Enhanced heat transfer by intermittent porous flow

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Understanding the distribution and transport of heat in the Earth is a primary aim of most geodynamic modeling, from the formation of the core to the evolution of sedimentary basins. Temperature strongly influences other modeling parameters such as density, viscosity, thermal conductivity and the progress of reactions. Large scale geodynamic models typically consider two main processes for the transport of heat, conduction and advection. Heat is advected with the convecting fluid in systems with a sufficiently high Rayleigh number, such as the Earth's mantle or some porous two-phase materials. The efficiency of heat transport by advection relative to conduction is usually represented by the Nusselt number Nu. Advective heat transport by porous flow is clearly important in high permeability shallow reservoirs (<10 km depth), but is often assumed to be negligible at larger depths in the crust and mantle where average permeability is low. Experimental measurement of crustal permeability and some first order calculations of the Nusselt number associated with pervasive Darcy flow indeed suggest that heat transport at >15 km should be dominated by conduction (Ingebritsen and Manning, 2010).

However, an increasing number of detailed studies on natural rocks (e.g. Ague and Baxter, 2007) strongly suggest that heat transport by porous flow through zones of enhanced permeability is an important process in metamorphism. The existence of enhanced permeability that is transient in space and time is supported by the observation that geothermal-metamorphic permeabilities derived from real crustal rocks on average are one order of magnitude higher than experimental permeabilities (Ingebritsen and Manning, 2010), and by theoretical modeling of porosity waves (e.g. Connolly and Podladchikov, 1998). Hence, enhanced heat transport by porosity waves may be important in many tectonic settings and should be considered in large scale geodynamic models.

Numerical modeling of these processes, however, requires solving a large set of non-linear coupled equations with high resolution in both space and time, and implementation into large scale geodynamic models operating on timescales of millions of years is therefore considered impractical. Instead we propose to derive parameterized formulations for the relative importance of heat transport by transient fluid flow, equivalent to the Nusselt number for conventional heat conduction/advection. These parameterizations are derived from high resolution finite difference models of fully coupled visco-elastic 2-phase flow, using implicit and explicit codes. The system of equations is derived from conservation of mass, momentum and energy, using the second law of thermodynamics as a closing relationship (e.g. Tantserev et al., 2009). Assuring that entropy production is zero (for reversible processes) or positive (for irreversible processes) guaranties that all equations are thermodynamically consistent and may also be complemented with a local equilibrium thermodynamics treatment of reactions. Porosity evolves due to deformation (visco-elasto-plastic) and reactions. Permeability depends on porosity via the Cozeny-Karman relation.

First modeling results of coupled deformation, heat and fluid flow indicate that heat transfer by porosity waves is significant under some conditions, for example during melt flow through thick cratonic lithosphere enabling the emplacement of large igneous provinces.

References:

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