Geophysical Fluid Dynamics: from the Lab, up and down!

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Lecture 2

Mantle convection and plate tectonics

FDEPS
Kyoto, November 27, 2018
2. Mantle convection and plate tectonics

2.1. The blinding evidence for plate tectonics

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2.1. The blinding evidence for plate tectonics
The many signatures of plate tectonics today

• a survey of geophysical observables compiled at http://jules.unavco.org/Voyager/Earth
(2.1) The blinding evidence for plate tectonics
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Holocene active volcanoes

(2.1) The blinding evidence for plate tectonics
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**Topography**

**Free-air gravity anomalies**

**Seismicity**

**Stresses**

**Oceanic floor age**

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**Figure captions for reference**

Topography

Free-air gravity anomalies

Seismicity

Stresses

Oceanic floor age

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(2.1) The blinding evidence for plate tectonics
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Questions...

• What happens to plates sinking into the mantle?
• What is the origin of hotspots?
• How does subduction initiate?
• When did plate tectonics begin?
• Why is it not seen on other planets?

(2.1) The blinding evidence for plate tectonics
2.2. Mantle convection with T-dependent viscosity
The viscosity of the constituents of the mantle varies strongly with temperature. The viscosity of the cold lithosphere is several orders of magnitude larger than the viscosity of the hot asthenosphere.

What are the consequences of this fundamental property of mantle convection?

Let’s look at a very simple problem: the linear stability of Rayleigh-Bénard convection in a fluid with a viscosity $\nu$ varying with temperature $T$ as:

$$\nu(T) = \nu_b e^{-\gamma(T_b - T)}$$

One can solve the linear stability of this (non-Boussinesq) problem, but we first look at it with heuristic arguments.
• Considering the sketch we have seen this morning, we start from the conductive solution. Therefore the temperature dependence of viscosity becomes a depth dependence: 

\[ \nu(z) = \nu_b e^{\gamma \Delta T \frac{z}{d}} \]

• Can convection develop in a sublayer between 0 and z, where viscosity is lower than at d?

(2.1) Mantle convection with T-dependent viscosity
Let’s compute the Rayleigh number $Ra_z$ of this sublayer, picking the viscosity at mid-height as its ‘representative viscosity’:

$$\nu(z/2) = \nu_b e^{\gamma \Delta T \frac{z}{2d}}$$

Let’s define: $Ra_b = \frac{\alpha \Delta T g d^3}{\kappa \nu_b}$, $r_\nu = e^{\gamma \Delta T}$, $\tilde{z} = \frac{z}{d}$

Then: $Ra_z = Ra_b \tilde{z}^4 e^{\frac{z}{2} \ln r_\nu}$, which reaches a maximum for $\tilde{z}_m = \frac{8}{\ln r_\nu}$ if

$$\ln r_\nu \geq 8 \iff r_\nu \geq e^8 = 2981$$

The viscosity ratio across this sublayer is always $e^8 = 2981$. 

(2.1) Mantle convection with T-dependent viscosity
Indeed, if we compute the actual critical Rayleigh number $Ra_c$ (still defined using viscosity at mid-height) as a function of viscosity ratio $r_\nu$, we get:

\[ \text{Critical Rayleigh number with } T\text{-dependent viscosity} \]

\[ r_\nu \]

\[ R_{a_c} \]

exponential viscosity law for real fluids

Richter et al, 1983

also: Stengel et al, 1982
Once convection is restricted to a lower sublayer, the top part acts as an **motionless conductive lid**. Therefore, if we have the convection solution for the sublayer, we can easily **extrapolate** to the whole layer, and to any larger layer but by adding more viscous material at the top:

\[ \nu(z) = \nu_b e^{\gamma \Delta T} \]

(2.1) Mantle convection with T-dependent viscosity
• This works well indeed, as demonstrated by the velocity eigenfunctions for linear instability at 3 different viscosity ratios ($10^4$, $10^6$ and $10^8$), plotted using a stretched coordinate

$$\tilde{z}^\dagger = \tilde{z} \frac{\ln r_v}{8}$$

(2.1) Mantle convection with T-dependent viscosity
The advantage of this approach is that it can be generalized to other viscosity laws and to developed convection, focusing on the horizontally-averaged temperature profile.
Measuring horizontally-averaged temperature profiles

- Measuring the **horizontally-averaged temperature profile** in actual laboratory experiments:

Richter et al, 1983

(2.1) Mantle convection with T-dependent viscosity
Experimental horizontally-averaged temperature profiles with $Ra_{1/2} \sim 10^5$, and three different viscosity ratios:

![Graph showing temperature profiles with different viscosity ratios](image)

$r_v = 3$

Richter et al, 1983

(2.1) Mantle convection with T-dependent viscosity
Two important conclusions:

1) Mantle convection beneath a **stagnant lid** is really what we expect and it seems that this situation prevails for most planets (+ volcanism). Unless the lid viscosity is low enough to allow for convective motions.

2) The **viscosity ratio across the lower boundary layer** is self-limited to values of the order of **10 only**.
2.3. The mantle plume paradox
Hotspots

• Plates don’t get it all: intra-plate ‘hotspot’ volcanism appears to be an additional key component of mantle dynamics.

• As pointed out by Wilson (1961), they appear to correspond to heat sources that do not move while plates pass above them.

• Hawaii is the best known hotspot, and the track it left on the Pacific plate is impressive.
(2.2) The mantle plume paradox

Free-air gravity anomaly map

GPlates plot
Geophysical and geochemical signatures of hotspots

- Hawaii is the best known hotspot, but geophysicists and geochemists have identified many more hotspots.

**Buoyancy flux of hotspots, determined from the swell they produce beneath the lithosphere.**

(from Sleep, 1990)

Radiogenic signatures of hotspots.

Figure 10.30. Three dimension plot of $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, and $^{206}\text{Pb}/^{204}\text{Pb}$. Most oceanic basalt data plot within a tetrahedron defined by the composition of EMI, EMII, HIMU, and DMM components. Oceanic islands and island chains tend to form elongate isotopic arrays, many of which seem to point toward a focal zone (FOZO) at the base of the tetrahedron. Adapted from Hart et al. (1992).
• The prevailing explanation is the ‘mantle plume’ model of Morgan (1972), in which some hot plume originates from a boundary layer deep in the mantle, where convective velocities would be much slower than plate velocities.

• An additional clue comes from noting that the eruption of several large igneous provinces (LIP) coincide with the start of a hotspot track, and often also to the breaking of the overriding plate.

• A well known example is the La Réunion hotspot whose birth seems to date back to the Cretaceous-Tertiary boundary (65 Ma ago), when the huge Dekkan Traps were emplaced.
Dekkan Traps and La Réunion hotspot

(2.2) The mantle plume paradox

Buiter & Torsvik, 2014
This prompted the idea that mantle plumes could be thermal cavity plumes with a large temperature-dependent viscosity ratio, characterized by a large head fed by a narrow tail (Courtillot et al, 1986; Richards et al, 1989; Griffiths & Campbell, 1990).

Experiments indeed show this behaviour when the hot injected fluid is some 100 times less viscous than its surrounding.
The viscosity ratio required to build thermal cavity plumes with a large head and a narrow tail appears to be one order of magnitude larger than the viscosity ratio built by T-dependent convection across its lower boundary layer.

How can we solve this paradox?
(1) Because of plate tectonics, some oceanic crust is returned to the mantle and accumulates at its base. It contains more heat-producing radioactive isotopes than the surrounding mantle. Therefore, it heats up gradually, and after a time of the order of a billion years, it forms a large buoyant plume.

This scenario, put forward by Hofmann & White (1982) also explains some geochemical properties of hotspot lavas.
Because of plate tectonics, the cold subducting slab spreads above the hot bottom, thereby increasing the temperature drop and viscosity ratio across the lower boundary layer.

This shows up (partly) in the experimental horizontally-average temperature profile of T-dependent convection with a moving upper lid.
(3) A **dense layer** at the base of the mantle is entrained by a thermal plume. Depending on the density and viscosity ratios, plumes can take different styles.

In the experiments of Kumagai et al (2008), the fluid contains **thermochromic liquid crystals**, which mark the positions of isotherms.

(2.2) The mantle plume paradox

*Kumagai et al, 2008*
2.4. Seismic tomography
Seismic tomography

epicentral distance

IRIS

time (minutes)

(2.3) Seismic tomography
Ancestors’ global models of the upper mantle...

Nataf, Nakanishi & Anderson, 1984

from 250 fundamental Rayleigh + Love waves

Woodhouse & Dziewonski, 1984

(2.3) Seismic tomography
A recent global model of the uppermost mantle from 1,359,470 Rayleigh waves, up to the fifth overtone!

Debayle et al, 2016

(2.3) Seismic tomography
Fukao & Obayashi (2013) conducted the most thorough and impressive survey of subducting slab behaviour, from cross-sections across their high resolution P-wave velocity global model. It was obtained from more than 10 million travel-times, using a finite-frequency extended ray theory.

**Figure 3.** Successive slices of slab images. (top, left) Across the northern Honshu are along profiles A–E shown in the top left map. (bottom, right) Across the northern Bonin are along profiles F–J shown in the bottom right map. The color scale is ±1.5% in P wave velocity perturbation (blue = positive, red = negative). White dots indicate earthquake hypocenters within a band 50 km wide on both sides.
Their study reveals that many slabs flatten out and stagnate either above or around the 660 km discontinuity, or at depth of about 1000 km. Only a few slabs penetrate deep into the lower mantle.

Fukao & Obayashi, 2013
The resolution of seismic tomography in the lower mantle is not as good as in the upper mantle. Mantle plumes are expected to be rather narrow features (diameter ~100-400 km) with a rather modest temperature excess (~200-400 K), yielding seismic velocity anomalies of ~2-5%.

Therefore, it seems difficult to image mantle plume conduits in the lower mantle. Nevertheless, several teams have developed tools for addressing this issue. I will present three of them.
Narrow velocity anomalies scatter seismic waves. Coherent scattering from a vertical structure, such as a plume, can produce a sizable scattered wave. **Scattering tomography** stacks waves that can be scattered from a given location.

A strong slow anomaly was detected that way, north-west of Hawaii.

*Ji Ying & Nataf, 1998*
Wavefronts ‘heal’ when travelling in a low-velocity region, thereby smearing out the travel-time anomaly it produces. Montelli et al (2004) used a finite-frequency theory, which goes beyond classical ray theory, and produced a global map of the lower mantle. Integrating over the full depth of the lower mantle to emphasize vertical structures such as plumes, they detected several slow anomalies that seem to be related to known hotspots.

The amplitude of these anomalies is stronger than expected for usual thermal mantle plume models.
Finite frequency P-wave tomography

Montelli et al, 2004

Fig. 1. Vertical average over the lowermost 1000 km of the mantle of the relative velocity perturbation $\delta v_p/v_p$. The averaging emphasizes features that are continuous with depth. Map has been wrapped around to have complete views of both the Atlantic and the Pacific oceans.
Wavefronts ‘heal’ when travelling in a low-velocity region, thereby smearing out the travel-time anomaly it produces. Montelli et al (2004) used a finite-frequency theory, which goes beyond classical ray theory, and produced a global map of the lower mantle. Integrating over the full depth of the lower mantle to emphasize vertical structures such as plumes, they detected several slow anomalies that seem to be related to known hotspots.

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More recently, French & Romanowicz (2015) produced a global mantle tomographic model, using a method that partly accounts for scattered waves. They find large slow anomalies that correlate with several hotspots.

French & Romanowicz, 2015

(2.3) Seismic tomography
Full waveform tomography

French & Romanowicz, 2015

(2.3) Seismic tomography
Two remarks

1. None of the mantle plume ‘detections’ presented above has yet received a large consensus.

2. All these studies show much larger anomalies than expected for ‘standard’ thermal plumes (another plume paradox!).
2.5. Plate tectonics: where, why and how?
lava lake tectonics

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