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Dynamics of melt segregation and extraction: from continental rifting to mid-oceanic spreading and crust accretion

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One of the major unresolved questions in geodynamics is the physical process of melt extraction from the mantle and its role in the dynamics of continental rifting and mid-oceanic spreading. This lecture will elaborate on the physics of this process and discuss approaches and applications. To start with, asthenospheric mantle regions need to exceed the solidus temperature by either heat addition (plumes), decompression (upwelling) or decrease of solidus temperature (water). The resulting partially molten source region may be described by two-phase flow physics (McKenzie, 1984; Schmeling, 2000; Bercovici et al., 2001), in which both the melt and deformable matrix are described by appropriate momentum equations. A critical parameter controlling this flow is the melt-porosity dependent effective shear and bulk viscosity. Together with the energy equation, these equations can be solved for typical mantle convection scenarios applying appropriate approximations such as the Compaction Boussinesq Approximation (CBA). In the CBA compaction is neglected in the matrix momentum equation and only accounted for in the melt equation. However, for a high degree of melting as in plumes or beneath ridges the CBA may break down and the matrix velocity field needs to compact/decompact. In 2D convection models using the stream function formulation, an additional irrotational velocity field can be introduced (Šrámek et al., 2007), which interacts with the stream function due to the porosity-dependent viscosity. Examples of such two-phase flows will be shown.

One important result of the two-phase flow solutions is that melt percolates and segregates rather slowly. In fact, it accumulates and solidifies near the top of the partially molten zone at the solidus temperature. How does it enter into and pass through the sub-solidus lithosphere? How does it generate and enter into dykes. A consequence of the above mentioned two-phase flow with melt-porosity dependent effective viscosity is the channeling instability, which focuses the melt into channels sub-parallel to the direction of the most compressive deviatoric stress. It might be conjectured that such channels exceeding a certain critical length might be the precursors of dykes, which need a certain length to allow self-propagation (Schmeling, 2006). Not all channels might result into dykes that completely pass the lithosphere and reach the earth's surface. Some may penetrate into the base of the lithosphere and then solidify, a process that has been described as episodic magmatic infiltration of cratons (Foley, 2008). The dynamics of this process is completely unclear, but it might have important consequences e.g. for processes such as continental rifting.

If the melts infiltrate and intrude into the base or higher levels of the lithosphere, the release of latent and internal heat heats up the lithosphere and weakens it. In a feed-back mechanism this weakening may assist rifting and melt production. Two-dimensional numerical extension models of the continental lithosphere-asthenosphere system will be shown, in which the conservation equations of mass, momentum and energy are solved for a multi-component (crust-mantle) two-phase (melt-matrix) system, but the infiltration process is modeled as an ad hoc process. It is found that in comparison with cases without melt intrusions these lithospheric regions may be heated by up to several 100 K, which leads to significant viscoius weakening. Consequently, in a feed-back mechanism rifting is dynamically enforced, leading to a significant increase of rift induced melt generation.

Once rifting progresses, the role of ascending and extracted melt continues to influence the rift process as shown by numerical models. Such a typical continental extension experiment is characterized by 3 phases: 1) distributed extension, with superimposed pinch and swell instability, 2) lithospheric necking, 3) continental break up, followed by oceanization. Melt solidification of ascended melt beneath rift flanks leads to basaltic enrichment and underplating beneath the flanks, often observed at volcanic margins. After continental breakup, a second time-dependent upwelling event off the rift axis beneath the continental margins is found, producing further volcanic volumes. Melting has almost no or only a small accelerating effect on the local extension value (beta-value) for a constant external extension rate, but it has an extremely strong effect on the upwelling velocity within asthenospheric wedge beneath the new rift. The melt induced sublithospheric convection cell is characterized by downwelling flow beneath rift flanks. Modeled magma amounts are smaller than observed for East African Rift System (EARS), indicating that active rifting associated with the presence of a plume may better fit the observed magma volumes.

Once an ocean has formed the focusing of melt from the wide mantle source region into the narrow crust generation zone is still not fully understood. Possible explanations include uphill flow of the magma along the inclined base of the lithosphere associated with the solidus temperature towards the ridge axis. Focusing due to stress induced dyke or channel orientation are other alternatives. The width of the crust accretion zone has important consequences for lateral crustal thickness variations for normal or anomalous spreading centres. For example, the Icelandic crust seems to be thinner at the ridge axis above the plume thickening towards the sides (Bjarnason and Schmeling, 2009, see Schmeling, 2010). Crustal accretion models, some of which include hydrothermal convection by appropriate scaling laws and distinguish between deep or shallow accretion, show the potential existence of four accretional modes with characteristic lateral crustal thickness variations. Mode 2 or 3 (moderately sideways thickening or constant thickness) may be identified with the situation in Iceland. No accretional mode with maximum crustal thickness above the plume at the rift axis has been found. The absence of mode 1 accretion (very thin crust at axis) on earth may be an indication that in general crustal accretion is not cold (and shallow).

In conclusion, numerically modeling of the two-phase flow equations of the melt-matrix system together with various physically or observationally based assumptions help understanding the relations and feed-back mechanisms between melt extraction and geodynamics in various scenarios spanning from continental rifting to mid-oceanic spreading.

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