Scientific and computational challenges in simulating fluid-rock interaction and its role in the long-term tectonics of continental lithosphere

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View ~ 5 mm; Photo: J. Selverstone
General challenges in models of continental lithosphere

1. Heterogeneity - at many scales
2. Anisotropy
   • Intrinsic: anisotropic minerals, e.g., olivine
   • Due to spatial distribution of small-scale anisotropic heterogeneity (Backus, 1962)
3. Multi-phase, multi-physics, non-linear
4. Strain localization
5. What to do about the (open) basal boundary?
   …
Effective rheology: diversity of approaches

Continuum mechanics
- elastic, thin-viscous sheet, elastic-visco plastic, viscoelastic, rigid-plastic, etc; with and without emergent strain localization at faults/shear zones

Damage theory

General problem: degeneracy e.g. in surface strain-rate patterns

See also overview by S. Willett at 2005 CIG-Long-term crustal dynamics workshop
Observations demand multi-physics

Episodic tremor and slip, Cascadia

- Short time scale (<10^1 yrs)
- Long spatial scales (10^1 to 10^2 km)

Rogers and Dragert, 2003

Fluid-related? Obara, 2002
Deviation from constant velocity (estimated from the previous 2.5 years of data)

- Short time scale (<$10^0$ yrs)
- Long spatial scales ($10^2$ to $10^3$ km)

Very long-range interactions: ?? Fluids?

Davis et al., 2006
Melt-rock interaction in continents: Strain localization and deformation

Magmatic brecciation: tonalite surrounding blocks of lower crustal diorite within a lower crustal shear zone

Scale: C. Manduca
Melt-rock interaction in continents: Metasomatism

Wholesale transformation of lherzolite into carbonate-bearing pyroxenite (Rio Puerco volcanic field, NM)

Olivine reaction with carbonatitic melts to form calcite

View ~ 5 mm; Photo: J. Selverstone
e.g., Lee et al., 2001
- CP more depleted in basaltic components removed by partial melting (higher Mg#) than Mojavia

see: [Alibert, 1990; Ehrenberg, 1982; Lee et al., 2001; Roden, et al., 1990; Smith, 2000]

Enigmatic lithospheric stability of CP correlates with Mg# not age
Goal: Coupled deformation and magmatism models for long-term tectonics

- Subduction zones
  GyPSM-S: Baker et al., AGU, 2005

- Intra-plate setting
  - Colorado Plateau, western US
    Roy and Jordan, in review, 2006;
    Callahan, Roy, and Jordan, in prep.
The diagrams on this page are from Roy and Jordan, in review, 2006.
Cenozoic magmatic pattern and rock uplift

Roy and Jordan, in review, 2006
Coupled chemical, thermal, rheologic evolution

- Intra-plate deformation (mainly buoyancy-driven vertical motion)
- Chemistry: couple thermodynamic phase relations using pMELTS and pHMELTS on the same grid as the thermal/deformation calcs

*Callahan, et al., in prep.*

*Wang, et al., 2002*
Magmatism and long-term tectonic deformation

• Long-term effect on rheology: “inherited” weakness
  – Planar zones of weakness
  – Volumetric inheritance
    • Responsible for large-scale compositional and rheologic heterogeneity within continents
    • Relationships between deformation during mountain building and crustal melting (anatexis)

• Mechanisms/processes:
  – Chemical effects of metasomatism (melt/fluid reactions - transform the dominant mineralogy and affect energy balance)
  – Removal of Fe leaves a less dense and rigid residue (particularly if Gt consumed)
  – Advective heating
  – Phase changes
Software Challenges - 1

- Magma-deformation feedback on short timescales ($<10^{2-3}$ yrs)
- Fluid flow in viscously deforming media (e.g., McKenzie, 1984) -- details of this may not be necessary for models of long-term deformation?
Software Challenges - 2

• Coupled PDE’s for deformation, chemistry, and rheology solved on coincident grids for thermodynamics and deformation

• Particle histories (proxy for species segregation between melt and residuum) for major and trace elements

• Modular implementation (turn magma migration/chemistry on/off?)

→ PDE-based multi-physics (FEMLab approach?)
Challenges for petrologic models

- Continental mantle lithosphere is not a simple residue of melting (we have no melting models for hydrated, previously metasomatized upper mantle)

- Kinetics are important in chemical evolution but are ignored

*Width = 0.4 mm; J. Selverstone*