A magma ocean origin of Earth's degree-2 mantle convection

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The Earth's residual geoid [1,2] and free-air gravity [3] reveal a degree-2 mantle convection pattern with antipodal columnar upwelling above the two large low S-wave velocity provinces (LLSVPs) and sheet-like downwelling in a longitudinal belt (about 105 ºE, 75 ºW) through the Arctic, east Asia, Australia, Antarctica and the Americas. Fluid dynamic modelling of magma ocean (MO) flow in rotating planets with variable gravitational acceleration (***g***) yields downwelling along the polar axis with maximum ***g*** and upwelling in the equatorial plane with minimum ***g*** [4,5].

The higher compressibility of MO liquid compared to liquidus bridgmanite (bm), and the strong partitioning of Fe to the MO liquid and Mg to bm, resulted in bm-melt density cross-over and initial accumulation of $MgSiO_3$-dominated bm in the 1600-2000 km depth range in the Earth [e.g. 6]. The MO convection pattern probably caused a discontinuous spherical shell of bm, breached by columnar downwelling along the polar axis and planar equatorial upwelling. Whereas the MO above the neutral buoyancy level might have solidified in 5-50 My [7,8], a well-insulated basal MO (BMO) was likely long-lived, possibly extending into the Proterozoic or Phanerozoic [6].

Spherical shell convection modelling with a solid, high-viscosity mantle, and with combined internal and bottom heating, tends to yield sheet-like downwelling and columnar upwelling [e.g. 9]. The large viscosity increase associated with the the solidification of the major part of the MO (e.g. the upper 2000 km or 81 vol% of the original MO), might therefore change the convective pattern into the current geometry with two antipodal upwelling columns close to the equatorial plane and a sheet-like longitudinal downwelling, as observed today.

A discontinuous and neutrally buoyant mid-lower mantle shell of early crystallised and Fe-poor bm with high viscosity can be convectively aggregated and repositioned into bm-enriched ancient mantle structures (BEAMS) [10-12], located around the periphery of the ascending LLSVP-rooted mantle columns. Deep partial melting in plumes originating at the top of the BMO might add further Fe-poor bridgmanitic residues to the BEAMS.

Chemical diffusion of SiO_2 from the core to the early MO and later BMO, in exchange for FeO and Fe_2O_3 in the opposite direction [6,13], would also increase the bulk mantle Si/(Mg+Fe), Mg/Fe and bridgmanite/ferropericlase ratios, prolonging the crystallisation of Fe-poor bm, and thereby increasing the proportion of refractory material. The high-viscosity BEAMS will, in combination with the Earth's rotation, stabilise and sustain the degree-2 mantle convective structure. Dense layers of Fe-rich BMO-cumulates might be swept passively into the root-zones of the ascending LLSVP-flow at a late stage when most of the BMO had solidified.

References: [1] Hager et al. 1985, Nat; [2] Steinberger & Torsvik 2010, GGG; [3] Ishii & Tromp 1999, Sci; [4,5] Maas & Hansen 2015, JGR & 2019, EPSL; [6] Trønnes et al. 2019, Tectonoph; [7] Elkins-Tanton 2008, EPSL; [8] Kruijer et al. 2020, EPSL; [9] Bercovici et al. 1989, Sci; [10] Manga 1996, GRL; [11] Ballmer et al. 2017, Nat Geosci; [12] Gülcher et al. 2020, EPSL.

Outline

Main story

Auxiliary pages

Mantle domains and structure

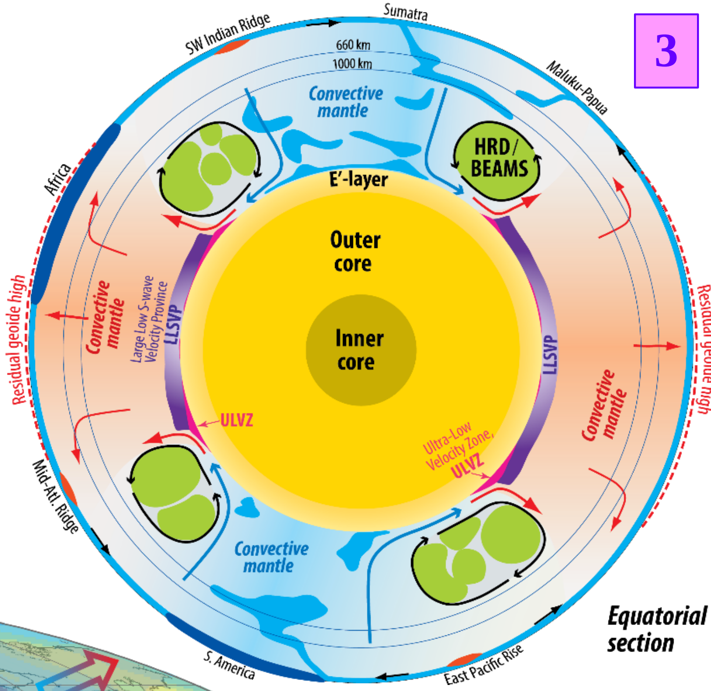
- **Convecting mantle** (~74 vol%)
- **SCLM** (sub-continental lithospheric mantle, ~2.6 vol%)
- **BEAMS**/**ERDs** (bridgmanite-enriched ancient mantle structures / early refractory domains, ~22 vol%)
- **LLSVPs** (large low S-wave velocity provinces, ~1.1 vol%)
- **ULVZs** (ultra-low velocity zones, < 0.1 vol%)

Strong petrological and tenuous seismic evidence for **ERDs**, organised in **BEAMS** (Ballmer et al. [11])

Degree-2 convection

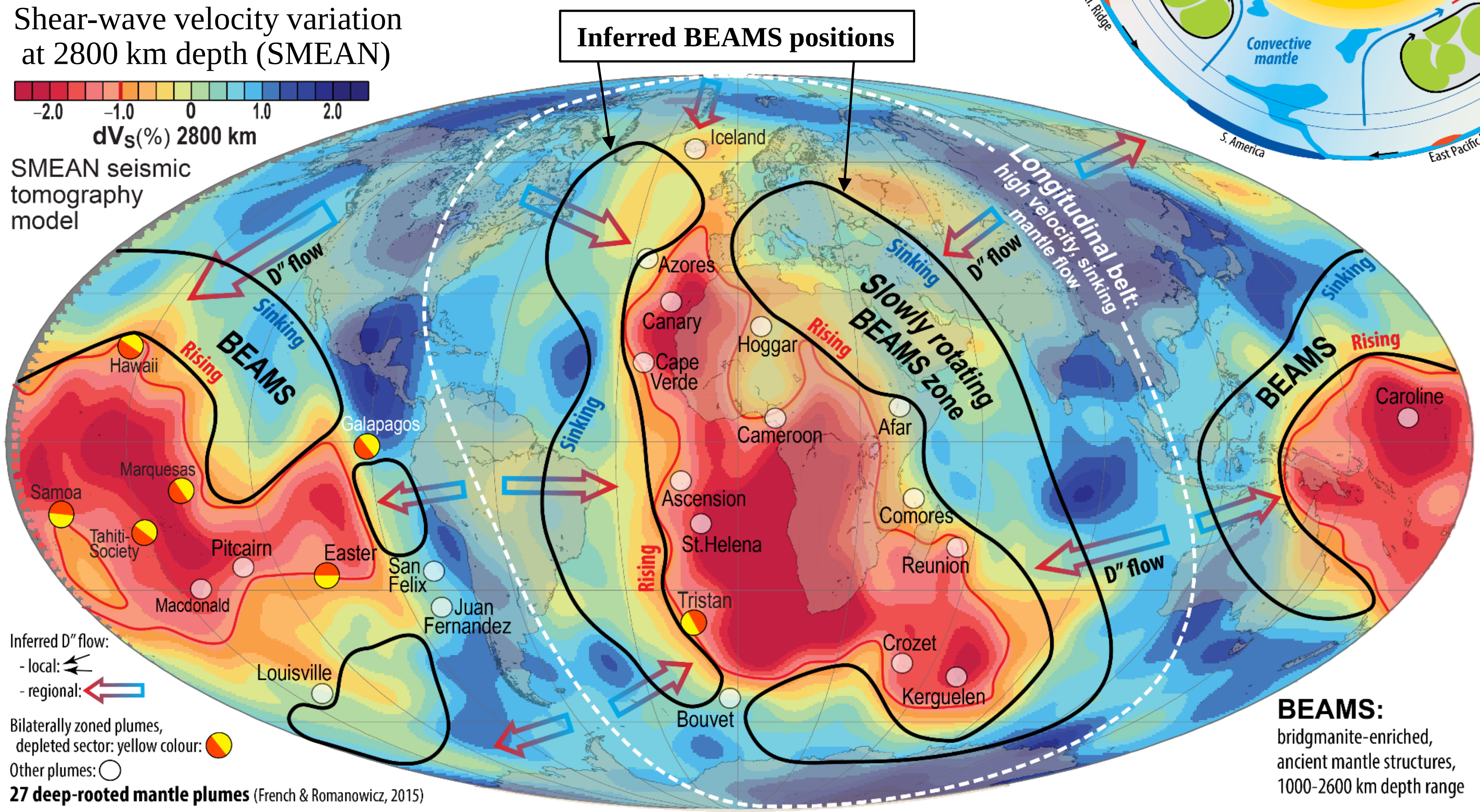
Indicated by the residual geoid [1,2] and free-air gravity [3].

- Rising columnar flow above the two antipodal LLSVPs
- Sinking sheet-like flow in a longitudinal belt through the Arctic, east Asia, Australia, Antarctica and the Americas



Equatorial section

Shear-wave velocity variation at 2800 km depth (SMEAN)



Inferred D″ flow:
- local: ←
- regional: ⇐

Bilaterally zoned plumes, depleted sector: yellow colour: ◐

Other plumes: ○

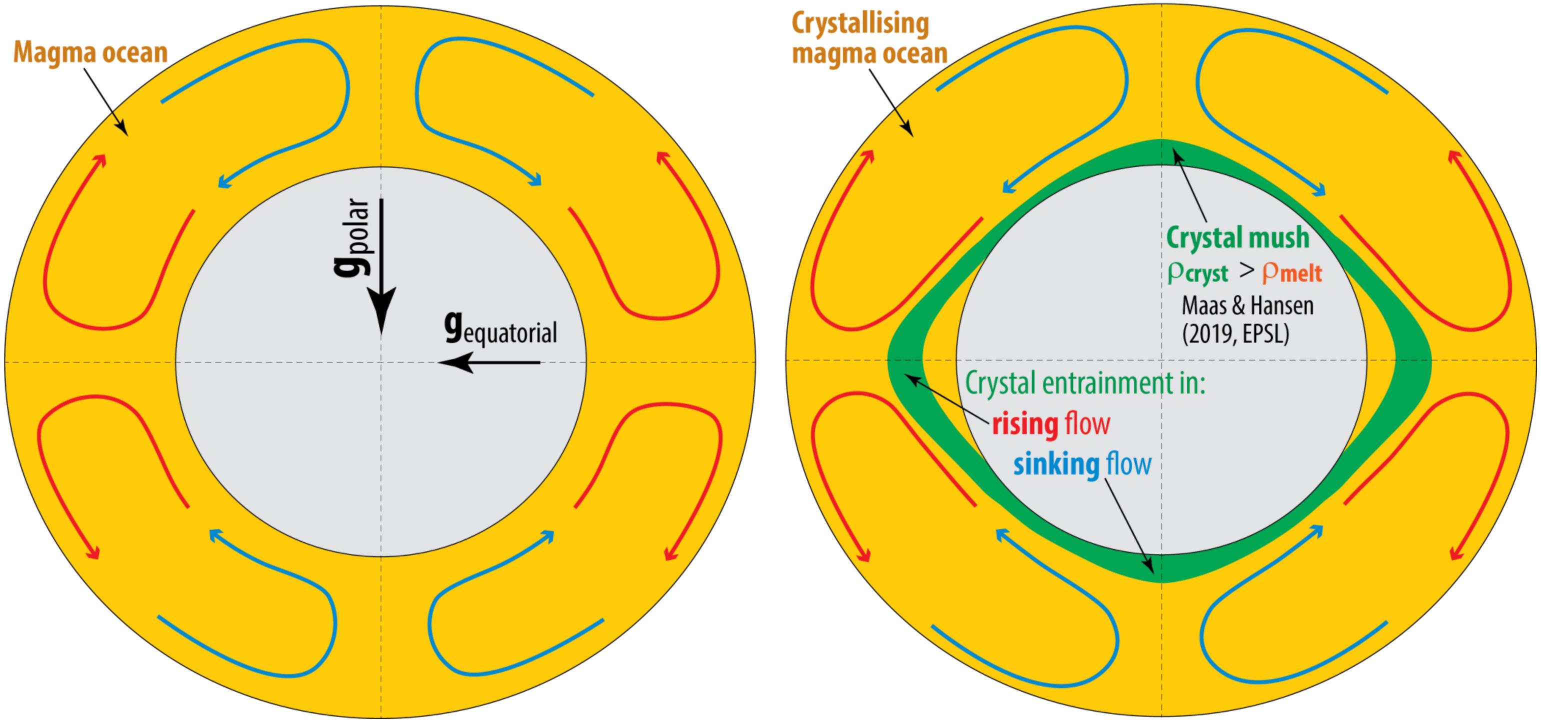
27 deep-rooted mantle plumes (French & Romanowicz, 2015)

BEAMS:
bridgmanite-enriched,
ancient mantle structures,
1000-2600 km depth range

Convection modelling of MO crystal settling in rapidly rotating planets with **differential gravitational fields**

Maas & Hansen,
2015, JGR,
2019, EPSL

Terrestrial planet without bm-melt neutral buoyancy ($m_{planet} < m_{Venus}$)



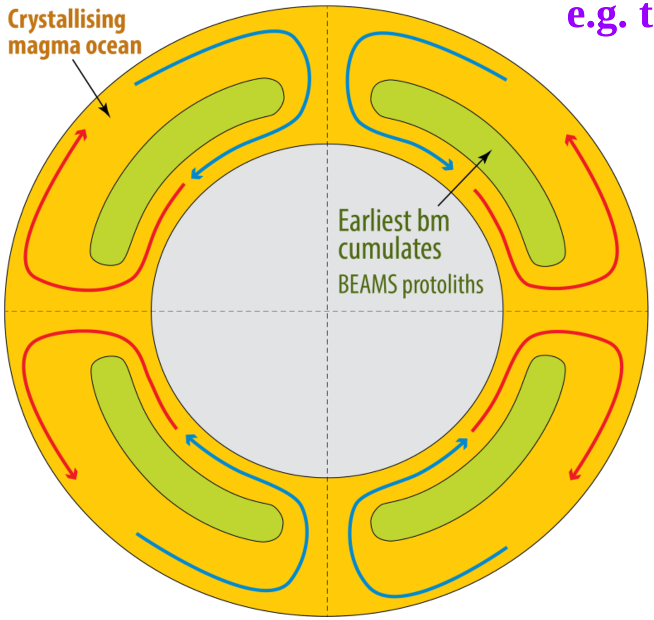
Terrestrial planet with bm-melt neutral buoyancy ($m_{planet} > m_{Venus}$)

e.g. the Earth

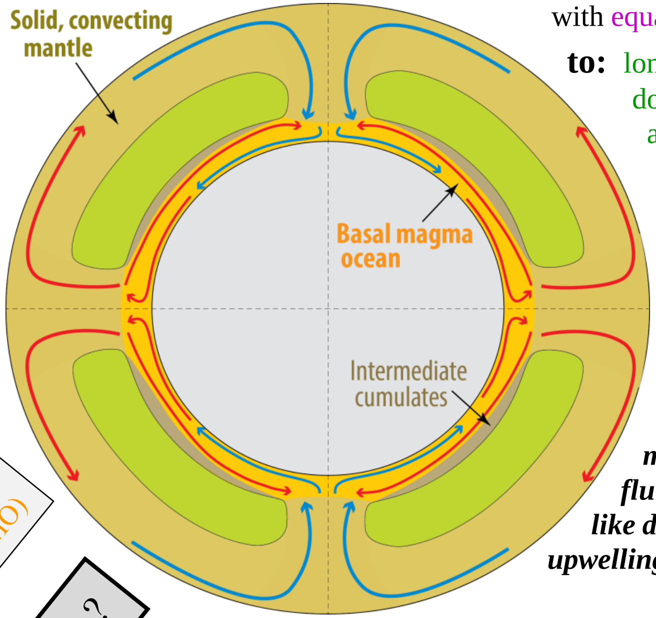
Change from mostly liquid to mostly solid mantle:

May cause change from: columnar polar downflow with equator-plane upwelling

to: longitudinal sheet-like downflow with columnar antipodal upwelling in the equatorial plane.



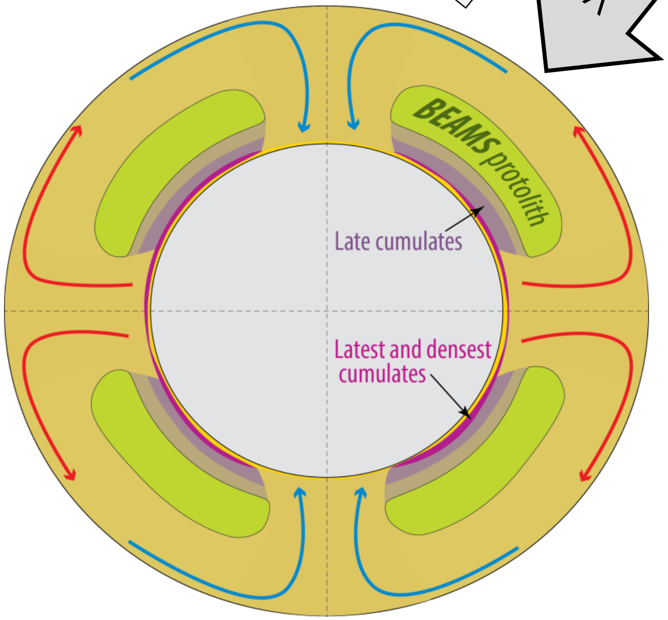
5-50 Ma ?

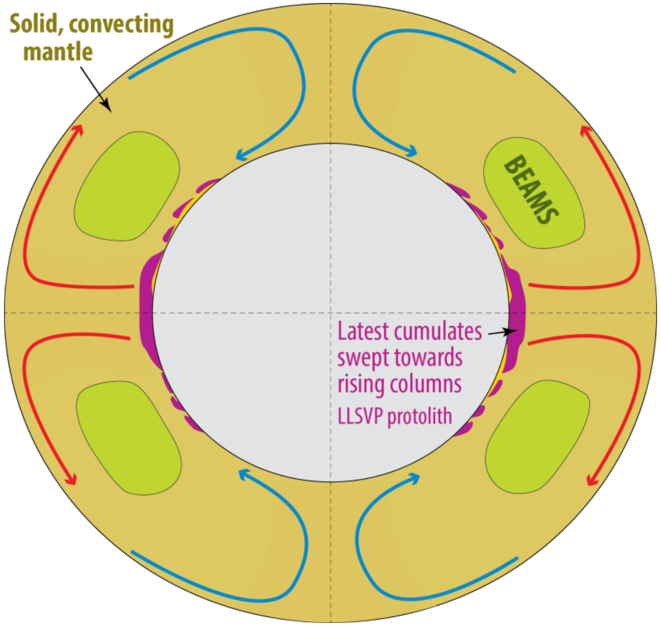


Spherical shell ***convection models with high-viscosity fluids*** *commonly yield* ***sheet-like downwelling*** *and* ***columnar upwelling*** *(Bercovici et al.1989, Sci.)*

Long-lived basal magma ocean (BMO)

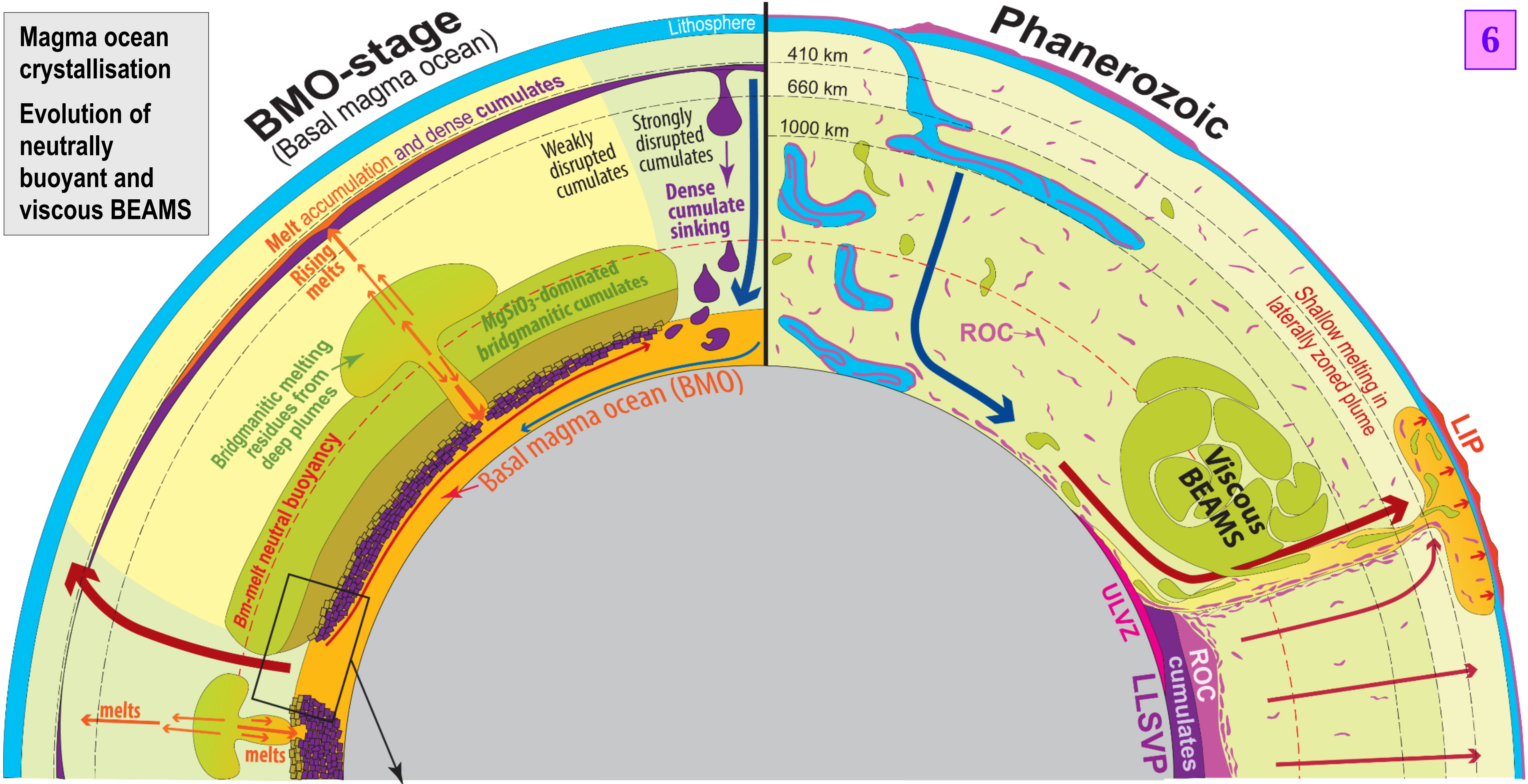
> 2 Gy ?

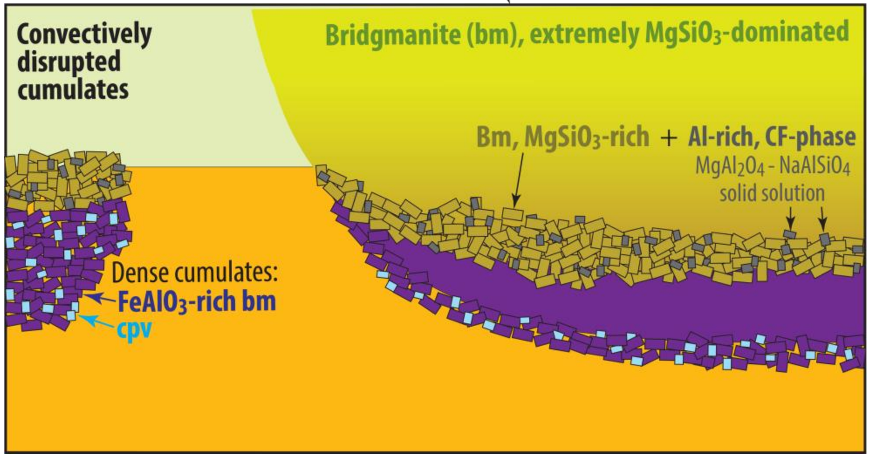




Magma ocean crystallisation

Evolution of neutrally buoyant and viscous BEAMS



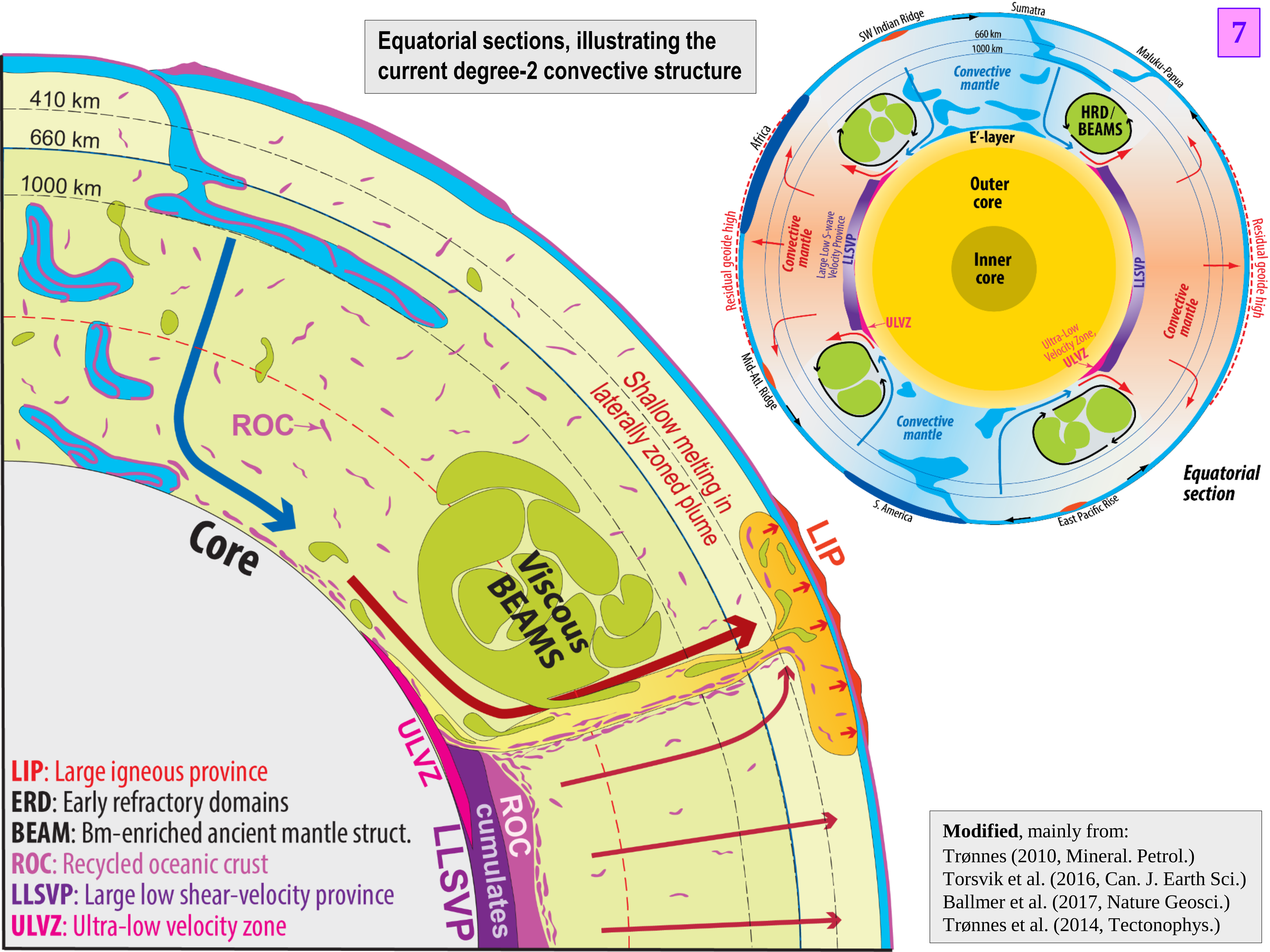


Solidification of the BMO and generation of:

1. early, refractory cumulates
2. late-stage, dense and enriched cumulates (with Ca-perovskite)

Modified, mainly from:
Torsvik et al. (2016, Can. J. Earth Sci.)
Ballmer et al. (2017, Nature Geosci.)
Trønnes et al. (2014, Tectonophys.)

Equatorial sections, illustrating the current degree-2 convective structure



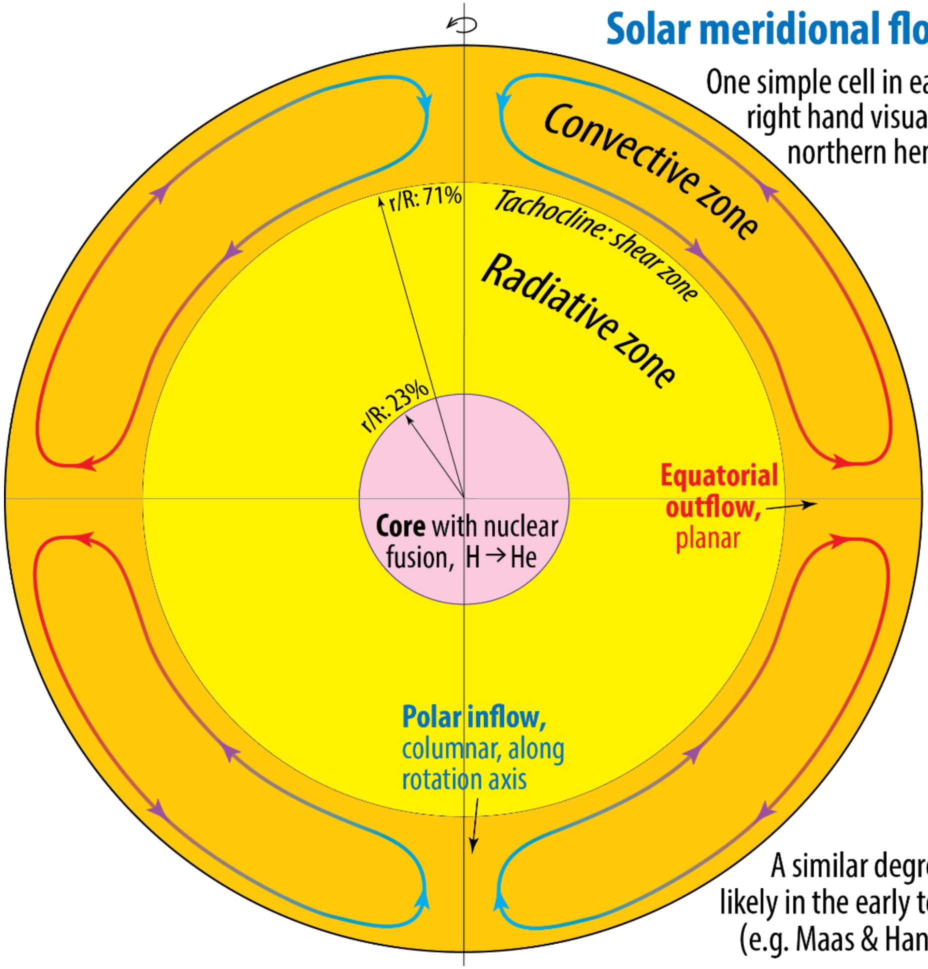
LIP: Large igneous province
ERD: Early refractory domains
BEAM: Bm-enriched ancient mantle struct.
ROC: Recycled oceanic crust
LLSVP: Large low shear-velocity province
ULVZ: Ultra-low velocity zone

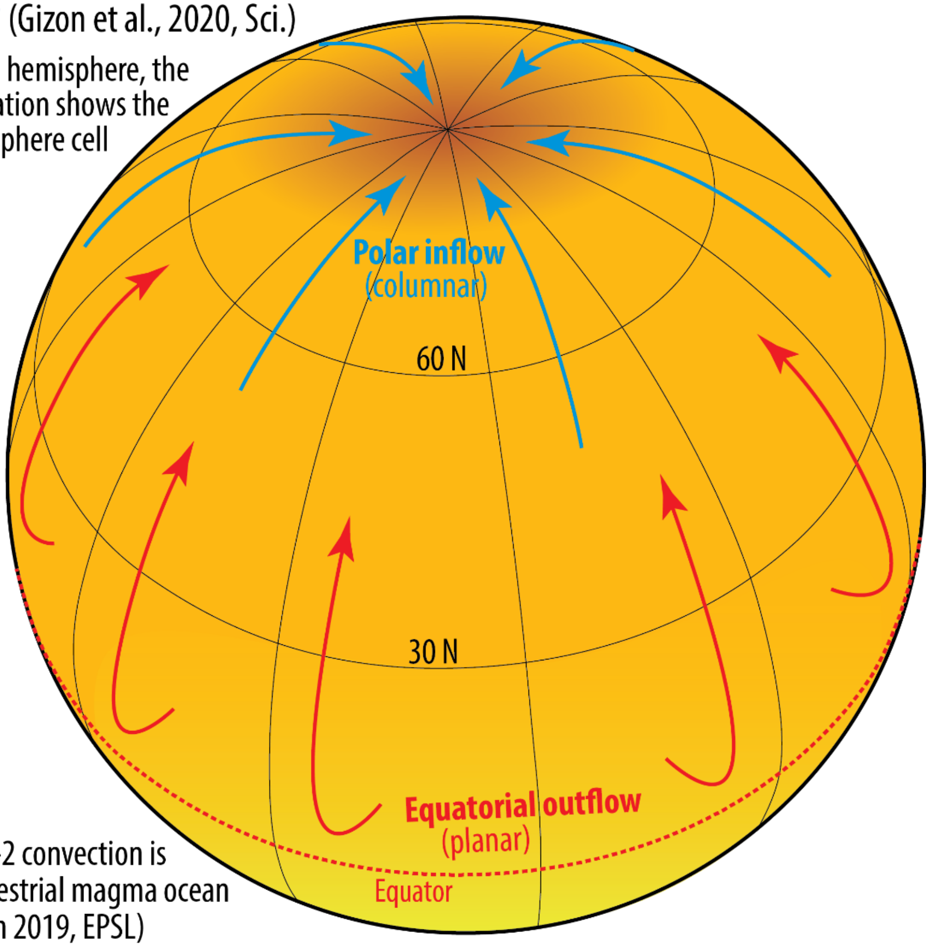
Modified, mainly from:
Trønnes (2010, Mineral. Petrol.)
Torsvik et al. (2016, Can. J. Earth Sci.)
Ballmer et al. (2017, Nature Geosci.)
Trønnes et al. (2014, Tectonophys.)

A solar analogue example: The simple meridional flow in the convective zone is similar to the inferred degree-2 convection in the early terrestrial MO

Solar meridional flow (Gizon et al., 2020, Sci.)

One simple cell in each hemisphere, the right hand visualisation shows the northern hemisphere cell





A similar degree-2 convection is likely in the early terrestrial magma ocean (e.g. Maas & Hansen 2019, EPSL)

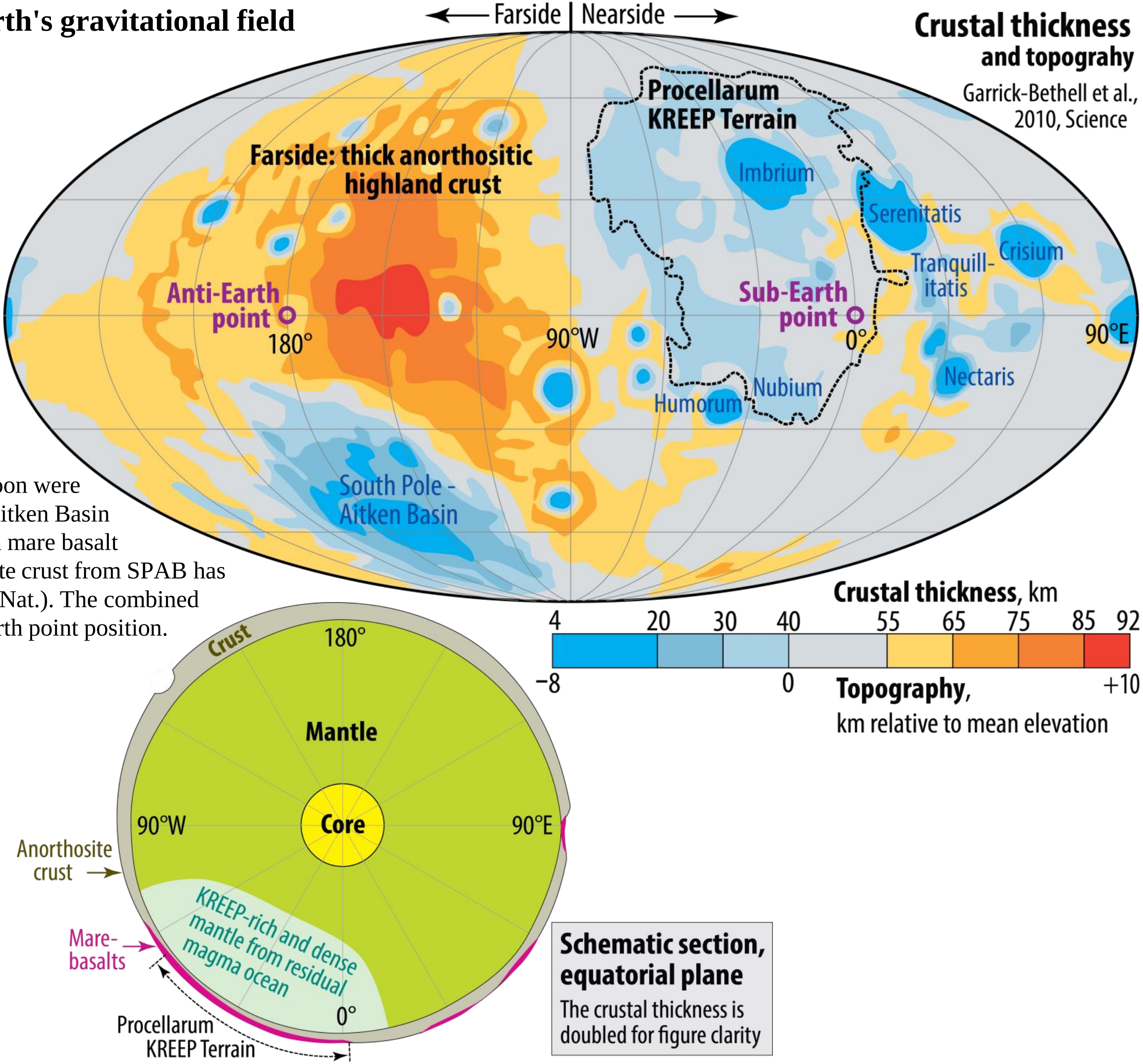
A lunar analogue example: MO crystal accumulation influenced by an asymmetric gravitational field

Thickness variation of the lunar primary crust resulting from
MO crystal accumulation in Earth's gravitational field

Wasson & Warren, 1980, Icarus
Looper & Werner, 2002, JGR
Werner & Looper, 2002, JGR
Garrick-Bethell et al., 2010, Sci.
Ohtake et a., 2012, Nat.Geosci.
Garrick-Bethell et al., 2014, Nat.
Quillen et al., 2019, Icarus
Elardo et al., 2020, Nat. Geosci

Moon orientation adjustment

The mass balance and orientation of the Moon were modified by the oldest and largest S.Pole-Aitken Basin (SPAB) and the nearside impact craters and mare basalt magmatism. The removal of light anorthosite crust from SPAB has exposed parts of the mantle (Li et al. 2019, Nat.). The combined changes are reflected by the current sub-Earth point position.



Crustal thickness and topograhy
Garrick-Bethell et al., 2010, Science

Crustal thickness, km
Topography, km relative to mean elevation

Schematic section, equatorial plane
The crustal thickness is doubled for figure clarity

Metal-silicate exchange equilibrium, leading to core - MO/BMO chemical exhange during cooling

Venus and Earth

Segregated cores at very high T, allowing
high Si^{core} **and** high FeO^{MO} (high f_{O_2})

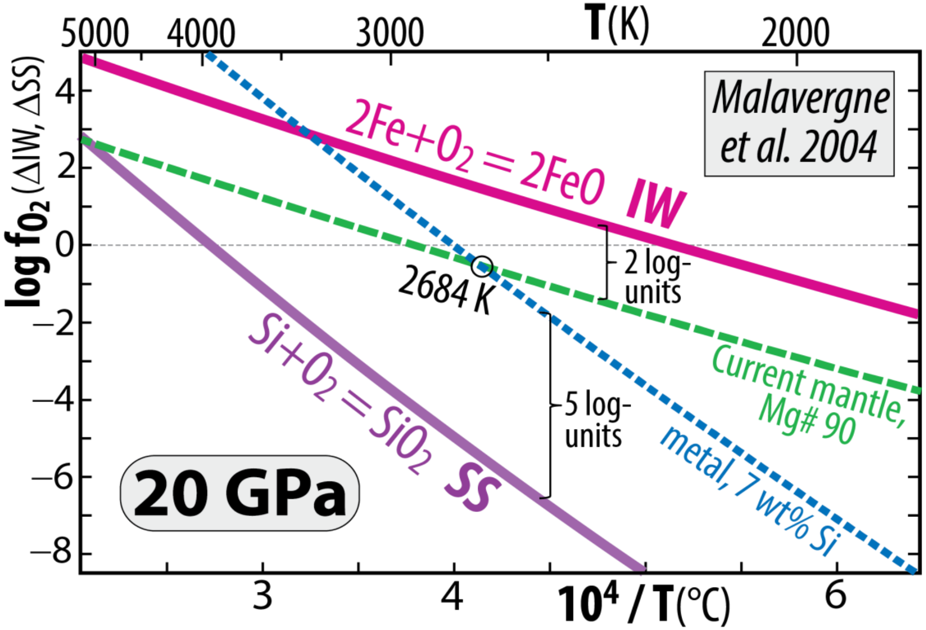
Because the chemical equilibrium:

$$2\,Fe^{met} + SiO_2^{sil} = Si^{met} + 2\,FeO^{sil}$$

is displaced towards the product side (right) with increasing T **and reversed with decreasing T**

$2\,Fe + O_2 = 2\,FeO$ (IW)
minus: $Si + O_2 = SiO_2$ (SS)

gives: $2\,Fe - Si = 2\,FeO - SiO_2$
or: $\mathbf{2\,Fe + SiO_2 = Si + 2\,FeO}$



Cooling of core and magma ocean (MO)

⇨ core-MO **chemical exchange**

- FeO and $FeO_{1.5}$ to the core
- SiO_2 to the MO (and BMO)

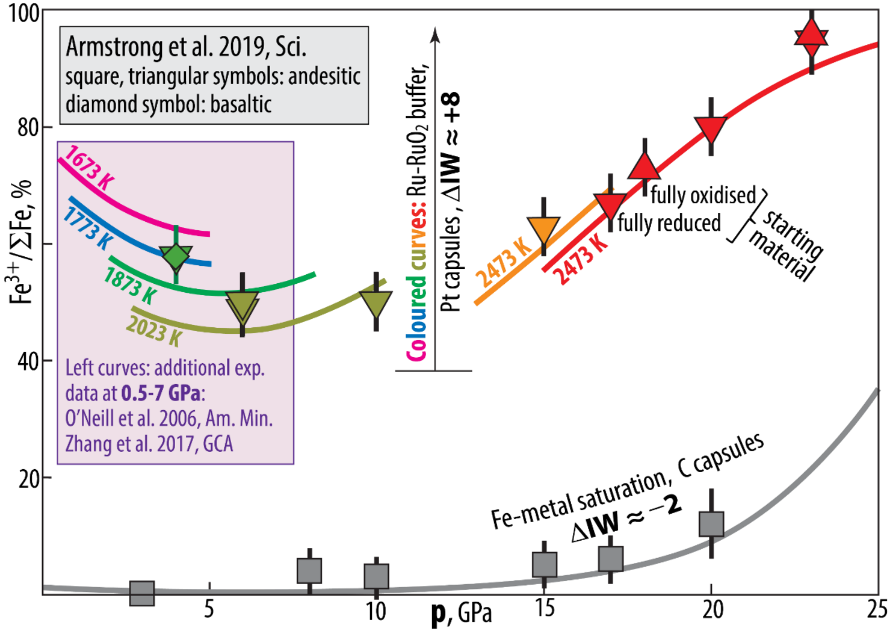
Additional pressure-effect – above 25 GPa

Armstrong and Frost (2019, Nature)

Disproportionation of FeO^{MO} at p > 25 GPa promotes high f_{O_2} in the MO, combined with core segregation:

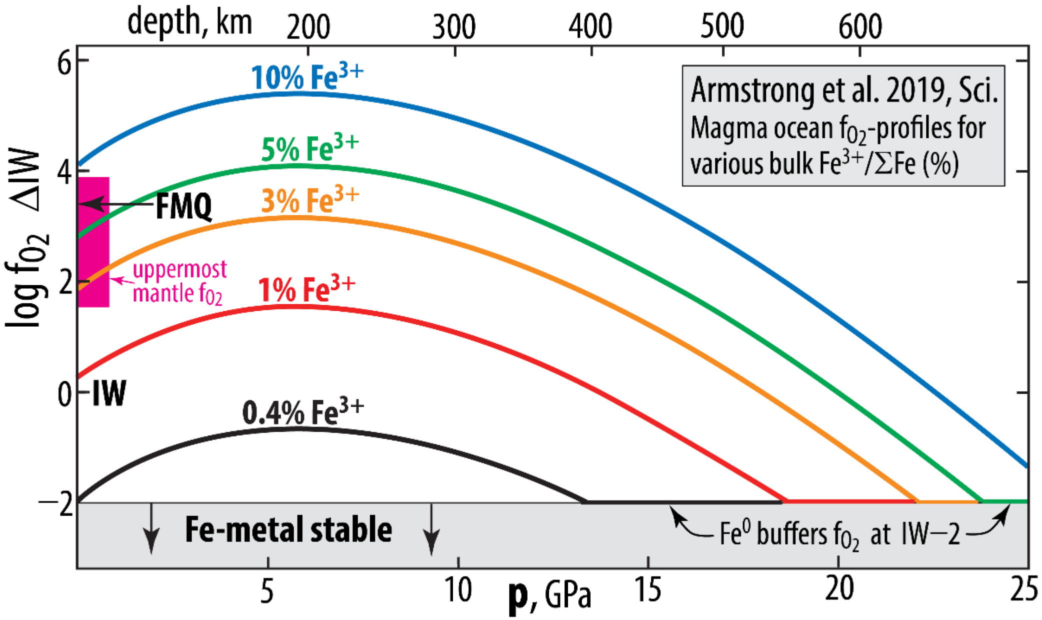
$$\underbrace{3\,FeO = 2\,FeO_{1.5}}_{\text{components in the MO}} + \underbrace{Fe}_{\text{liquid metal segregating and sinking to the core}}$$

Pressure-induced self-oxidation of a magma ocean, accompanied by Fe-metal segregation



f_{O_2}-buffered experiments, andesitic melts

Armstrong et al. (2019, Sci.)



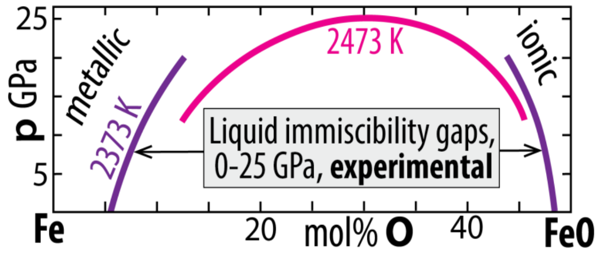
Magma ocean oxygen fugacity profiles for different bulk $Fe^{3+}/\Sigma Fe$ percentages

Armstrong et al. (2019, Sci.)

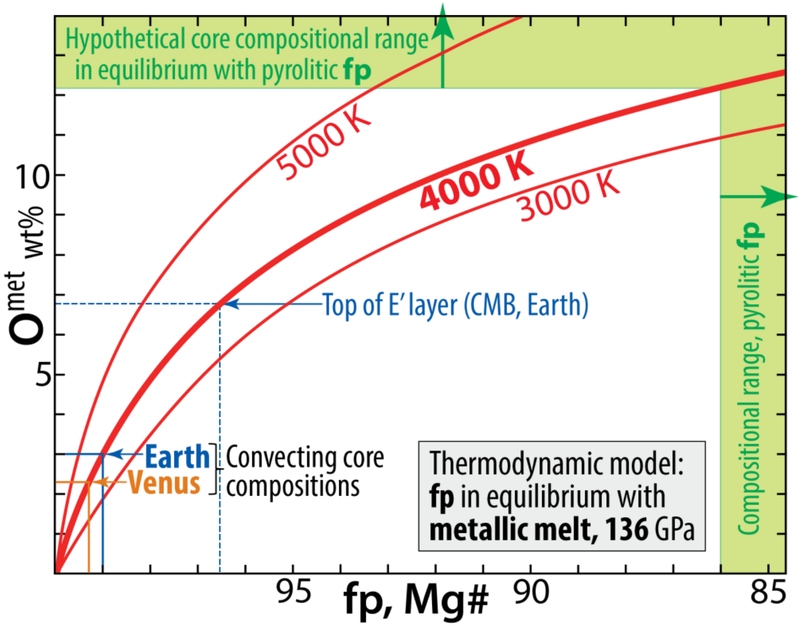
O and Si in Fe-alloys Cooling ⇨ core-BMO chemical exchange

System: Fe-Mg-O
metal-ferropericlase equilibrium

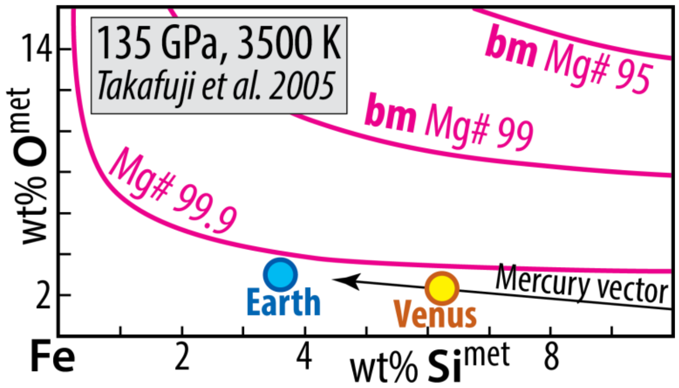
Solvus closure with increasing **p and T**



Based on Frost et al. (2010)

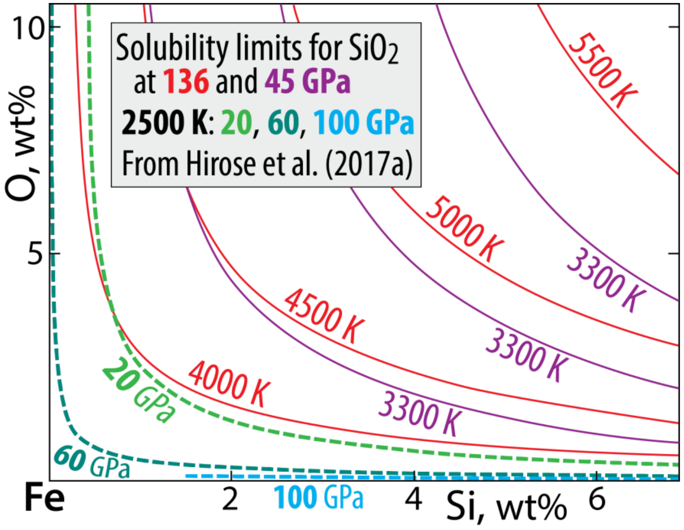


System: Fe-Mg-Si-O
metal-bridgmanite equilibrium



Ferropericlase-metal and bridgmanite-metal equilibria, demonstrate ***extremely strong*** **FeO-partitioning** from oxide and silicate to O-undersaturated core metal

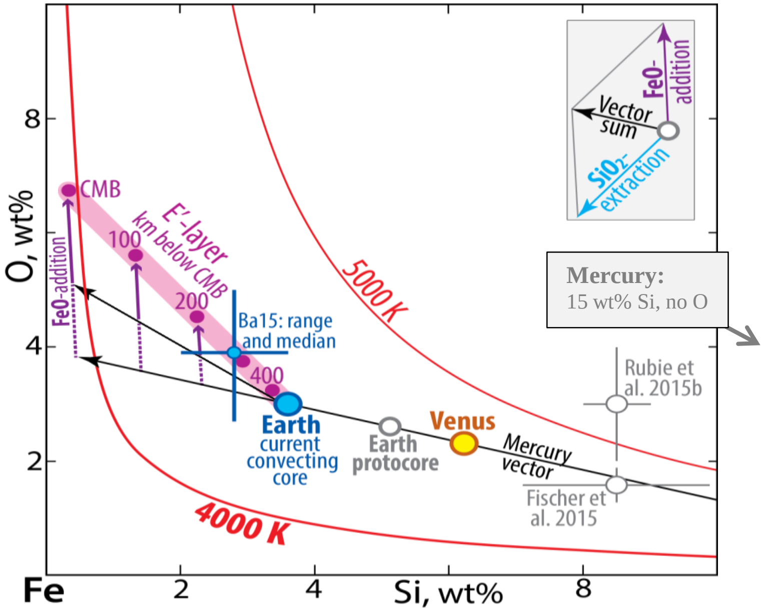
System: Fe-Si-O
Solubility of O and Si in Fe-alloy



- O and Si: mutually exclusive
- Solubility increases with **T** and decreases with **p**
- Related to the silica liquidus surface in systam Fi-Si-O

Estimated core compositions

Trønnes et al. 2019,
Tectonophys., Table 3



The **E'-layer compositional gradient** (figure above), used as input into Stage-2 of the mass balance model below, is **precisely constrained** by the KHOMC seismic model (Kaneshima 2018, PEPI) combined with mineral physics data (Badro et al. 2014, PNAS; Brodholt & Badro 2017, GRL). See pages 13-14.

Mass balance modelling (Trønnes et al. 2019, Tectonophys., Table 3)

Step 1: protoC + earlyMO = convC + pyrolitic MO (C: core, total volumes)

Step 2: upper convC + BMO = **E'-layer** + mod.lmM (modified lowermost Mantle)
34 vol% 28 vol%
31 wt% of core 34 wt% of mantle

	Composition, wt% (normalised to 100% sums)										mol% minerals			mol-ratio
	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	NiO	MnO	FeO	MgO	CaO	Na_2O	bm	fp	cpv	bm/fp
earlyMO, adjust.	42.0	0.20	4.29	0.36	0.24	0.13	12.4	36.6	3.39	0.35	74.2	19.6	6.2	3.8
pyroliteMO, calc.	44.9	0.21	4.43	0.37	0.25	0.13	8.05	37.8	3.50	0.36	78.4	15.3	6.3	5.1
mod.lmM, calc.	48.7	0.21	4.68	0.40	0.26	0.15	1.80	39.7	3.73	0.38	83.3	10.0	6.6	8.3

Outermost **stagnant** E'-layer?

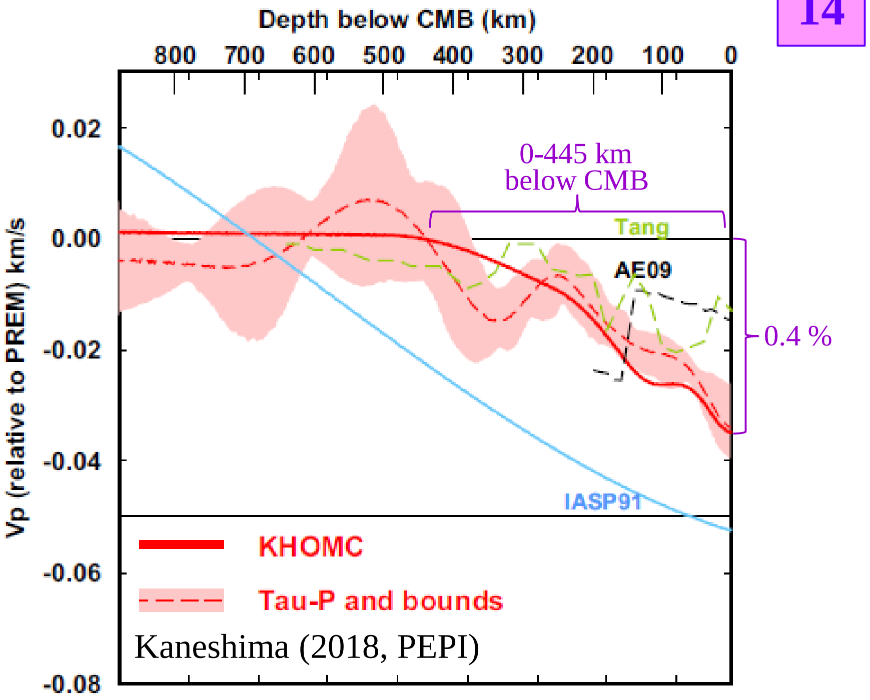
gradationally stratified, low $\mathbf{V_\Phi}$ - low ρ

Caused by **core-BMO interaction?**

Feasible because:

- high thermal conductivity supresses convection
- low viscosity reduces viscous entrainment
- an E'-layer may stabilise the geodynamo

(Hernlund & McNamara, 2015, Treat. Geophys.)



Kaneshima (2018, PEPI)

Seismology
Lay & Young, 1990
Garnero et al., 1993
Helffrich & Kaneshima, 2010
Kaneshima & Helffrich, 2013
Kaneshima & Matsuzawa, 2015
Kaneshima, 2018
Irving et al., 2018: Adiabatic outermost core

Models
Buffet, 2010
Buffet & Seagle, 2010
Gubbins & Davies, 2013
Hernlund & McNamara, 2015
Brodholt & Badro, 2017

Outermost **stagnant** E'-layer?

gradationally stratified, low $\mathbf{V_\Phi}$ - low ρ

Caused by **core-BMO interaction?**

E'-layer chemical characteristics, material properties poses a long-standing **conundrum,** apparently solved by Brodholt & Badro (2017, GRL):

Each of the light element candidates (Si, O, S, C) reduces ρ and **increases** $\mathbf{V_\Phi}$ (or V_P)

BUT:

O reduces ρ **more** and increases $\mathbf{V_\Phi}$ **less** than Si.

Therefore:

E'-layer with **elevated O** and **reduced Si** relative to the convecting core **solves the conundrum**

The E'-layer of the mass balance model (page12, upper right figure and stage-2 model input) is **precisely constrained** by the KHOMC seismic model (Kaneshima 2018, PEPI) and the mineral physics data (Badro et al. 2014, PNAS; Brodholt & Badro 2017, GRL)