constant temperature boundary condition on the seafloor and constant heat flux on the bottom, and various permeability distributions (Fig. 4, 5). A steady state solution of the conductive heat transfer problem was used for the initial conditions .

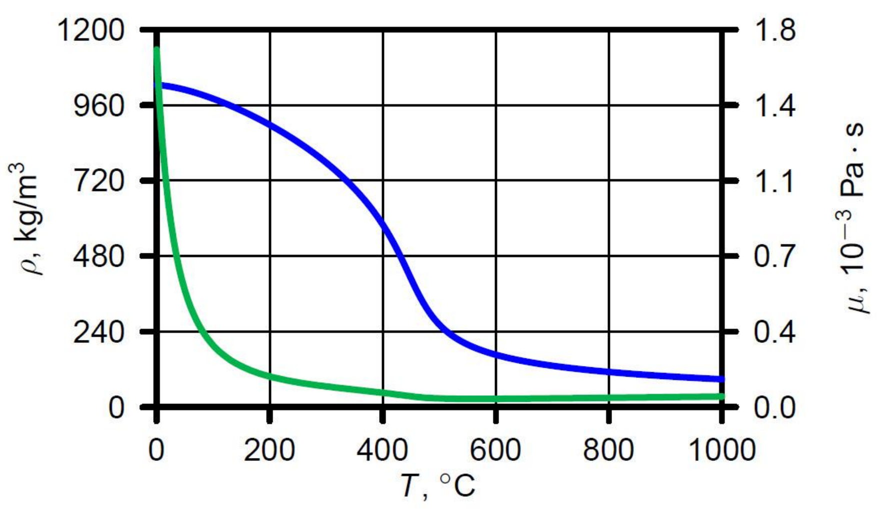

Figure 2. Water properties

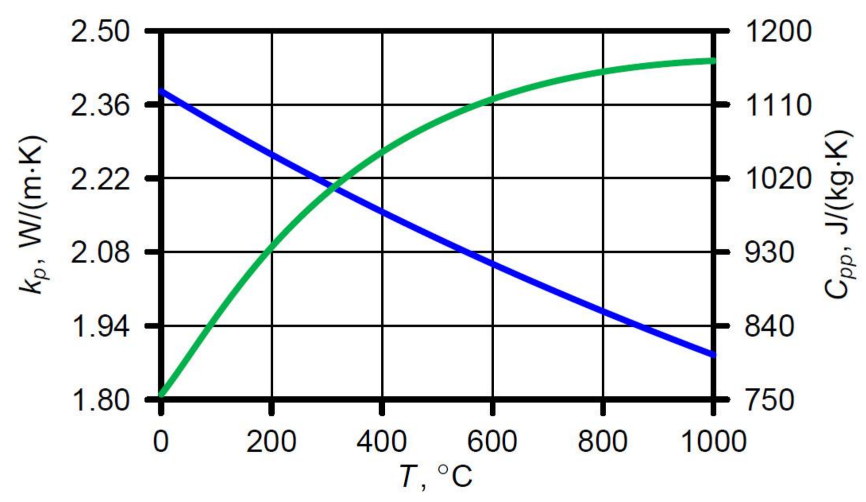

Figure 3. Porous material properties

Both 2D and 3D models have a higher permeability layer on the top of the domain. We varied the value of permeability to match the gradient in the bore hole.

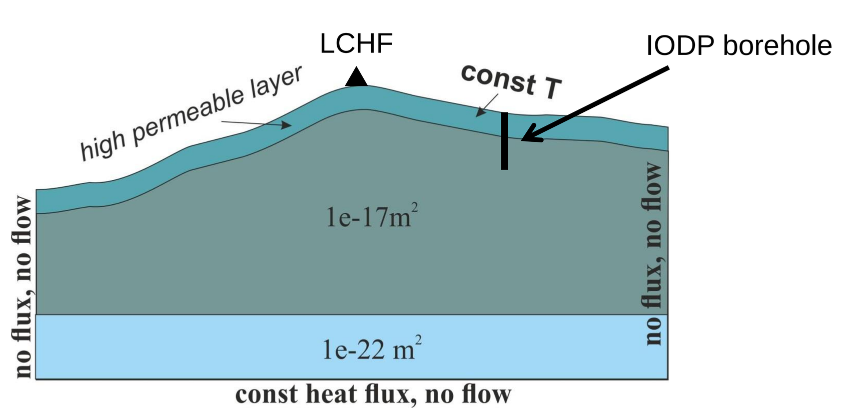

Figure 4. 2-D model A, with permeable layer on the top

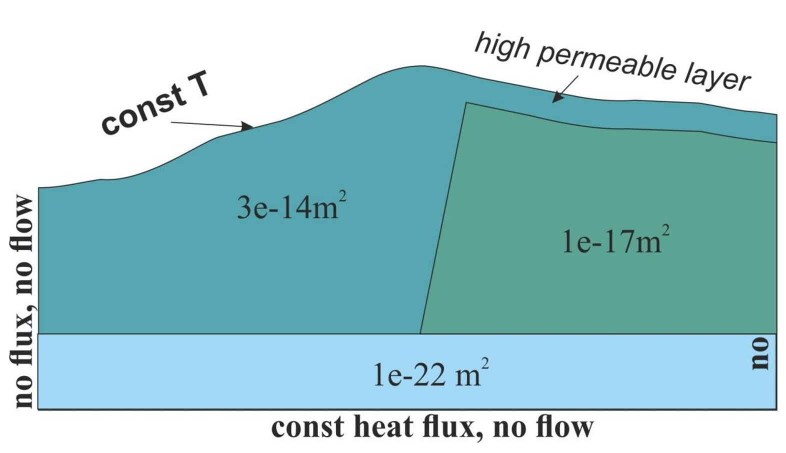

Figure 5. 2-D model B, with permeable layer and deep higher permeability zone under the Lost City Hydrothermal Field (LCHF)

Results: Results of 2-D modelling (Fig. 6) show upflow at the crest of the Massif and at the small hill north of the borehole, with downflow at the location of the borehole. The borehole gradient can be best matched (Fig. 7) with a basal heatflow of 0.22 W/m^2 and a permeability in the upper layer of 3e^{-14} m^2. Addition of a deep zone of high permeability (Fig.5) allows the vent temperature of the LCHF to be matched.

3-D modelling (Fig. 8) with the same boundary conditions gives a less stable flow pattern in the upper layer, with a series of convective rolls forming parallel to the slope with point source vents migrating up the rolls to the highest topography. Flow is normally downwards in the vicinity of the borehole, and the gradient is best matched (Fig. 9, 10) by a basal heatflow of 0.26 W/m^2 and a permeability in the range of $3\cdot10^{-14}$ to $5\cdot10^{-14}$ m^2

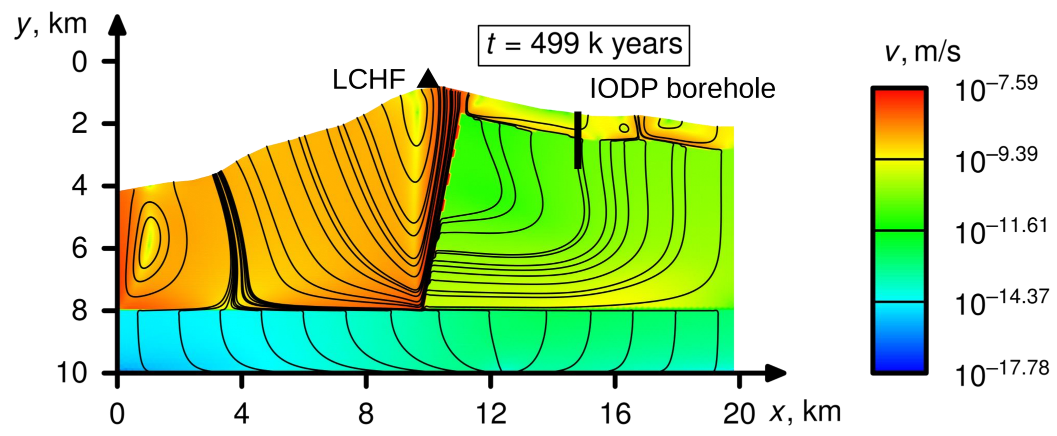

Figure 6. Model B, circulation pattern

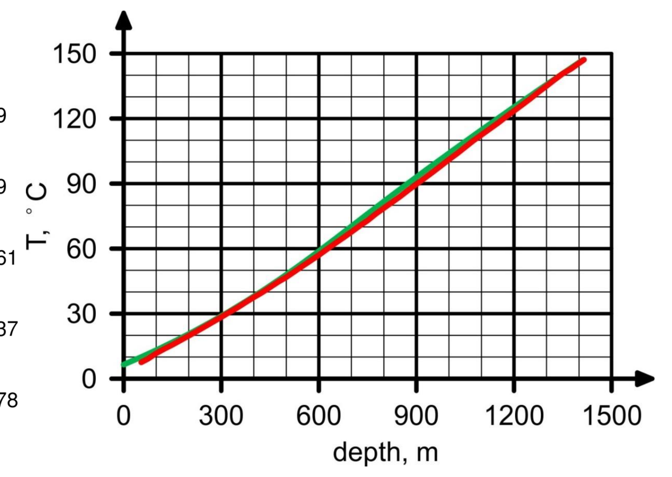

Figure 7. Model A, borehole temperature profile (red) and best fit model (green)

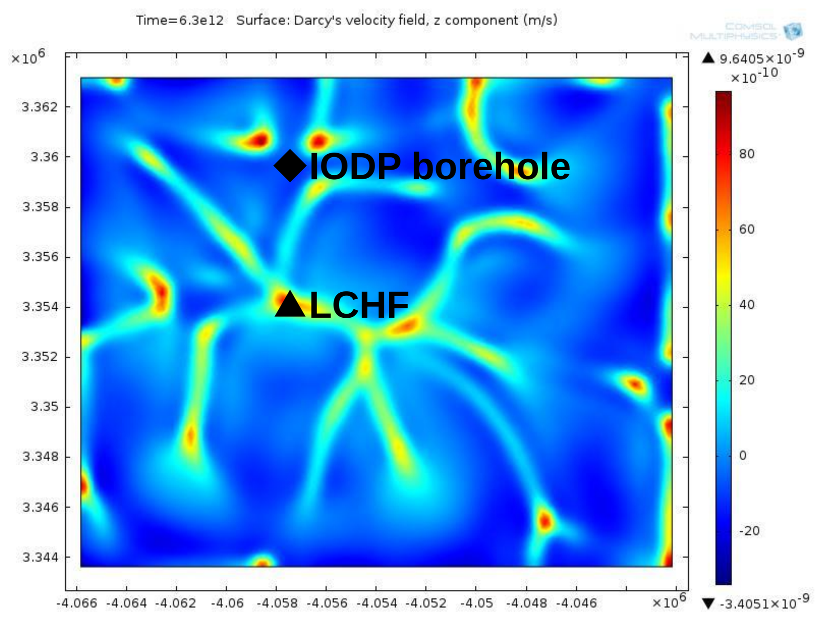

Figure 8. 3-D model in map view. $5\cdot10^{-14}$ m^2 permeability layer

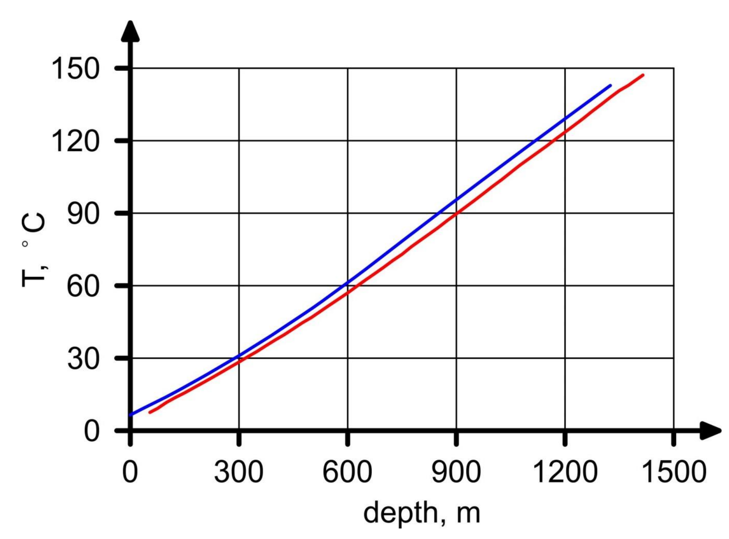

Figure 9. 3-D model, 3e^{-14} m^2 layer. Modelled temperature at the maximum value of the downflow. Red line is measured profile

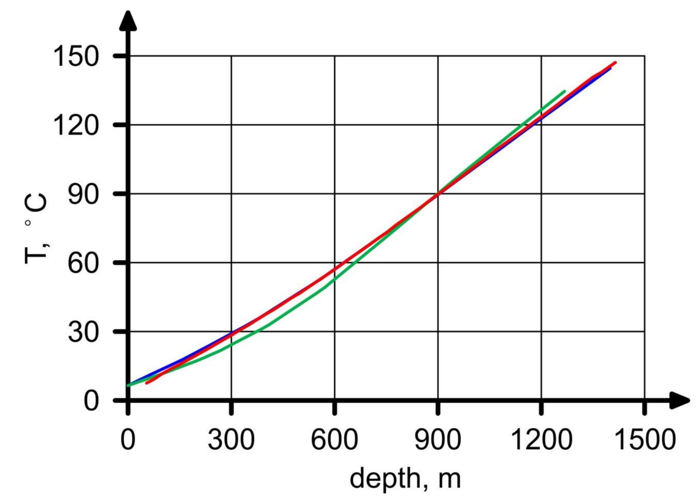

Figure 10. 3-D model, $5\cdot10^{-14}$ m^2 layer. Green line shows the match for the maximum downflow. Blue line shows the best match. Red line is measured temperature.

Conclusions: Our results show that the general features of circulation can be matched in both 2-D and 3-D, but significant differences in basal heatflow and permeability of the upper layer are need to match the present-day borehole thermal profile in 3-D. This suggests that in detail the 2-D model is inadequate. Further work is in progress to model circulation in a permeable slot to mimic active faulting beneath the LCHF.

References:

1. Blackman, D. K., and others (2011), Drilling constraints on lithospheric accretion and evolution at Atlantis Massif, Mid-Atlantic Ridge 30°N, Journal of Geophysical Research: Solid Earth, 116 (B7), n/a–n/a, doi:10.1029/2010JB007931.
2. Blackman, D., A. Slagle, A. Harding, G. Guerin, and A. McCaig (2013), IODP expedition 340T: Borehole logging at Atlantis Massif oceanic core complex, Preliminary Report 340T, Integrated Ocean Drilling Management International, doi: 10.2204/iodp.pr.340T.2012
3. Ludwig, K. A., C.-C. Shen, D. S. Kelley, H. Cheng, and R. L. Edwards (2011), U–Th systematics and ^{230}Th ages of carbonate chimneys at the Lost City Hydrothermal Field, Geochimica et Cosmochimica Acta, 75(7), 1869–1888, doi: 10.1016/j.gca.2011.01.008.

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