

Possible mechanism of beginnings of the Lunar core and crust

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A conceptually new model of compaction is introduced. The key innovative factor in the model is the appraisal of the presence of a multi-phase fluid. We apply the model to a lunar iron core formation hypothesis to test the theoretical possibility of its genesis through iron sinking from magmatic lakes.

Key words: compaction, two-phase compaction, Lunar iron core formation

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We examine the formation mechanism of the Earth-group planets' iron core at the initial stage of its formation, assuming that at the initial stage (partly-melt condition) planets were intensely collided by huge meteorites and asteroids. "Lakes" of melt matter appeared on the surface of the planets after such collisions. Due to the process of differentiation that took place at those magmatic lakes, iron with addition of some other metals sunk to the bottom. At this stage of planet formation its temperature was rather high (~1450°C) and was near the solidus of peridotites. The melting point of iron is about 100° higher. Iron is warming the environment with the gravitation energy due to viscous friction while shrinking. That's why iron is going to the centre of the moon, being melt. By the way, lighter silicate fractions of peridotites are going up along the melted channels.

In the inner layers of the planet some physical parameters could change, so we are taking into consideration only the near-surface layer. We connect parameters with the Moon, but this model could be applied to other planets of the Earth group. At this region process of two-phase compaction takes place [Karakin, 2005]. One-dimensional approximation could be considered. On Earth such mechanism is still working in the mid-ocean ridges with the basalt layer formation of ocean crust.

Heavier iron (and its alloys) moves significantly faster than silicates. That's why duration of the iron core formation is short compared to cosmic scales (hundreds of millions of years).

Non-isothermal model of two-phase compaction is considered (two liquid phases are melts of iron and magmatic silicate and quasi-solid skeleton silicon phase). Phase transition between silicate phases is possible. Let's name r and f the density and porosity of porous viscous matter.

Values that belong to the whole matter would be left without indexes. Values with upper indexes (o) and (k), (where $k=s, f$) belongs to skeleton and liquid silicate and iron phases.

Let's write the Terzaghi relation and the force balance equation:

$$s_{ij} = s_{ij}^{ef} - pd_{ij}. \quad (1)$$

$$\frac{\nabla s_{ij}}{\nabla x_j} + r g_i = 0. \quad (2)$$

$$\sigma_{ij}^{ef} = \eta \left(\frac{\partial w_i}{\partial x_j} + \frac{\partial w_j}{\partial x_i} - \frac{2}{3} \frac{\partial w_k}{\partial x_k} \delta_{ij} \right) + \zeta \frac{\partial w_k}{\partial x_k} \delta_{ij}. \quad (3)$$

where s_{ij} , s_{ij}^{ef} – are full and effective stress tensors, p – porous pressure, \vec{w} – skeleton velocity, z and h – coefficients of volume and shear viscosity, \vec{g} – gravitation acceleration. Let's add the equations of continuity of mass for each phase and the Darcy's law for each liquid phase.

$$\frac{\partial}{\partial t} [(1-f)\rho^{(0)}] + \text{div} [(1-f)\rho^{(0)}\vec{w}] = -Q. \quad (4)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho^{(s)} f^{(s)}) + \operatorname{div}(\rho^{(s)} \vec{v}^{(s)}) + \operatorname{div}[\rho^{(s)} f^{(s)} \vec{w}] &= Q, \\ \frac{\partial}{\partial t}(\rho^{(f)} f^{(f)}) + \operatorname{div}(\rho^{(f)} \vec{v}^{(f)}) + \operatorname{div}[\rho^{(f)} f^{(f)} \vec{w}] &= 0. \end{aligned} \quad (5)$$

$$\operatorname{grad} p = - \frac{h^{(k)}}{k^{(k)}} \vec{v}^{(k)} + r^{(k)} \vec{g}, \quad k = s, f, \quad (6)$$

where $\vec{v}^{(k)}$ – partial filtration velocity, $h^{(k)}$ – coefficient of viscosity of fluid phases, $k_p^{(k)}$ – coefficient of absolute phase permeability of k -phase, Q – mass source density (transition between silicate phases). Due to process' logic, taken at micro-level of elementary volume all phase pressures are equal.

Values z , h are in general functions of porosity and invariants of tensors of stress and velocity of deformation. In linear rheology case, those values depend only from porosity. Let's separate filtration and hydrostatic components in porous pressure: $p = \tilde{p} + p^G$, $p = \tilde{p} + p^G$, $\operatorname{grad} p^G = \rho^{(0)} \vec{g}$. Thus the equation of filtration (6) would reduce to:

$$\operatorname{grad} p = - \frac{h^{(k)}}{k^{(k)}} \vec{v}^{(k)} + D r^{(k)} \vec{g}, \quad \text{where } k = s, f, \quad D r^{(k)} \in r^{(k)} - r^{(0)}. \quad (7)$$

Value $D r^{(k)}$ has sense of phase density difference. Equations (1) – (7) could be modified to a form of equations of motion with skeleton velocity

$$\operatorname{grad} \left[\left(\zeta + \frac{1}{3} \eta \right) \operatorname{div} \vec{w} \right] + \eta \nabla^2 \vec{w} = \operatorname{grad} p - \rho \vec{g}. \quad (8)$$

With (7) equation (8) could be modified to

$$\begin{aligned} \operatorname{grad} \left[\left(\zeta + \frac{1}{3} \eta \right) \operatorname{div} \vec{w} \right] + \eta \nabla^2 \vec{w} &= - \frac{\eta^{(f)}}{k^{(f)}} \vec{v}^{(f)} + (1 - f^{(f)}) \Delta \rho^{(f)} \vec{g} - f^{(s)} \Delta \rho^{(s)} \vec{g} \\ \operatorname{grad} \left[\left(\zeta + \frac{1}{3} \eta \right) \operatorname{div} \vec{w} \right] + \eta \nabla^2 \vec{w} &= - \frac{\eta^{(s)}}{k^{(s)}} \vec{v}^{(s)} + (1 - f^{(s)}) \Delta \rho^{(s)} \vec{g} - f^{(f)} \Delta \rho^{(f)} \vec{g}. \end{aligned} \quad (9)$$

Due to low porosity equation (9) could be reduced to

$$\begin{aligned} \operatorname{grad} \left[\left(\zeta + \frac{1}{3} \eta \right) \operatorname{div} \vec{w} \right] + \eta \nabla^2 \vec{w} &= - \frac{\eta^{(f)}}{k^{(f)}} \vec{v}^{(f)} + \Delta \rho^{(f)} \vec{g} \\ \operatorname{grad} \left[\left(\zeta + \frac{1}{3} \eta \right) \operatorname{div} \vec{w} \right] + \eta \nabla^2 \vec{w} &= - \frac{\eta^{(s)}}{k^{(s)}} \vec{v}^{(s)} + \Delta \rho^{(s)} \vec{g}. \end{aligned} \quad (10)$$

Let's modify equations of continuity (4), (5), assuming that phase density are constants,

$$\begin{aligned} \frac{\partial f^{(s)}}{\partial t} + \operatorname{div}(\vec{v}^{(s)} + f^{(s)} \vec{w}) &= \frac{Q}{\rho^{(s)}}, \\ \frac{\partial f^{(f)}}{\partial t} + \operatorname{div}(\vec{v}^{(f)} + f^{(f)} \vec{w}) &= 0, \\ - \frac{\partial f}{\partial t} + \operatorname{div}(1 - f) \vec{w} &= - \frac{Q}{\rho^{(0)}}. \end{aligned} \quad (11)$$

Particularity of compaction equations (10–11) is based on the presence of some kind of medium's own size, called compaction length:

$$H \in \sqrt{\frac{z^* k}{h}}.$$

If characteristic zone of motion scale significantly differs from compaction length, compaction equations degenerate and medium transforms to another state. Having two-phase fluid leads to two peculiar phases' compaction length

$$H^{(k)} \epsilon \sqrt{\frac{z^* k^{(k)}}{h^{(k)}}}. \quad (12)$$

In such case phase equation degeneration could happen. In other words, degeneration by one phase doesn't mean degeneration by another. Viscosity of iron and silicates differs by two orders. According to the introduction, the porous space structure and partial volumes of both liquid phases are nearly equal. This leads to the fact that the phase permeability is also nearly equal.

$$k^{(s)} = k^{(f)} \epsilon k.$$

That means compaction length of iron and silicate differs by one order (see (12)).

$$\frac{H^{(f)}}{H^{(s)}} = \sqrt{\frac{h^{(s)}}{h^{(f)}}} = 10. \quad (13)$$

Using (13) makes it clear that compaction length of liquid phases differs significantly. The main point of all facts is heavy iron phase down movement due to ascending force. Silicate upwards migration is only a concomitant process. Compaction length at silicate matters of asthenosphere is about 200-300 m (at depth c.a. 100km). Assuming this and using (13) compaction length of iron phase is c.a. 3km, with the help of Darcy's Law (6) phases filtration relation can be obtained.

$$\frac{h^{(f)} v^{(f)}}{Dr^{(f)}} = \frac{h^{(s)} v^{(s)}}{Dr^{(s)}}, \quad \frac{v^{(f)}}{v^{(s)}} \gg 10^3. \quad (14)$$

Knowing some other data we can obtain absolute phase velocities:

$$v^{(f)} \gg \frac{k^{(f)} Dr^{(f)} g_{\text{sun}}}{h^{(f)}} \gg 10 \text{m/year}, \quad v^{(s)} \gg 10 \text{cm/year} \quad v^{(k)} = \left| \frac{\mathbf{r}^{(k)}}{\mathbf{v}^{(k)}} \right|.$$

Iron phase moves 1000 times faster than silicate (14), assuming this the compaction equation could be reduced to one-phase compaction with only iron fluid phase (silicate fluid phase could be included into skeleton phase). After filtration downwards or incrusting of iron, compaction of silicate fluid could be taken into account. Thus, compaction with two-phase fluid splits into two independent compaction processes with one fluid phase [McKenzie D. 1984, Karakin A.V. 1999]. Firstly, iron phase moves downwards significantly more fast and intensively, than silicate fluid phase filtrates upwards.

Results obtained higher could be discussed in frame of the core formation hypothesis by sinking of iron from magmatic lakes to the planet center. Lateral dimension is rather big (1mm). This means that iron could move through these channels though it doesn't wet silicate matters. At the front of motion iron is enshrouded by melt silicate and partial pores pressures are equal. At this stage silicate phase could be viewed as static. As soon as iron has migrated, silicate phase begins to move upwards. Both phases movement occurs independently within different channels with different velocities and partial porous pressures.

Gravity decreases linearly with depth till zero at the center. So, at rather low depths compaction mechanism as the main factor of iron sedimentation strictly weakens and another one takes place. Numerical calculations for each model with one-phase fluid were provided. They showed that wave packages have a tendency to collapse and create clear melt lenses while moving. Cameras of iron melt after getting critical size can break down (due to Rayleigh-Taylor instability) and create iron core. Later accompanied fact upwards migration of silicate melt takes place. It can be described as one-phase fluid compaction. This occurs much more slowly but with similar patterns. Particularly, wave packages could collapse and create volcano eruptions. Lunar volcanoes could have such origin.

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