

# Modeling platform for 3D melt migration in plate boundaries

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## Summary

The generation and migration of magma are important aspects of geological systems. However, there is virtually no software that can simulate melt migration in the Earth interior in a realistic setting. I propose that CIG develops a modular software package aimed at modeling magma migration in 3D coupled with mantle flow. The boundary conditions should be defined with enough flexibility not only to allow coupling with other codes but also to enable an object-based description of the major elements of plate boundaries. Geochemical evolution of the melt and mantle residuum must be included in this package to facilitate the comparison between model predictions with the geochemical data. I suggest a first application to modeling melt migration at ridge-ridge-ridge triple junctions. A strong community interest in this package is certain owing to the numerous 3-dimensional setting in which melt output and composition can be studied.

## 1 Scientific motivation

The composition of magma erupted at the Earth's surface reflects a wide range of deep processes such as melting, due by decompression or heating, reaction and partial re-equilibration with the rocks encountered during melt extraction, and crystallization in magma chambers and in colder areas of lithosphere. Information about these processes is recorded in the major, minor, and trace element abundance as well as disequilibrium within radiogenic decay chains, both in large volume magma batches and in low volume melt inclusions.

Unraveling the geochemical record of these processes is impeded by the paucity of detailed models of melt migration and resulting geochemical evolution in a realistic geological setting. Most models are analytical, assuming a one dimensional melting column which is at best an idealization of the melting process. The work of Spiegelman (1996) and co-workers is remarkable in that it considers two-dimensional melt migration and distribution. Even so, coupling between melt migration and mantle flow is handled only in an approximate sense in these models. CIG should develop a software package to solve the trajectory and geochemical evolution of melts at plate boundaries in three dimensions. I suggest that the building of such a software package be a strong priority for CIG and volunteer to participate in this effort. The first application of this software would be a model of melt migration at a ridge-ridge-ridge triple junction as analytical solutions are available for related but simpler configurations.

In addition to clarifying the geochemical observable of accessible magma samples, the proposed software will permit the investigation of various tectonic couplings that are currently suspected but not easily modeled. For instance, melting may stabilize regions of plate divergence and with it global plate tectonics. Testing this requires coupling a magma migration code with a global mantle circulation simulation like CIG's CITCOM. In addition, magma is suspected to influence fault localization and the tectonic style of rifts. This can be studied by coupling a magma migration code with an elastic-viscoplastic software like CIG's SNAC. Earthquakes, tremors and volcano eruption are known to be spatially and temporally collocated, a link that can be studied by coupling a magma migration code with a dynamic rupture code such as EqSim. These links are evidently easier if these codes are written in a common framework. Therefore, it is natural that CIG be entrusted in the creation of the missing piece of all these coupled system, the magma migration code.

## 2 Theory and numerical technique

In the earth interior, melt is most likely present in an interconnected pore space. The solid matrix of this two phase system is viscous. Relevant theories of two-phase flows were developed by

McKenzie (1984) and Bercovici et al. (2001). Where McKenzie (1984) assumes a compressional viscosity, Bercovici et al. (2001) obtain this behavior from considerations of surface tensions at the microscopic solid/liquid interface at the cost a slightly more complex set of equations. Both formulations should be implemented in the melt migration package.

These theories require solving for compressible viscous flow. The dilatational component of the solid matrix can be decoupled from the shear motion. It would therefore be advantageous to consider separate solvers for the shear and compaction motion. The shear motion can be readily determined using the Finite Elements method provided that pressure is accurately determined. A stand-alone code can be used for this aspect of the solution. Spiegelman wrote a Finite Difference multigrid algorithm to determine the compaction component of motion, and this strategy can be followed here. Spiegelman's algorithm follows a semi-Lagrangian reference frame for which he and Matt Knepley are currently extending the PETSc library. It should therefore be possible for CIG to use PETSc to develop a compaction flow solver similar to Spiegelman's and couple it to an independent Finite Element package. The two are coupled through porosity and pressure variables. Finally, the solution is completed by solving temperature, solid and melt composition, which requires a semi-Lagrangian advection-diffusion solver. Again, Spiegelman's work can be used as a starting point for this application. The thermal solver in particular could be reused for other codes for long term tectonics. The envisioned melt migration package is strongly modular, having separate solvers for shear flow, dilatant flow, melt motion, temperature and composition evolution. Additional modules determine the rates of melting, crystallization, and melt-rock reaction.

The boundary conditions include prescribed motions or pressure at the domain edges in addition to composition. In that aspect, this software is similar to other CIG software such as CITCOM. However, an interest for solving melt migration stems in the detailed workings of plate boundaries. It would therefore be useful to derive an object-based definition of plate boundary. For instance, the user would specify the type of plate boundary (ridge, transform, subduction), its geometry, and the definition of a plate (rigid, deformable, with or without weak zone at the boundary) and the software would determine the correct surface or far field velocity conditions and defined optional weak zones for the correct geometry. This formulation is not specific to the melt-migration model. Elastic-visco-plastic models such as SNAC would benefit of this definition as well.

### **3 Work Plan**

I received seed money from WHOI's Deep Earth Ocean Exploration Institute to initiate a 3-D mantle flow in a Ridge-Ridge-Ridge triple junction. I believe that this project should take advantage of the existing libraries such as PETSc and Cubit. I would like to interact with CIG on this project so that the software can be coupled with existing software such as CITCOM and SNAC. The first step is to identify or construct a Finite Element code for compressible deformation of the mantle. The second step is to generalize the series of software developed by Marc Spiegelman to 3 using PETSc. The third step is to adapt the thermal and composition solvers to this formulation. Finally, the flexible plate boundary definition should be defined. This is probably a 2 year effort, with two steps realized each year.

### **4 References**

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