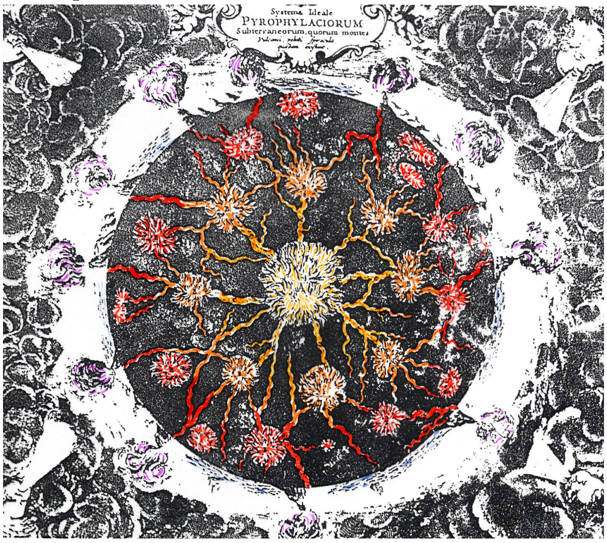
1. INTRODUCTION TO THE EARTH

1.1

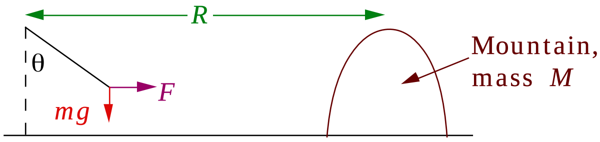
1. Basic Description



An early view (about 1664) of the Earth's interior. The writer A. Kircheri conceived the Earth as a ball of solid material fissured by tubes of magma, connecting pockets of eruptive gases to volcanic vents on the Earth's surface.

1.2

The advent of Newton's laws of gravity allowed the earth to be weighed, in 1775, by the following means.



EARTH radius R_E

$$= G m_1 m_2 / r^2 \qquad \text{(Newton)}$$

$$F = mg \tan\theta = G m M / R^2$$

but $$mg = G m M_E / R_E^2$$

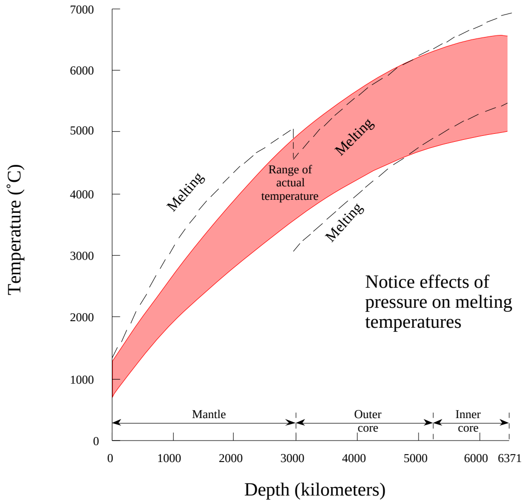
$$M_E = (R_E / R)^2 (M / \tan\theta) \qquad \bar{\rho} = 4.5 \text{ g cm}^{-3}$$

which is almost twice the density of rocks at the surface

variation of density with depth

Miners noticed that
temperature increased with depth ~ 1˚C / 30m ~ 30˚C / km
(c.f. oceans, 20˚C / km and atmosphere, 6 ˚C / km)

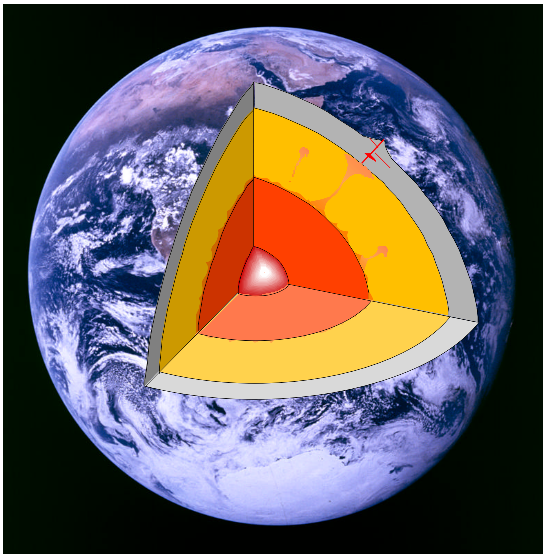
1.3



These curves indicate the range of estimates of temperature variation inside the Earth. At present the uncertainty is quite high. The consequences of adopting any particular estimate can be important in terms of the prediction of melting in the Earth.

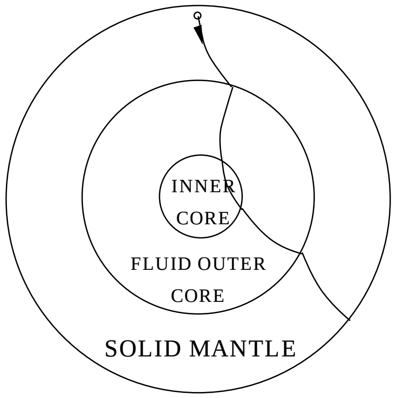
Inge Lehman discovered in 1936 that the inner core was solid, leading to the current gross view of the Earth.

1.4



H[2] (2000)

1.5



Current Values

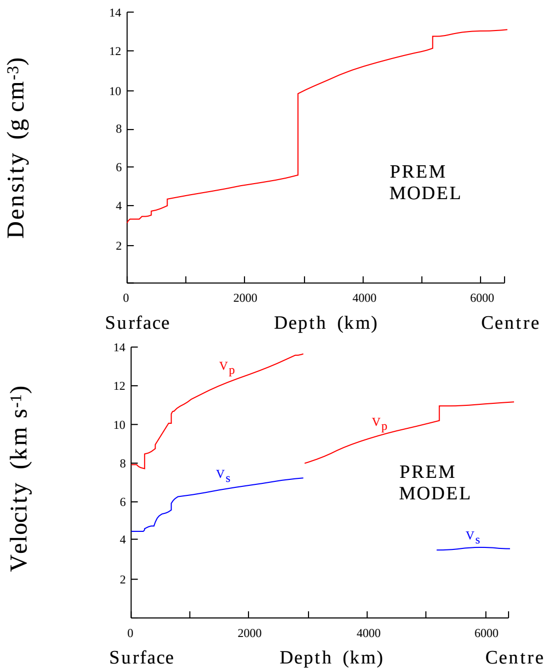
c = 1221 km V_i = 7.6 x 10^9 km^3 M_i = 9.7 x 10^{22} kg

b = 3480 km V_o = 1.7 x 10^{11} km^3 M_o = 1.9 x 10^{24} kg

R =6371 km V_m = 9.1 x 10^{11} km^3 M_m = 4.0 x 10^{24} kg

M_{oceans} = 1.41 x 10^{21} kg M_{atmos} = 5.1 x 10^{18} kg

1.6



Notice pressure effects again

1.7

inner core :

almost pure Fe

outer core :

Fe plus light elements

O, S, Ni.....

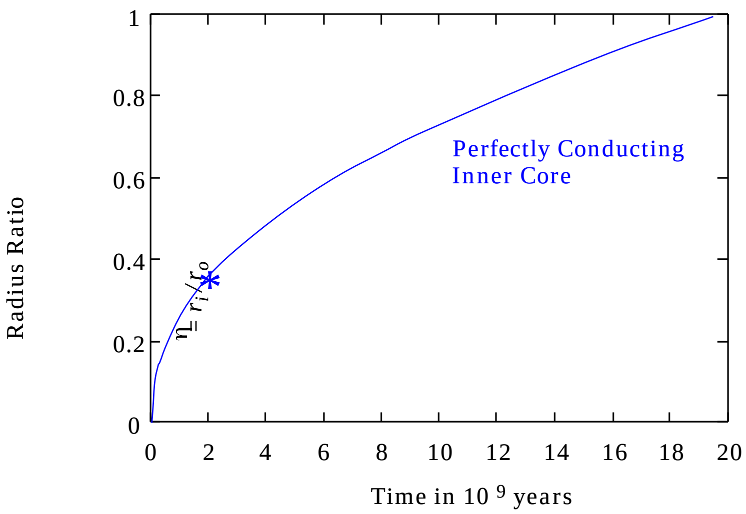
Pressure, temperature and composition all play a role

$M_{core} \sim 2 \times 10^{24}$ kg

$\dot{M}_{core} \sim 2 \times 10^{6}$ kg s^{-1}

1.8

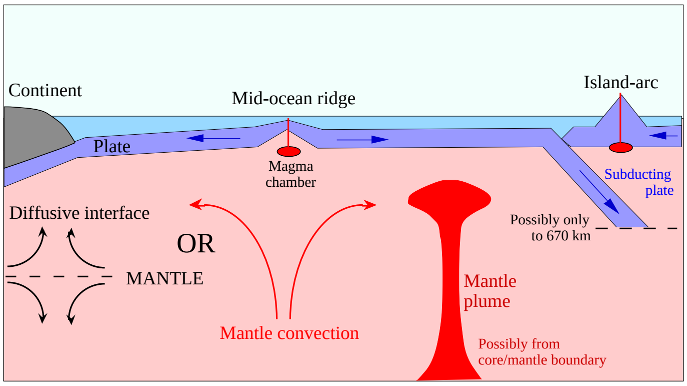
(Buffett, H^2 , Lister and Woods, 1992 and 1996)



The ratio of the radius of the solid inner core to the outer core, η, as a function of the time since the initiation of the solid inner core. The current value is denoted by the star.

2. Large scale motions

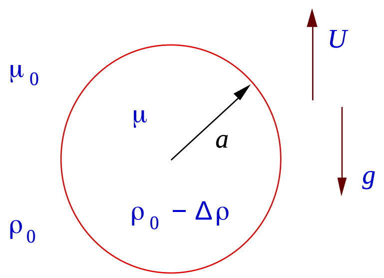
1.9



a) There are three general large scale forms of motion in the "solid" mantle: broad convective motions; plumes; and subducting plates. Convection is thought to be either throughout the whole mantle (thickness 2890 km) or separated into motions in the upper mantle (thickness 670 km) and the lower mantle.

1.10

b) A spherical blob of fluid of radius a, density $\rho_0 - \Delta\rho$ and dynamic viscosity μ rising slowly and steadily in a uniform infinite fluid of density ρ_0 and dynamic viscosity μ_0, at low Reynolds number, $Re = \rho_0 U a / \mu_0 << 1$, is a famous problem in Stokes flow (c.f. GKB textbook pp 230-240) with solution



$$U = \frac{2}{9}\frac{(\Delta\rho\, g)}{\mu_0} a^2 f(\mu/\mu_0)$$

1.11

c) A hot isolated blob expands as it rises due to conduction. The neighbouring fluid becomes warm and light and rises with the blob. This is laminar entrainment by conduction, in comparison with turbulent entrainment by mixing (subsequent lecture) in volcanic plumes, etc. Solution of equation indicates and laboratory experiments confirm that

$$a = K z$$

with $K = (\pi / f) Ra^{-1/3}$, where $Ra = \underbrace{\overset{z^{-3}}{\Delta\rho}\,\overset{z^{3}}{V}}_{\text{constant}} / \kappa \mu_0$

(Griffiths, 1986)

1.12

d) In a starting plume driven by a constant flux , initially (while still attached)

$$\tfrac{4}{3}\pi a^3 = \quad t$$

$$a \quad t^{1/3} \qquad\qquad U \quad t^{-2/3}$$

Thus detachment must result, and lead to a rising head followed by a continuously flowing tail. After detachment from the source, the head and tail are insensitive to the details of the source geometry and flow prior to detachment, with a continuous inward spiral of material.

For large t $\quad V \quad z^{9/5} \quad \left(a \quad z^{3/5}\right) \quad U \quad z^{1/5}$

and hence knowledge of a gives z .

1.13

e) Assuming that a plume arises from the core mantle boundary, a ~ 1000 km (and possibly flattens to 2000 km). If it arises from the base of the upper mantle a ~ 300 km . Both probably exist.

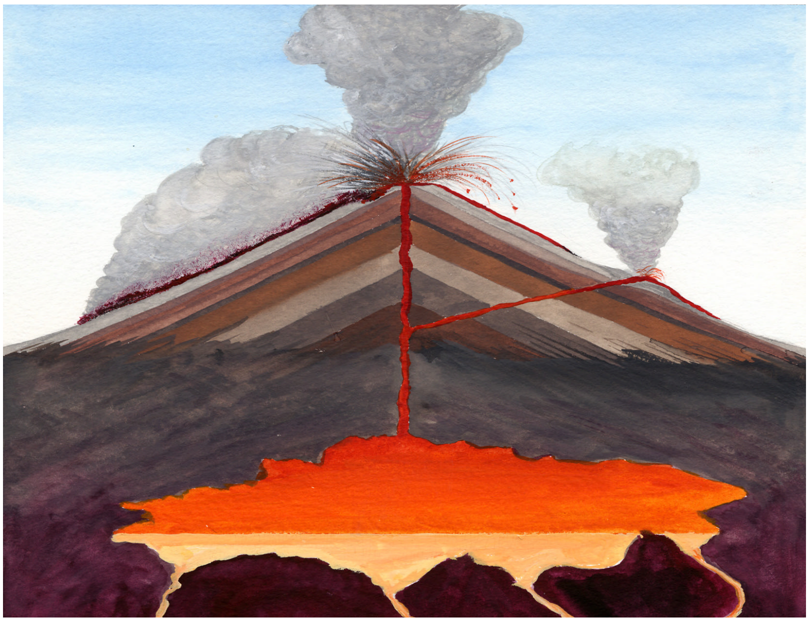
f) The broad scale convection takes 'solid' rock into regions where due to pressure release some of the material will melt. If the density of the melt is less than that of the surrounding matrix it can rise through the matrix by a process known as compaction. This is governed by Darcy's law for flow through a porous medium.

permeability

$$\mathbf{q} = \frac{k}{\mu} \quad p$$

viscosity

1.14



3. Physical properties of magma

1.15

These are known mainly from observations on lava flows and lava lakes, and from laboratory experiments with associated empirical relationships.

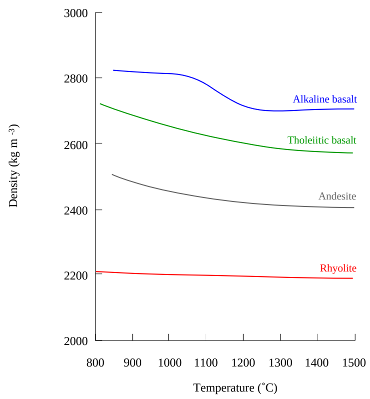
a) Compositional variations

	Rhyolite[1]	Andesite	Basalt[2]	Komatiite[3]
SiO_2	72.8	57.9	49.2	46.9
TiO_2	0.3	0.9	1.8	0.2
Al_2O_3	13.3	17.0	15.7	3.7
Fe_2O_3	1.5	3.3	3.8	---
FeO	1.1	4.0	7.1	10.2
MgO	0.4	3.3	6.7	33.0
CaO	1.1	6.8	9.5	5.3
Na_2O	3.5	3.5	2.9	0.5
K_2O	4.3	1.6	1.1	0.2

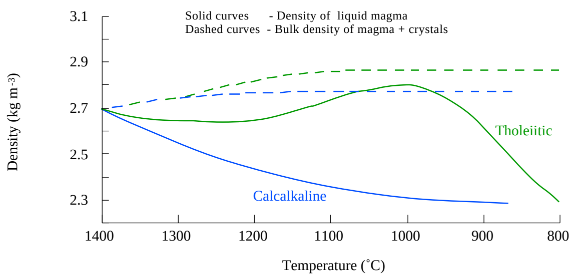
Average compositions of selected magmas, expressed as wt.% major element oxides.
[1]Average composition of continental crust. [2]Average composition of oceanic crust; makes up 90% of extrusive volcanic rocks. [3]Ancient magmas no longer erupted; high MgO content.

b) Density

1.16

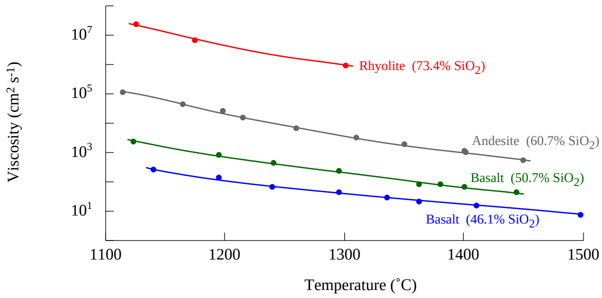


(Murase & McBirney 1973)



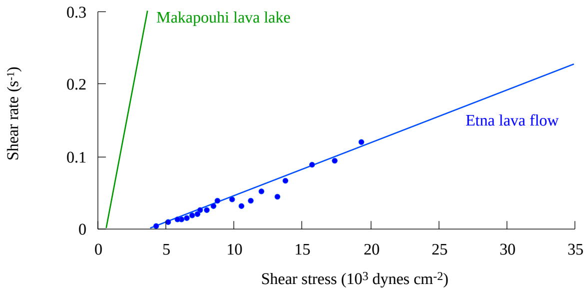
c) Viscosity

1.17



d) Rheology

(From Murase & McBirney 1973)



1.18

Main new physical concepts

(in order of appearance)

- compositional convection, due to compositional differences between melt and solid
- laminar entrainment by rising hot plumes
- separation of small amounts of melt from the interstitial crystal mush by compaction
- large (huge?) variation of physical (and chemical) properties between magmas
- density of melt originating from solid determines subsequent motion
- variety of solidification processes
- solidification/ melting of retaining boundaries due to thermal transfers
- slow flows of viscous fluids
- ingestion of floor by melting due to the heat transfer from a hot turbulent gravity current
- role of hot ash particles in driving volcanic plumes and blast flows

Lecture 1. Introduction to the Earth

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