Toward New Methods for modeling complex mantle dynamics

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Frontier of Understanding Earth's Interior and Dynamics

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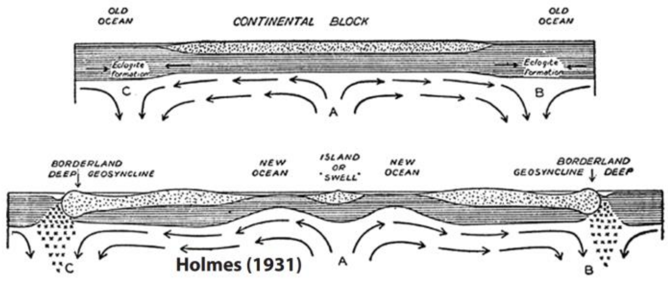
Scientific Research Questions:

How does the rocky majority of the Earth's interior move and deform to produce plate tectonics, earthquakes, volcanic eruptions, circulate its inventory of elements in and out and create suitable conditions for the origin and evolution of life?

The "fluid-like mantle ": A historically useful abstraction

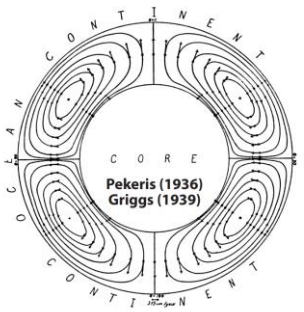


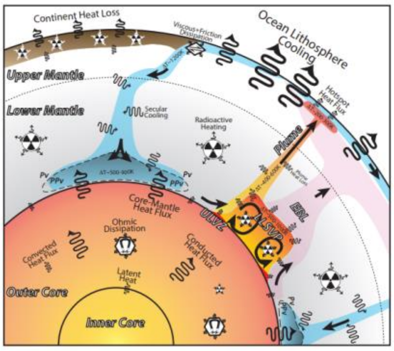
Classic conceptual sketch of fluid-like motions in the rocky mantle that would accompany tectonic activities

Fluid-like thermal convection in the Earth's mantle is an old idea brought into prominence by Arthur Holmes, Felix Vening Meinesz, and others. It followed on the heels of pioneering laboratory and theoretical work on thermal convection in fluids by Bénard, Rayleigh, Jeffreys and others. This rough analogy between the movements of the thick, rocky mantle shell of the Earth and thermal convection in ordinary fluids came to be known as "mantle convection".

Weakness of such a simplistic analogue

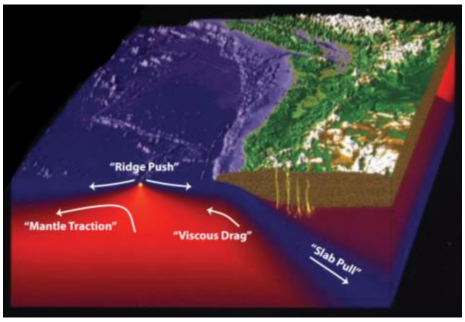
Mantle convection theory is presently based on experimental analogue study of fluids in the laboratory and in numerical models. Such an approach is easy to implement, deterministic, and reproducible, which carries benefits for scientific coherency and consistency. The critical weakness is that such a simplistic analogue is intrinsically incapable of capturing important behaviors of rock and explaining key observations.





In reality the Earth's mantle is way more compex…the description of solid rocks as "a fluid" has limitations in accounting for observations bearing on the physical and chemical state of the interior.

1.Problem: Plate tectonics vs. fluid mantle convection

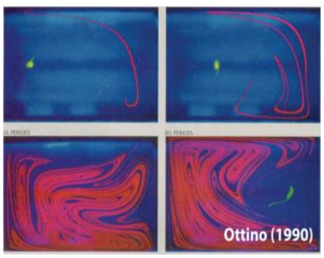


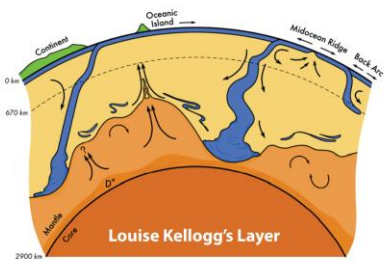
Observations show that fluid-like convection is a poor analogue for the observed behavior of the crust and lithosphere.

Mantle convection models utilize unrealistic fluid-like rheologies that mimic instantaneous aspects of plate tectonics, like stress-dependent viscosity, but fail to capture the realistic temporal evolution of rock-like **strain-dependent rheologies**.

Therefore, there are inconsistencies between - fluid mantle thermal convection and plate tectonics.

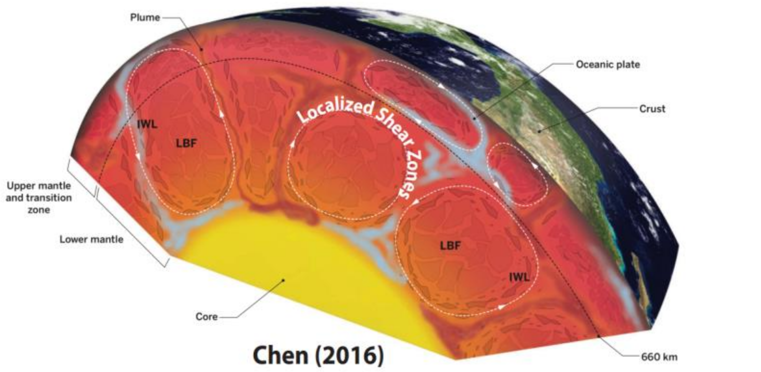
2. Problem: Mixing /Preservation of Heterogeneities





A hallmark of fluid-like thermal convection is the efficiency of mixing heterogeneities, via a process of "stretching and folding." In a fluid-like convection model one may vary 2 parameters: viscosity and density. Scientists tried just about every combination of both, assigning an anomalous viscosity and/or density to compositionally distinct material in an attempt to alter its mixing/recycling and match geochemical observations. No single model there is satisfactorily explains all the geochemical observations.

Approach: Modeling the Mantle as a rock rather than a fluid

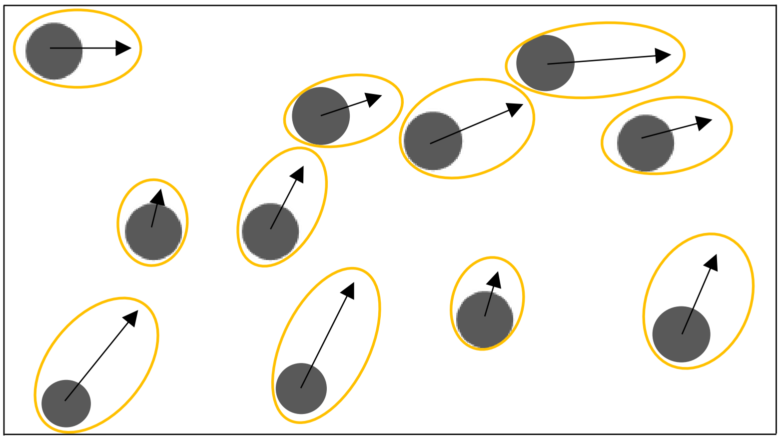


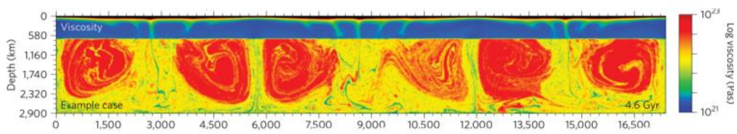
The "fluid-like" conception of mantle convection supposes that sub-grain processes such as vacancy diffusion directly scale up to ~100-1000 km, without any non-linear interactions, feedbacks, or other complexities manifesting at intermediate scales.

Idea: Stochastic Mantle Dynamics

Probability that particle moves in a given direction is a function of density relative to surrounding particles, viscosity, coupling to neighboring particles, etc..

At each time step, the random number is generated and then the probability function applies the motion. This allows freedom to add numerous complexities, such as shear zones, hysteresis, that are very difficult in fluid like simulations.





Ballmer et al.

Step 1: Reproduce simpler fluid-like behavior, convection, etc.

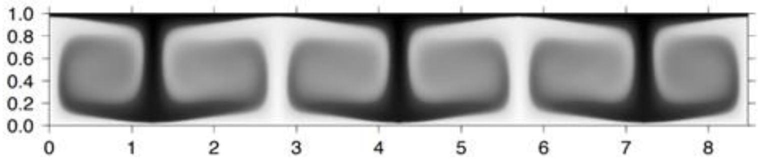
Step 2: Make a rigorous proof that the Monte Carlo simulation converges on the exact solution in order to derive important parameters

Step 3: Begin adding complexities and treating the material like rocks rather than fluids

Step 4: Incorporate multi-scale effects (group movements of particles, transfer information, and other factors between scales)

Takeaway Message

Developing models that explain the complex dynamic of the mantle is most probably one of the most challenging problems in all geophysics. However, we really need to think "outside the box" and develop some new approaches that are better suited for approaching the question of realistic Earth rheology to better understand our planet. The old idea of fluid-like thermal convection in the Earth's mantle, although having some benefits, is ready for an update.



References

Bercovici,D (2000) et al. *The Relation Between Mantle Dynamics and Plate Tectonics: A Primer*

Hernlund,J (2019) *Grand Challenge: Addressing an Inconvenient Truth About Mantle Rheology*