Final report of the "Melt in the Mantle" programme at the Isaac Newton Institute, February – June 2016

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Deep beneath our feet lies the Earth's mantle, a 3000 km thick layer of rock that is slowly convecting at about the same speed as our fingernails grow. At plate-tectonic boundaries the mantle melts; that melt rises to the surface to fuel volcanism. Melt generation in such circumstances is well understood but much less is known about the transport of that melt. Particularly puzzling is the rapid (geologically speaking!) melt segregation inferred from the chemistry of volcanic rocks, which disagree with more modest rates of transport predicted from porous flow theory.

Modelling melt transport presents a series of significant mathematical challenges, of which two were of particular concern to the INI programme. The first challenge was associated with the intrinsic multi-scale nature of the problem: melt is formed along boundaries between mineral grains at scales of millimetres but it is transported over hundreds of kilometres at the tectonic scale. A fundamental question addressed by the programme is how a description of physics at the grain scale can be upscaled to the tectonic scale. The second key challenge was enabling numerical simulation of melt transport at the large scale. The optimal discretisation of the governing PDEs is not obvious and, moreover, there are many issues associated with the numerical solution of the discretised equations.

Programme activities

Three workshops acted as focal points for the programme. The first workshop reviewed the existing state-of-the-art for continuum models of melt transport and identified areas where theory was lacking. Porous flow was discussed in a broad context and theoretical commonalities were explored by researchers working in very different fields. This discussion included flow through porous rocks, of course, but also porous through glacial ice and even through babies' nappies!

The second workshop brought together two distinct communities that had never previously interacted. It hosted rock mechanicists with expertise in the behaviour of partially molten rock at the laboratory scale; and mathematicians expert in homogenisation theory and upscaling. These two communities met with the aim of bridging the gap between grain-scale physical models and macro-scale continuum models. By the end, both communities had an appreciation of the difficulty and richness of one another's problems.

The final workshop, held near the end of the programme, focused on melt transport at the planetary scale. Connections were explored between theory and geophysical observations. There was much discussion of advances in the numerical solution of the relevant PDEs.

Between workshops there were weekly seminars and a weekly reading group that brought participants together to identify and discuss key challenges.

Scientific highlights

- Arbogast, Yi and Showalter made progress in establishing the well-posedness of the McKenzie equations of magma dynamics. Moreover, this work is a foundation for the development of finite-element schemes that are valid in the limit of vanishing porosity.

- Antoshechkina is developing a library which allows the thermodynamics software package MELTS to be used in large scale geodynamics codes. This will enable a new generation of numerical models that can combine the thermodynamics of melting with the fluid dynamics of melt transport.

- Heister and Dannberg have added melt migration to the community mantle convection code ASPECT. The latest version of the code, ASPECT 1.4.0 was released at the INI, and is available for download at http://aspect.dealii.org.

- Katz has written much of a new book entitled "Introduction to the Theory of Magma/Mantle Dynamics," to be published by Princeton University Press.

- Keller and Katz have submitted a new manuscript in which they model genesis and transport of carbon-rich melt at the tectonic scale of mid-ocean ridges.

- May, in collaboration with many others, has developed a four-field finite element formulation of the McKenzie equations that offers the potential for a more accurate and efficient numerical solution.

- Rees Jones and Tian have developed new models of the effect of melt on the thermal structure of subduction zones. This effect may play a key role in focusing melt toward arc volcanoes.

- Rudge, Takei, and McKenzie have developed a new 3D grain-scale model of diffusion creep, rigorously quantifying the weakening effects of melt.

- Takei and McKenzie have combined theory with laboratory and seismological data to produce a new anelasticity model for the mantle, which allows a direct conversion from variations in seismic properties to mantle temperature.

Figures

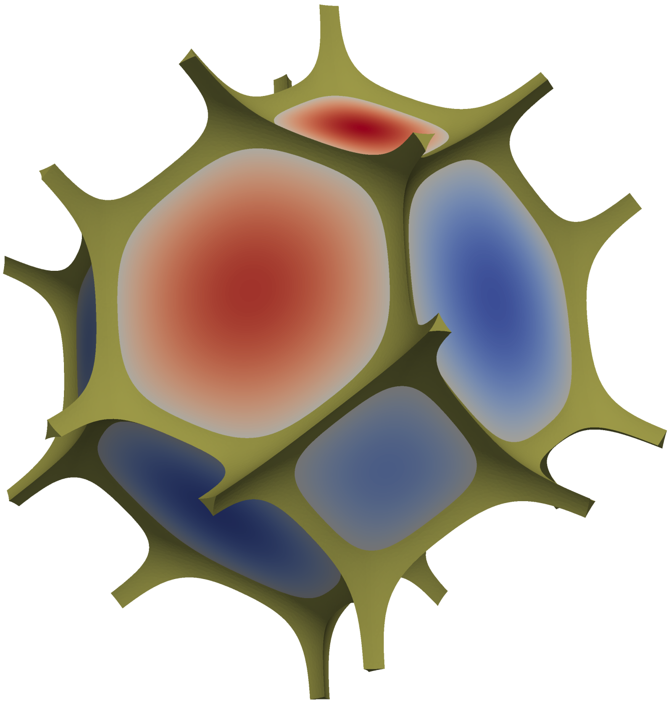

Figure 1: Melt geometry around a tetrakaidecahedral grain. Grains faces are coloured according to vacancy concentration when undergoing diffusion creep. Calculation by John Rudge.

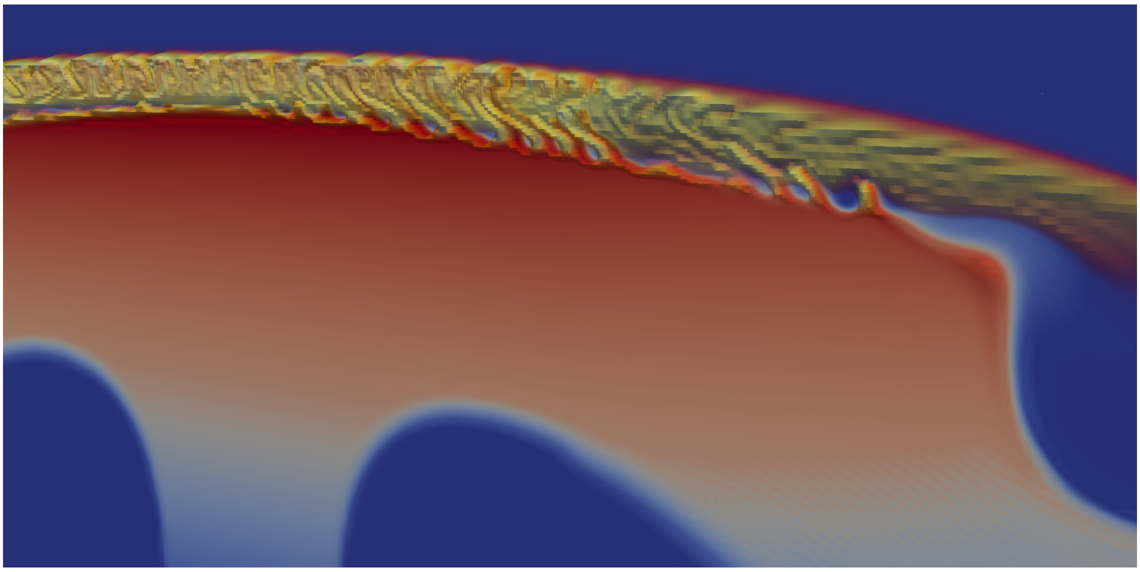

Figure 2: Melt transport in the head of a mantle plume. Calculation by Juliane Dannberg.

Photos

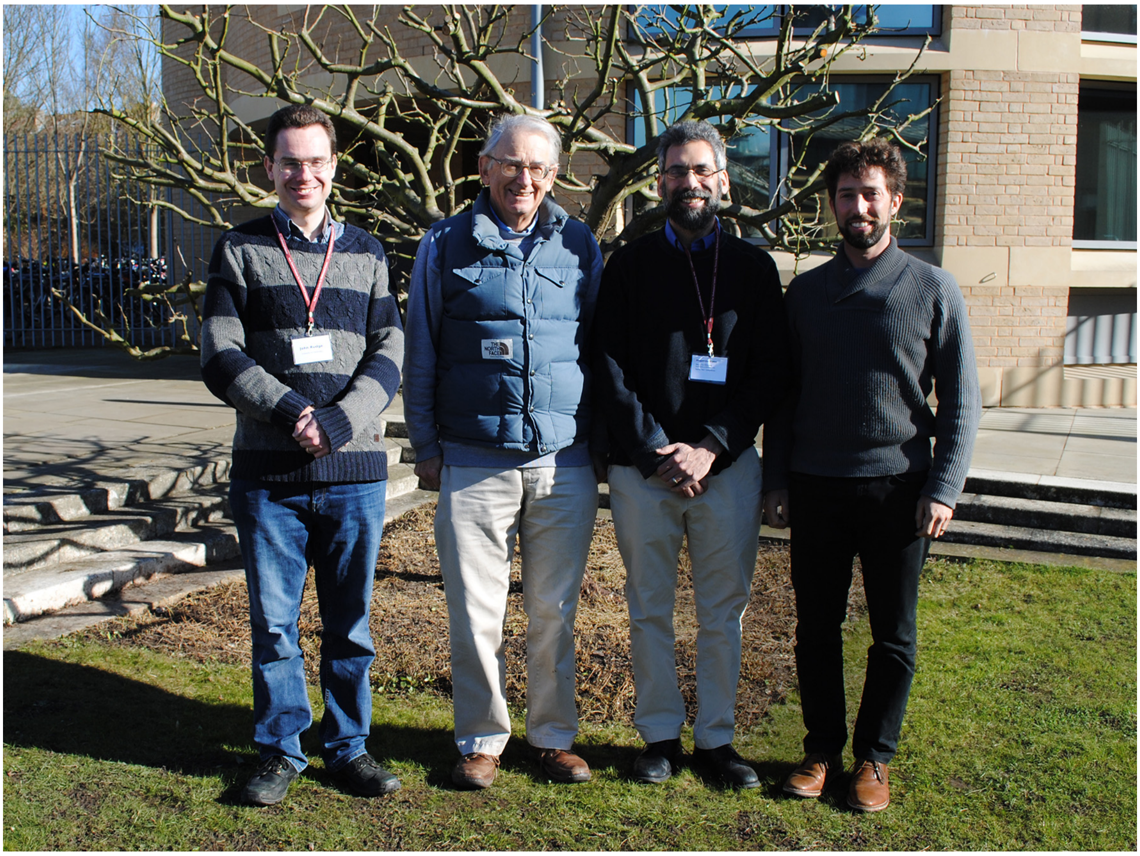

Figure 3: Three generations of "Melt in the Mantle" researchers. From left to right: John Rudge, Dan McKenzie, Marc Spiegelman, Richard Katz.

Figure 4: Participants at the third workshop.

Figure 5: A garden party at the home of Dan McKenzie.