The continental lithosphere

And what we currently know about it

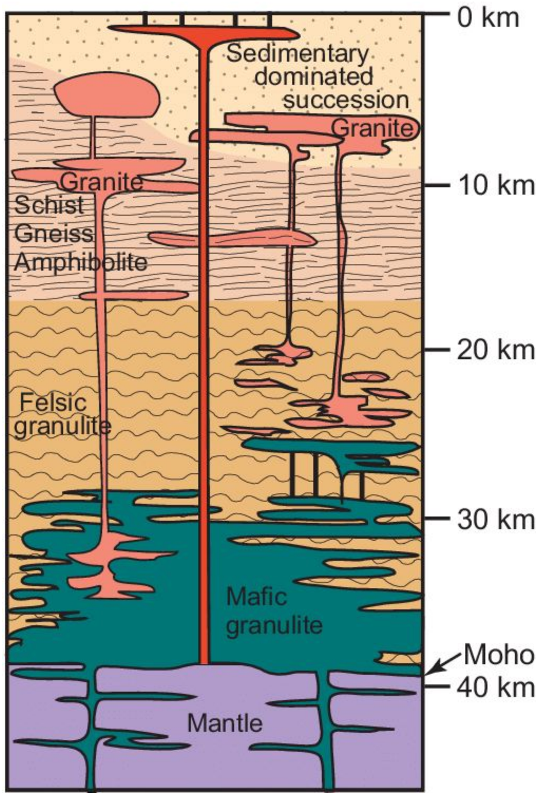
What is the lithosphere, in general? (Repetition?)

Lithosphere = Crust + Lithospheric Mantle

“The rigid outer part of the Earth, consisting of the crust and upper mantle.”

= The part of the Earth, which behaves only as a solid on a geological time scale.

Broad range of thicknesses, from <100km to >300km



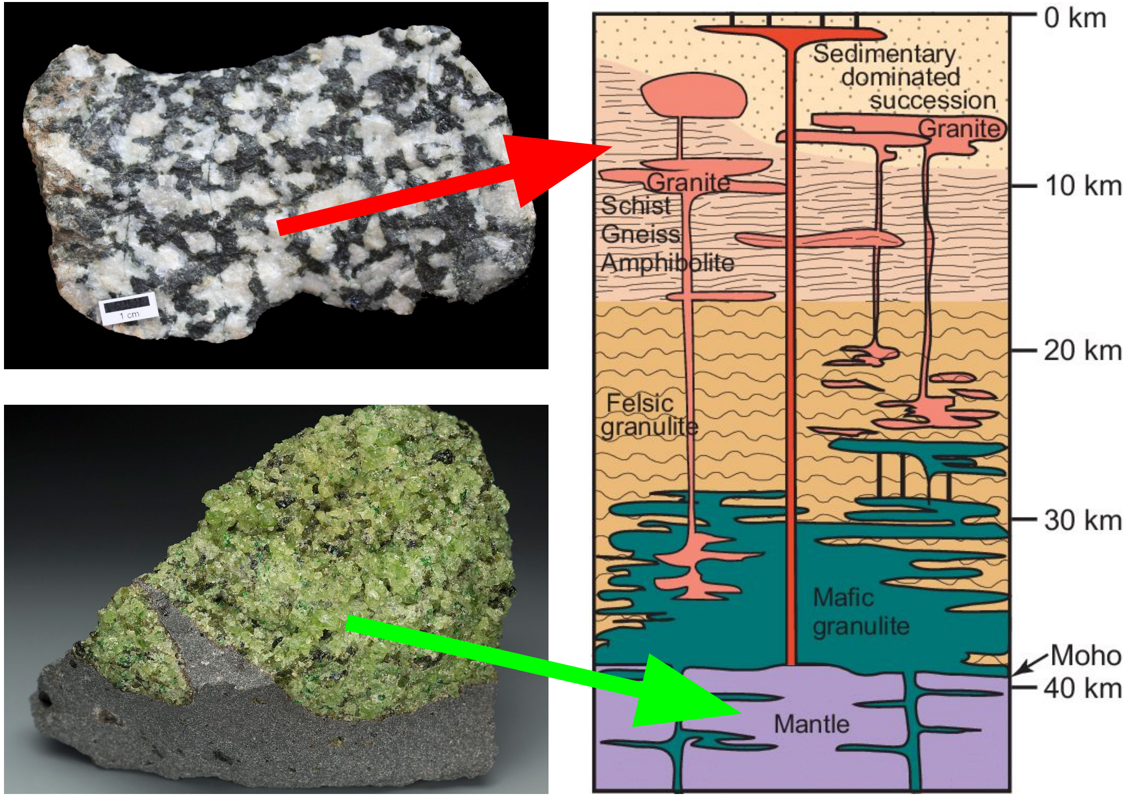
Cawood et al. 2013

Schematic cross-section through the continental lithosphere

Wait, aren't these things very different?

Yes, chemically.

In the most important geo-dynamic system governing our planet's surface (Plate Tectonics), they behave as one "layer" that "floats" on the Asthenosphere and interacts with other elements of Earth's Plate Tectonic system



The Continental Crust

The most accessible, well-studied part of the geosphere!

Naturally, due to the presence of its topmost parts on the surface, we are able to study the crust with all of the analytical methods currently available to geoscientists.

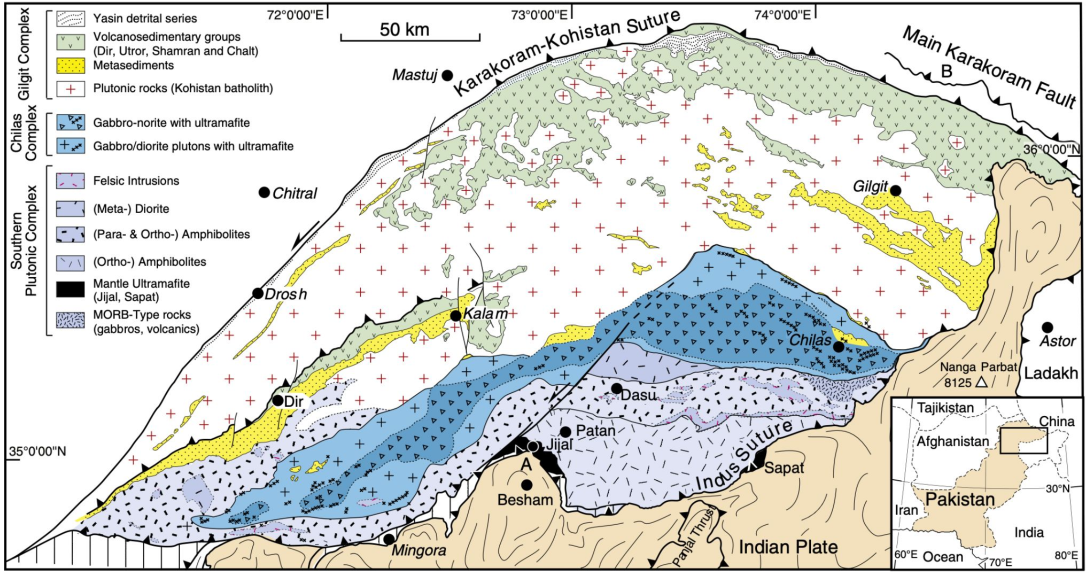
QUESTION:

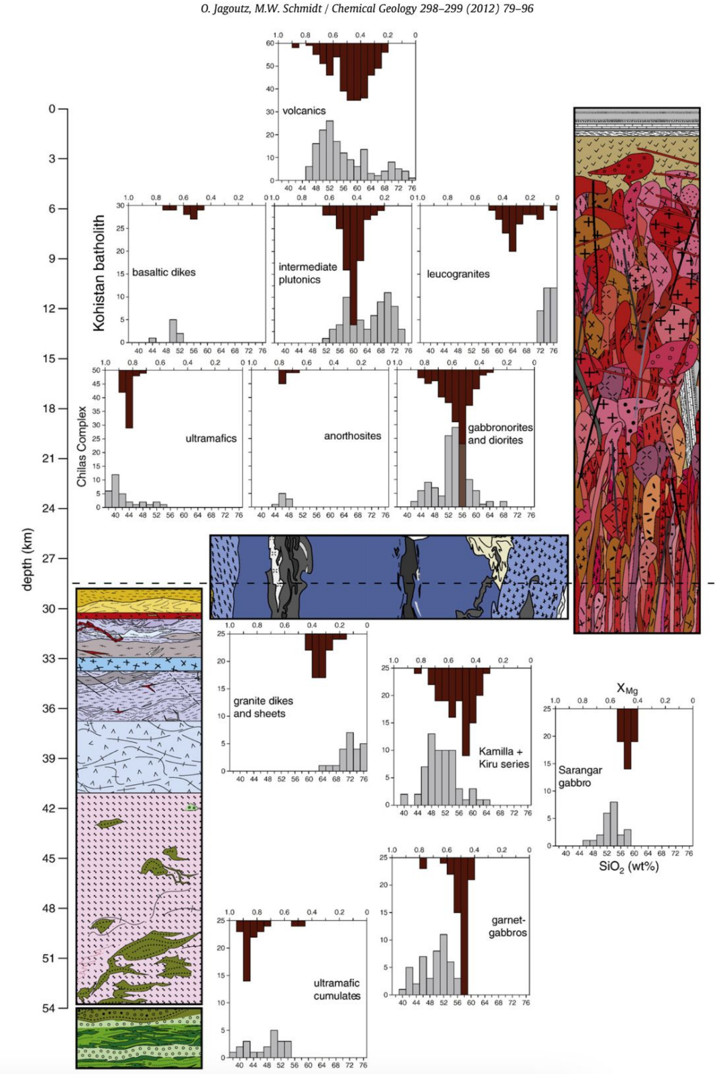
Does this apply to the lower sections of the continental crust? Which methods can we use to investigate its structure, chemistry and physical properties?

Answer: Yes it does, actually!

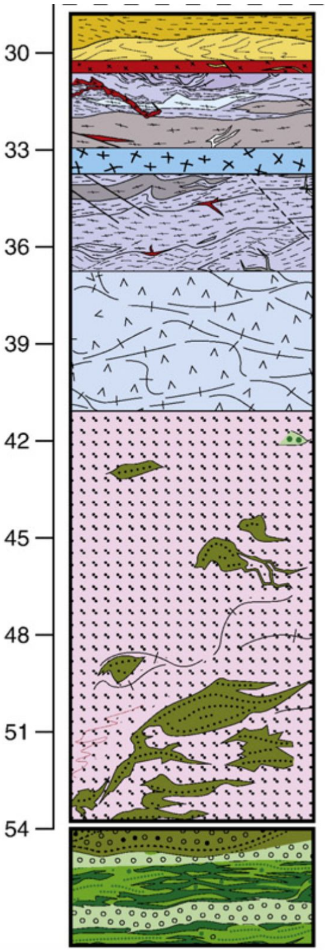
Just as with ophiolites, there is (at least one) complete lithospheric section, fully available for sampling and analysis on the surface: The Kohistan Arc.

Jagoutz & Schmidt (2012)



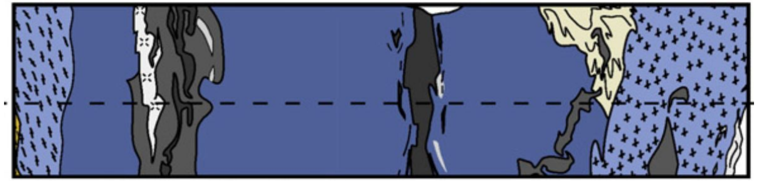


The chemical composition of the Continental Crust.

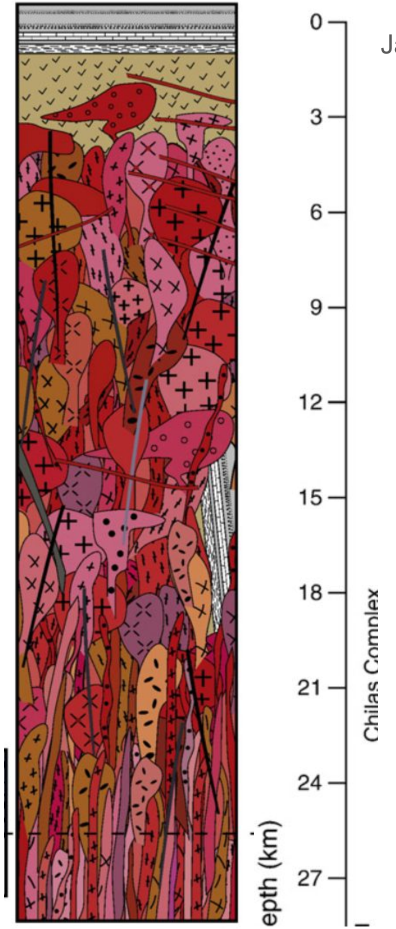


Let’s zoom in!

(This is cool but ignore it) - calc-alkaline gabbroic batholith

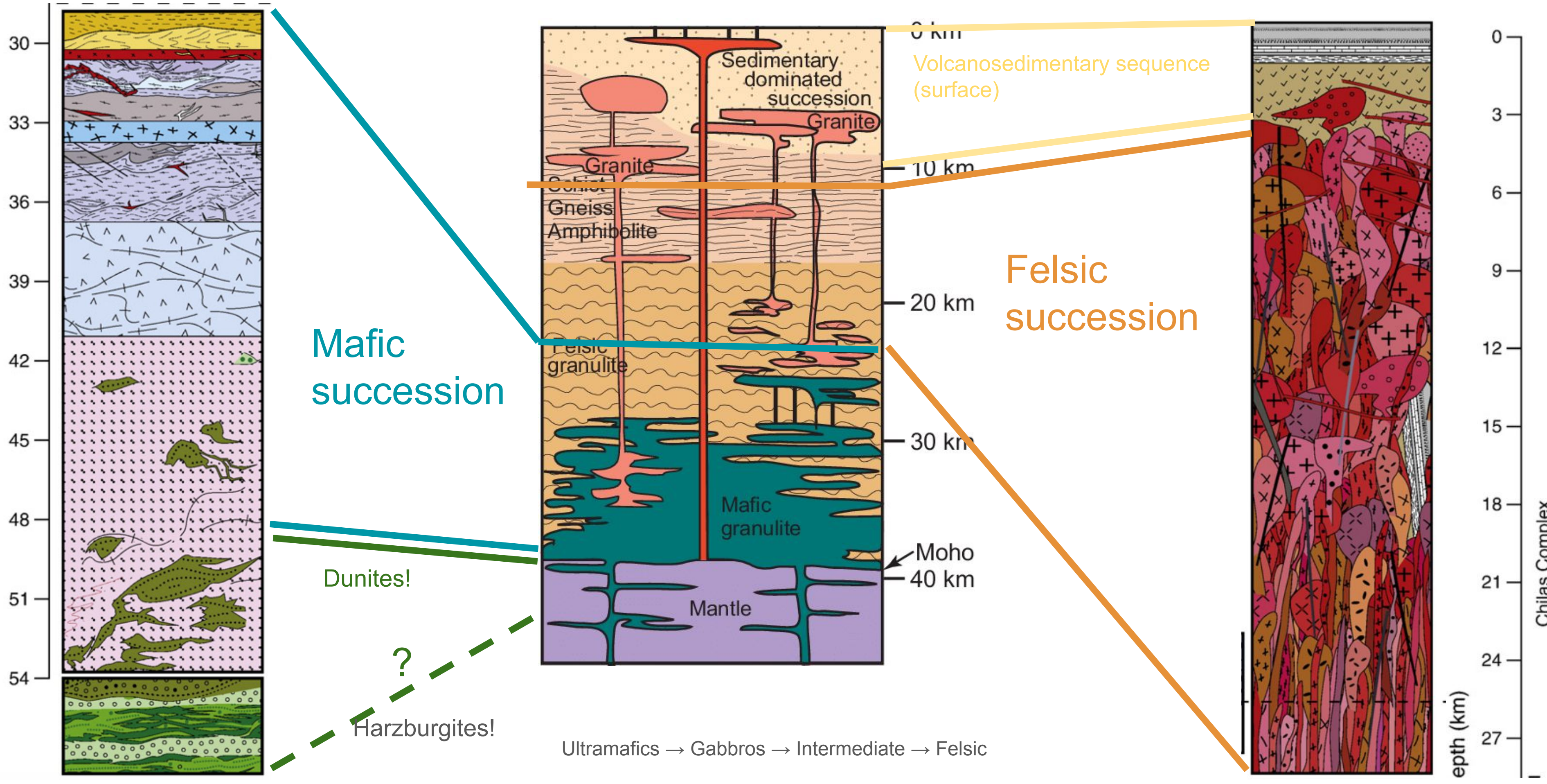


(Thickness derived from geobarometry)



Jagoutz & Schmidt (2012)

The chemical composition of the Continental Crust.

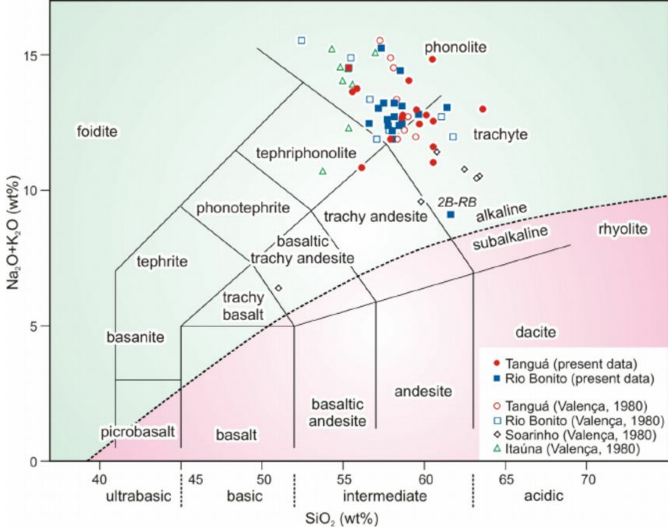


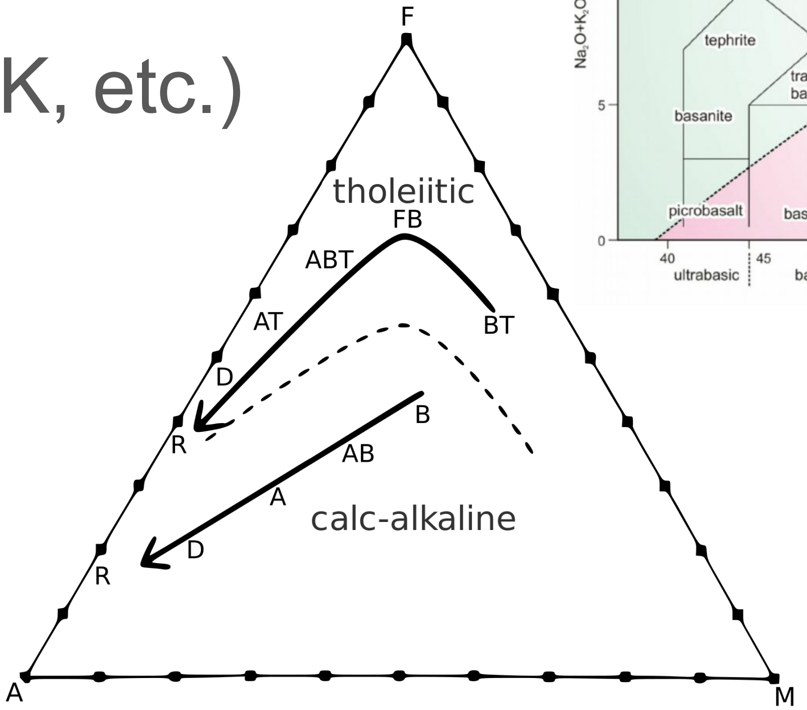
Calc-alkaline volcanism

A = “Alkalis” (Na, K, etc.)

F = Iron

M = Magnesium

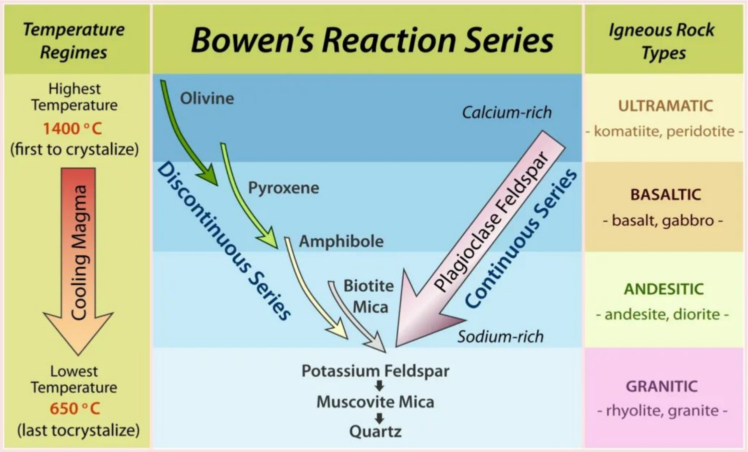


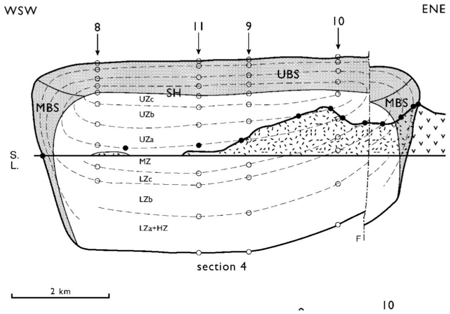


Calc-alkaline trend is typical for subduction settings and some oceanic islands. It’s caused by differences in oxygen fugacity, In the “calc-alkaline suite”, fO2 is higher and magnetite (Fe3O4) crystallizes early, quickly decreasing the iron content.

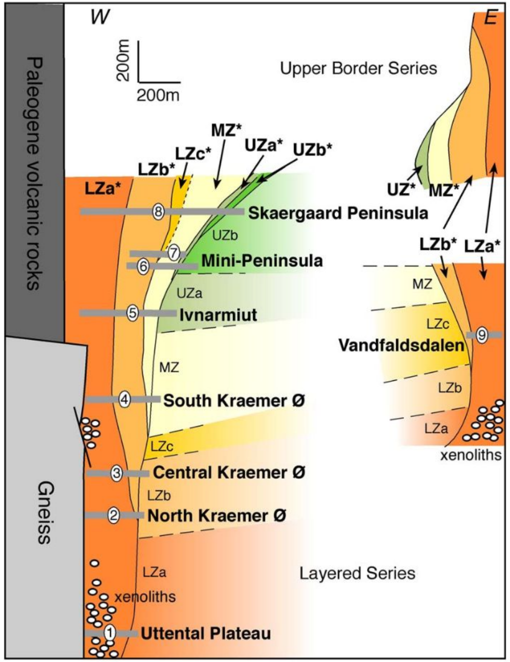
How do melts rise through the lithosphere, and what do they leave behind?

If basaltic melts remain in place and undergo fractional crystallization…



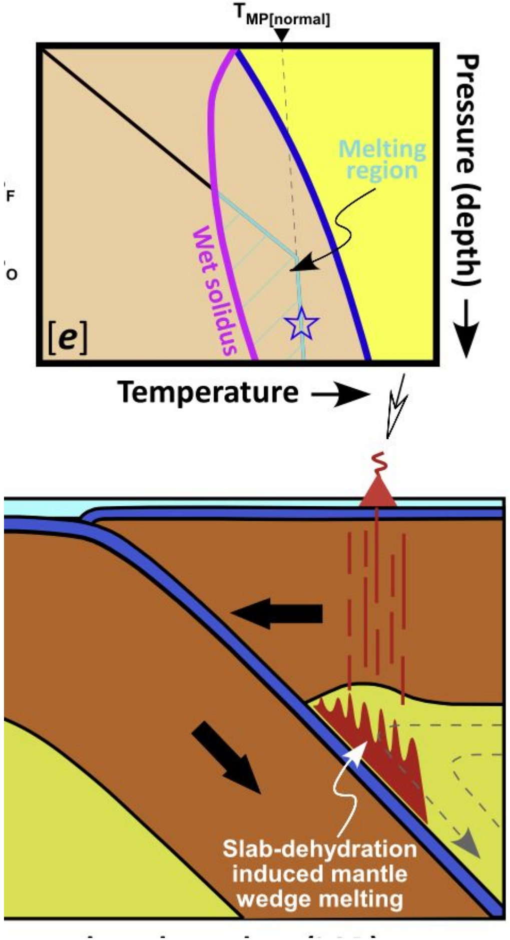


Nielsen, 2004



Holness et al., 2022
Skaergaard intrusion

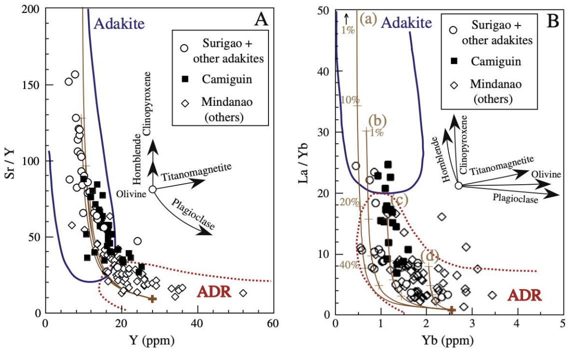
In arcs, magmas rise upwards and fractionate “on the go”



1. Melt generation. Partial melting of the “mantle wedge” (and sometimes, the slab! - ask later).

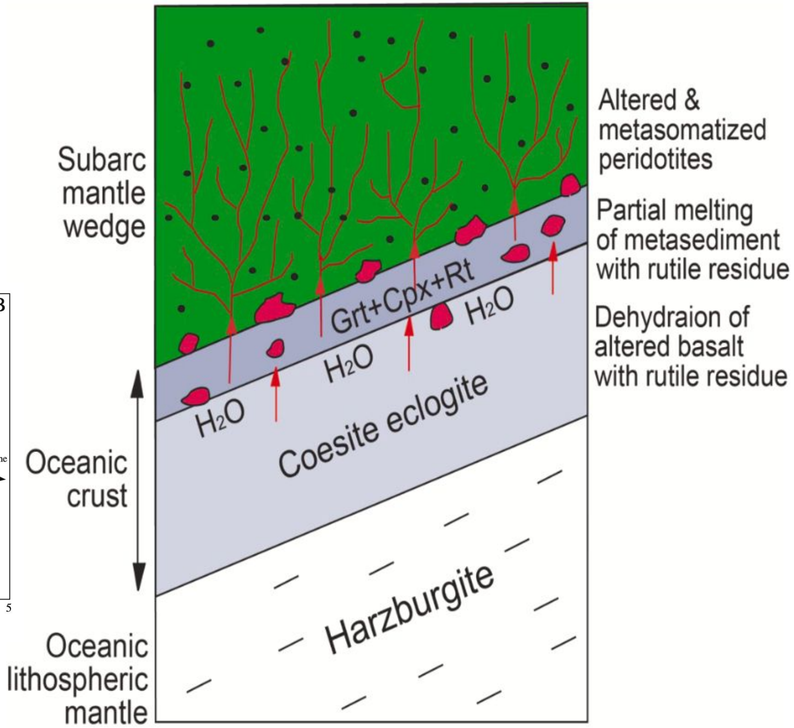
How do we know that the oceanic crust doesn’t (usually) melt during subduction?

= Because when it DOES, Adakites are produced.



Sr, La = highly incompatible, Y, Yb = HREE, highly compatible in garnet

Niu (2021)



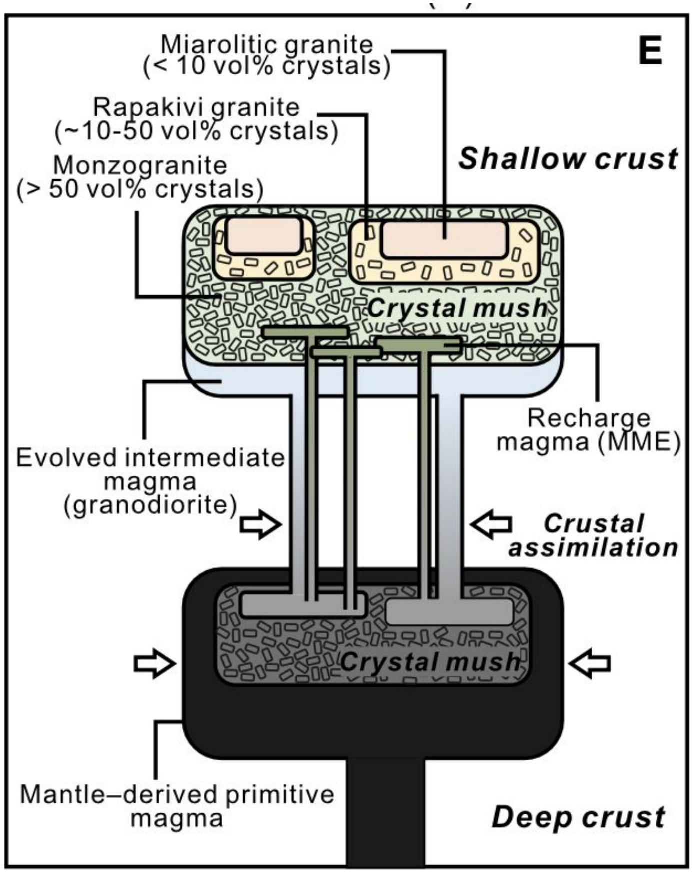
Ringwood (1990)

In arcs, magmas rise upwards and fractionate “on the go”

“Primitive” (i.e. mafic) magmas stall at certain levels in the crust because they reach a point where they are as dense as the material that surrounds them.

Sketch diagram ⟶

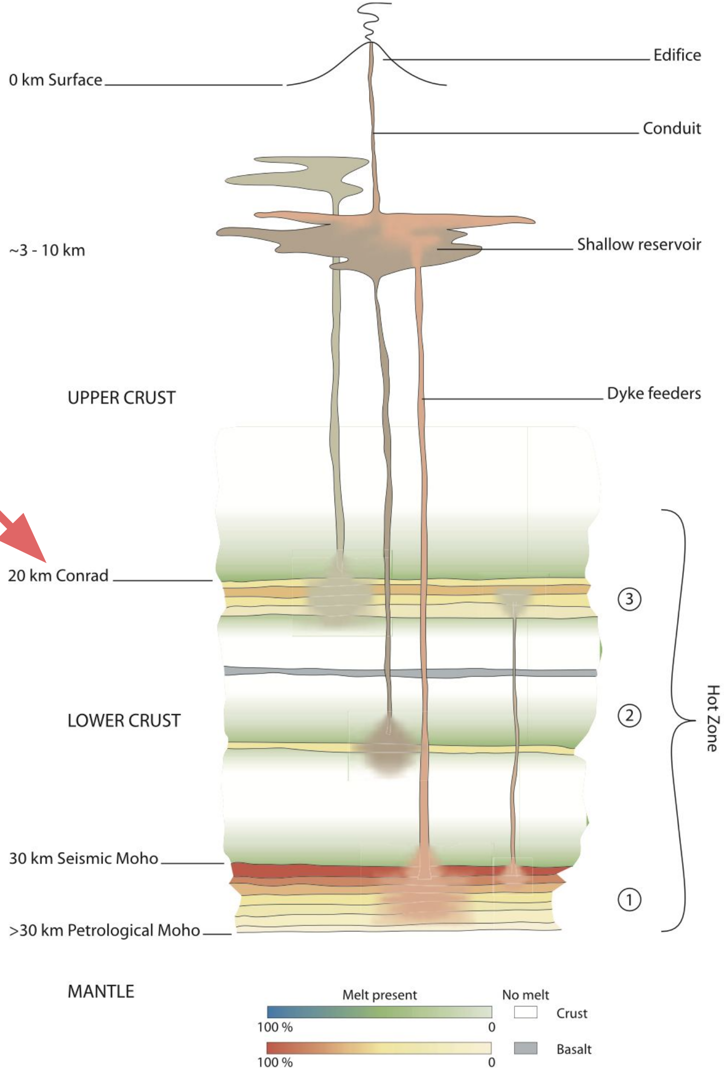
Think more of something like this, but concentrated in a “conduit”:



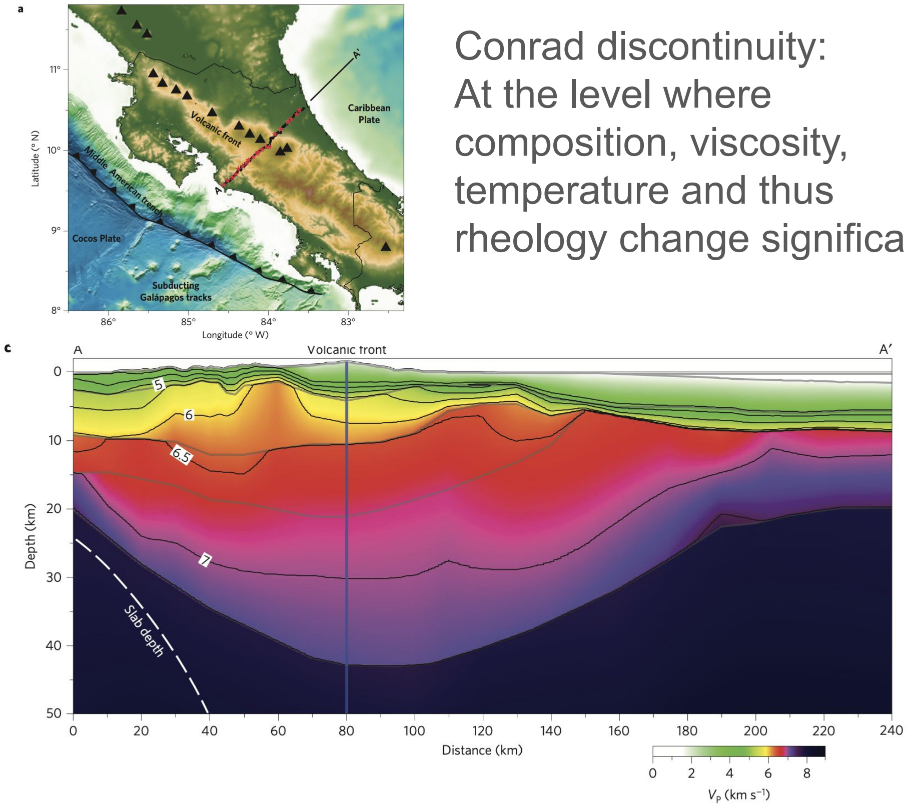
Lu et al., 2022

The full(er) picture

Annen et al., 2015



Conrad discontinuity:
At the level where composition, viscosity, temperature and thus rheology change significantly

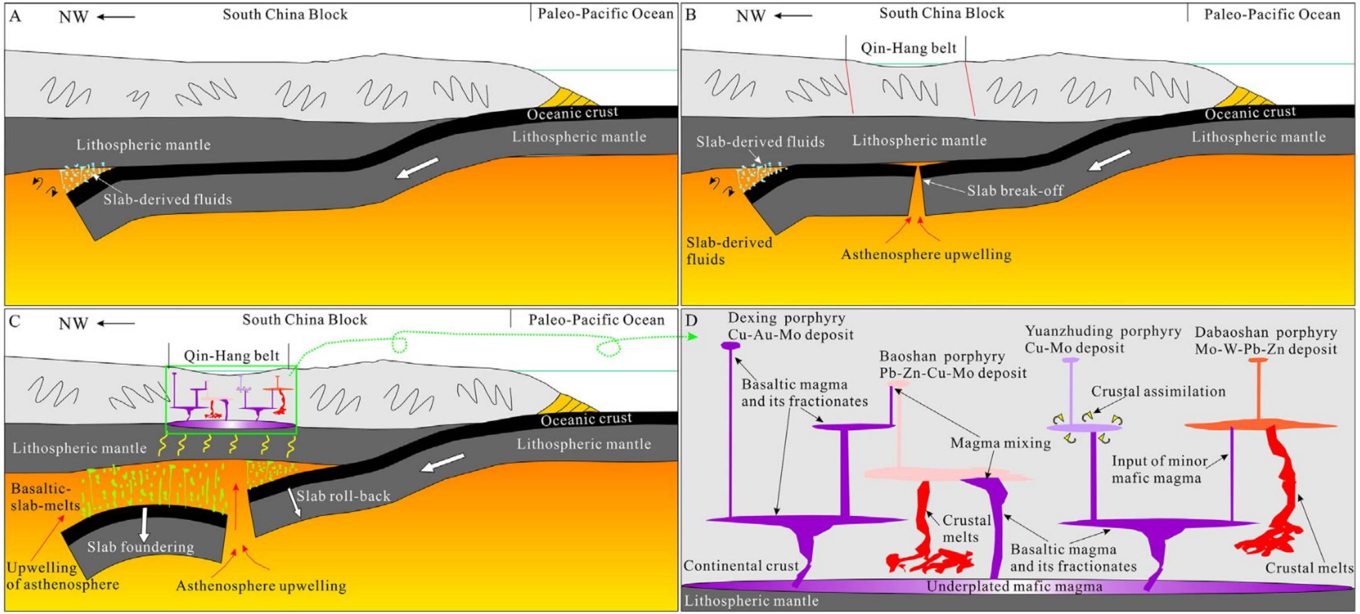


Gazel et al., 2015

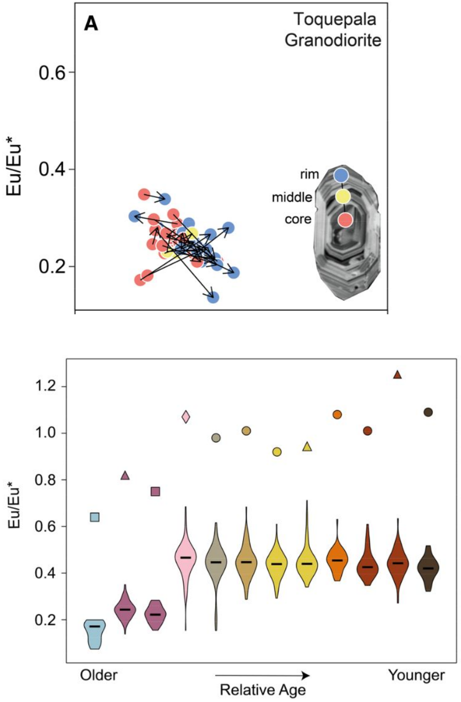
Intermediate* p-wave velocities in juvenile continental lithosphere

Exceptions are the rule!

Fully explaining the chemical signatures and by proxy, the deep structure of continental lithosphere found in different arcs remains the holy grail of igneous petrology.

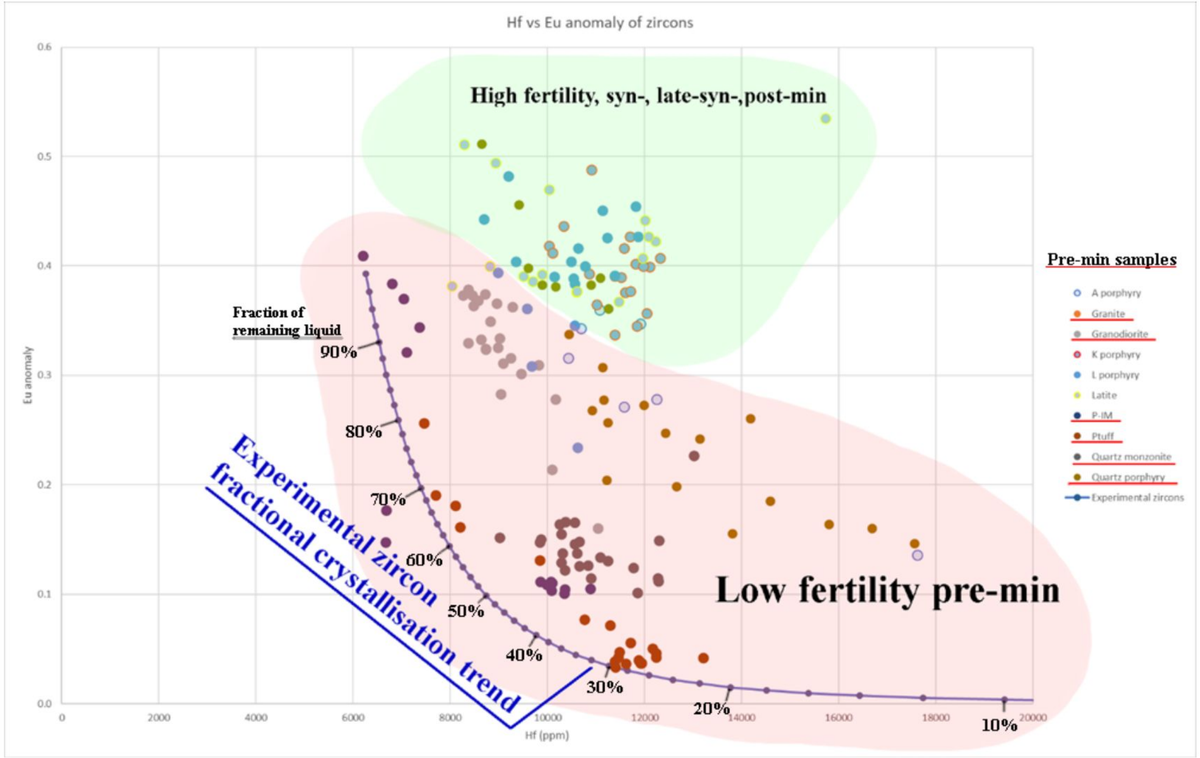


Ren et al., 2020



Nathwani et al., 2021

Geochemical modelling has a long way to go!



The Continental Lithospheric Mantle

The lithospheric mantle – physical properties

Geochemistry + seismic surveying

First: **seismic evidences**

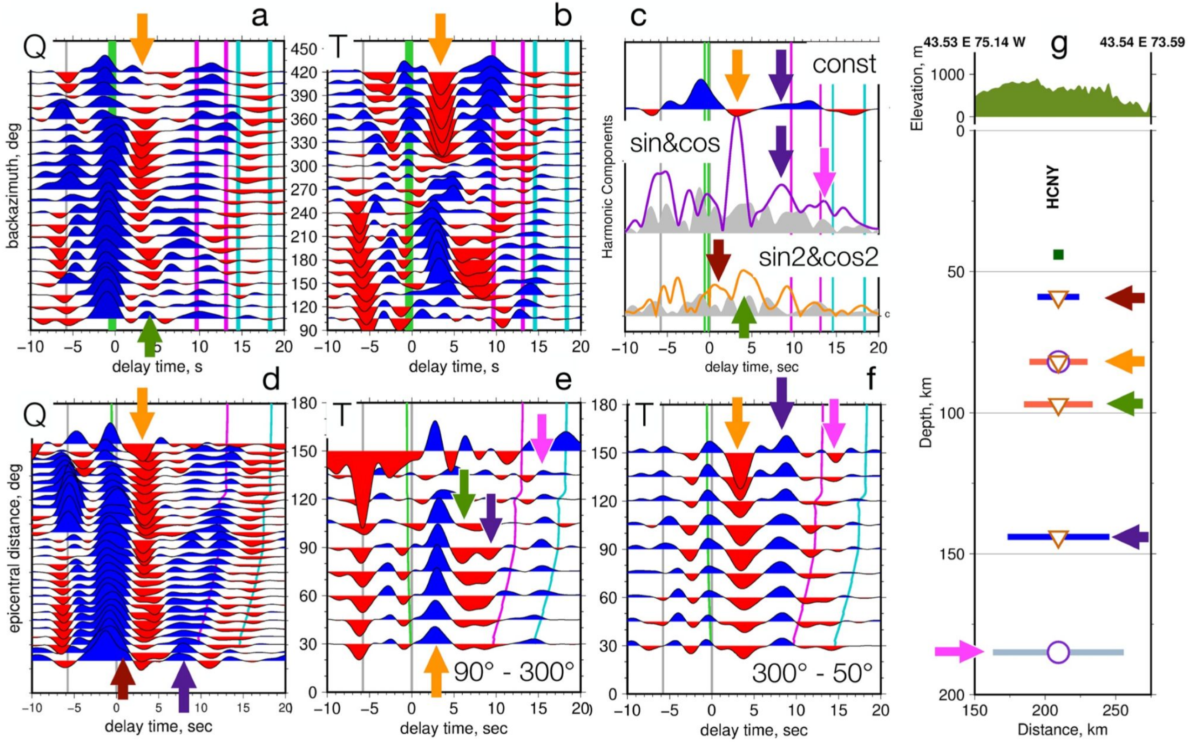
- Tomography
- Velocity discontinuity imaging
- Anisotropy mapping
- Receiver functions
  - P-receiver functions: lower crust and Moho
  - S-receiver functions: continental lithospheric mantle + LAB

The continental lithospheric mantle – seismics

- **Discontinuities**
- Lower- and higher velocity zones
- Anisotropy changes

Why?

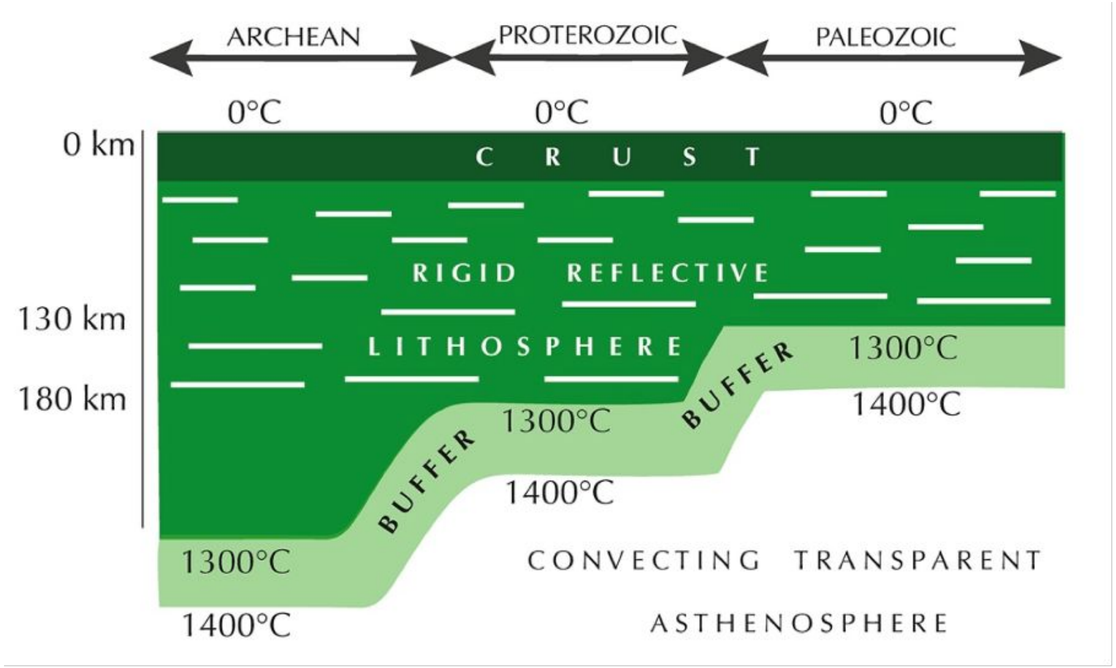
- Phase transitions
- Composition
- Structural



Levin et al. (2023)

The continental lithospheric mantle – seismics

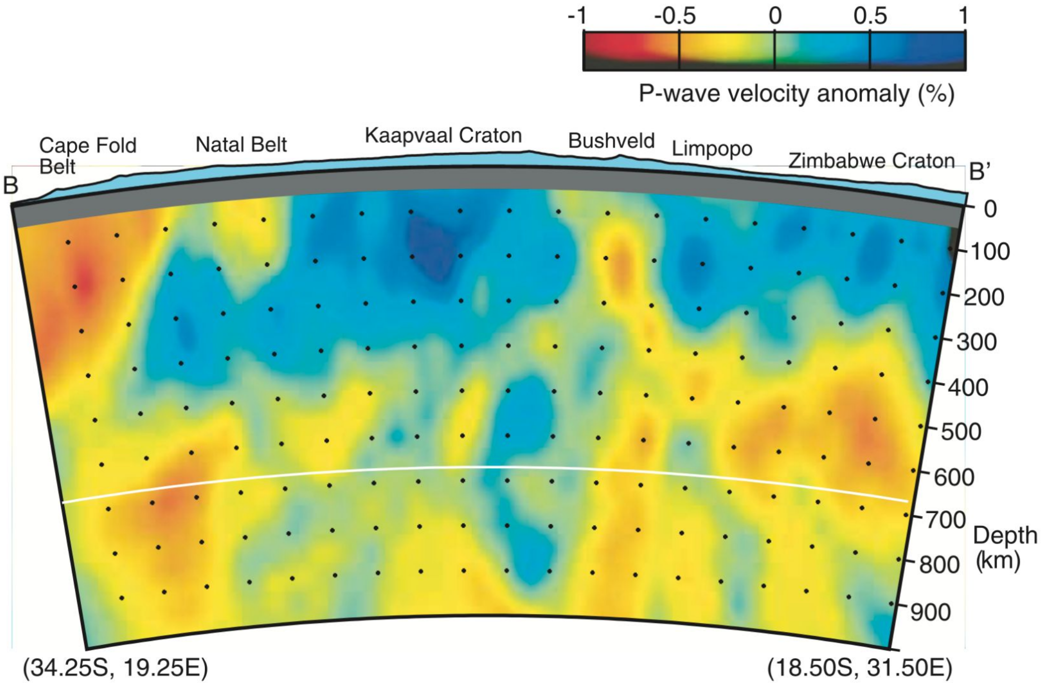
- Relationship between age and thickness
- Higher and lower velocity discontinuities
- A story of evolution!



Levin et al. (2023)

The continental lithospheric mantle – seismics

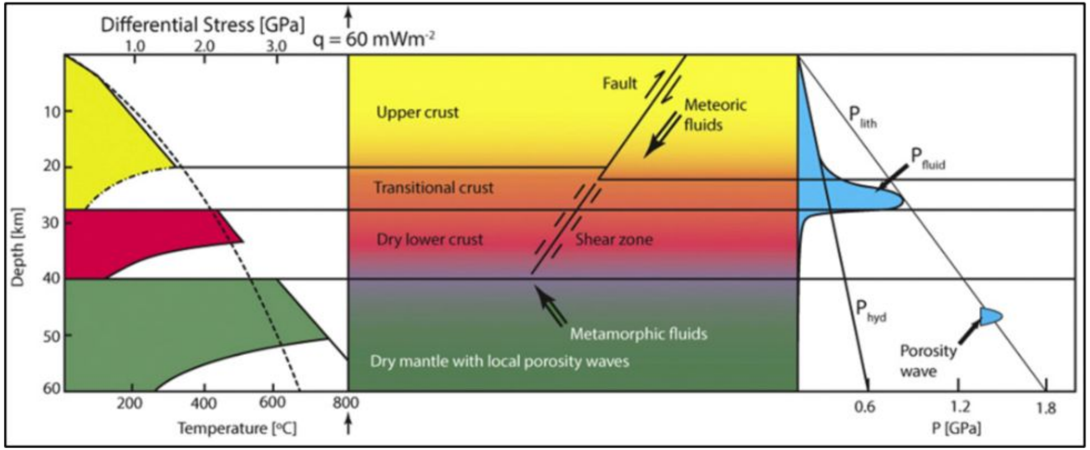
- *Usually* higher velocity anomalies beneath cratons



Carlson et al. (2005)

What about the rheology in the CLM?

- Rigid, strong, cold and **dry**
- Supports cratons
- Seismic observations: mostly high velocities



Jamtveit et al. (2015)

What challenges the strength?

- Chemical properties – heat producing elements
- Available water

To be continued…

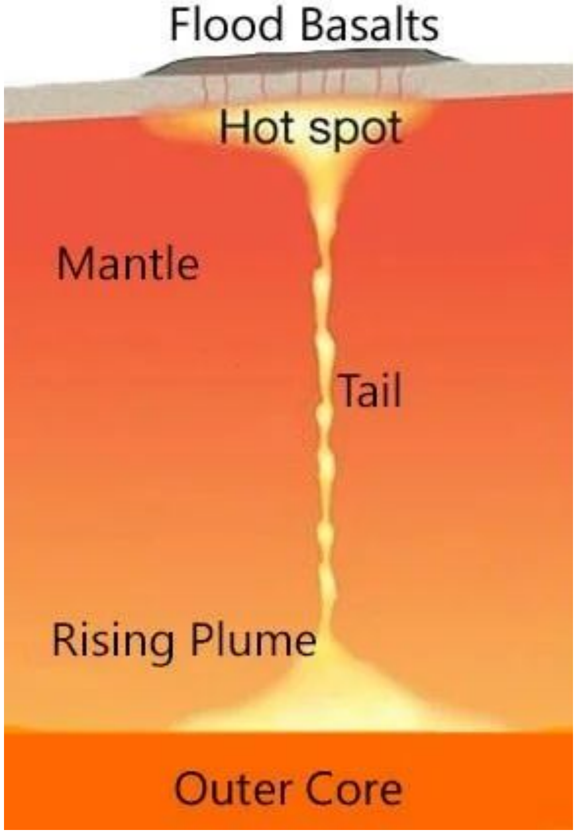
The continental lithospheric mantle - what we don’t understand:

- How does it form?And what is the difference with the **oceanic lithosphere**?
- How can we **study** it?
- What is the **age**? Is it coupled with the crust or it is not?
- Why there are differences in **seismic velocities**? Is it heterogeneous?
- How can it be thick and buoyant?
- How can we explain “density compensation"?
- What are the chemical processes that affects its compositions?
- How can we explain continent-continent subduction?

The main proposed theory (and its weaknesses)

Plume model was invoked to explain the formation of **continental lithosphere** because**:**

- Melting begins at high pressure and, without a thick lithosphere, it continues to shallow depth
- high Si contents



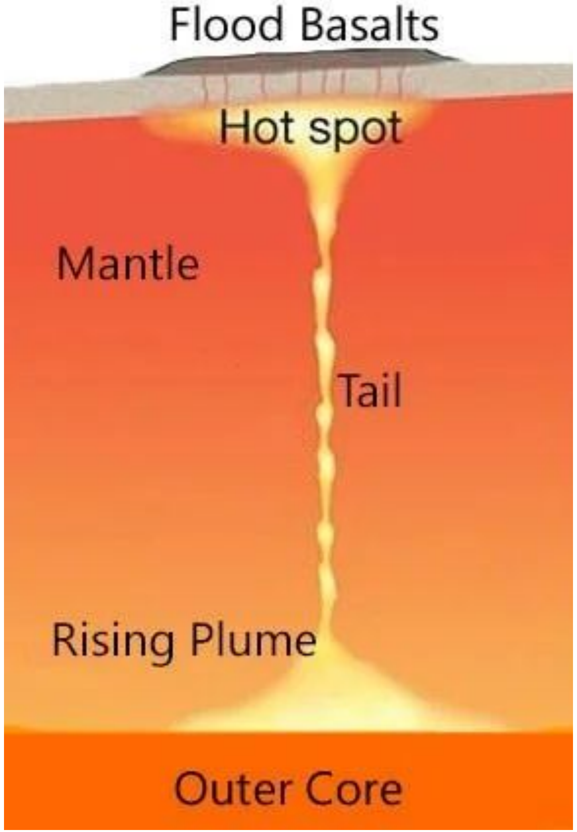
The main proposed theory (and its weaknesses)

Plume model was invoked to explain the formation of continental lithosphere **BUT we are not convinced…**

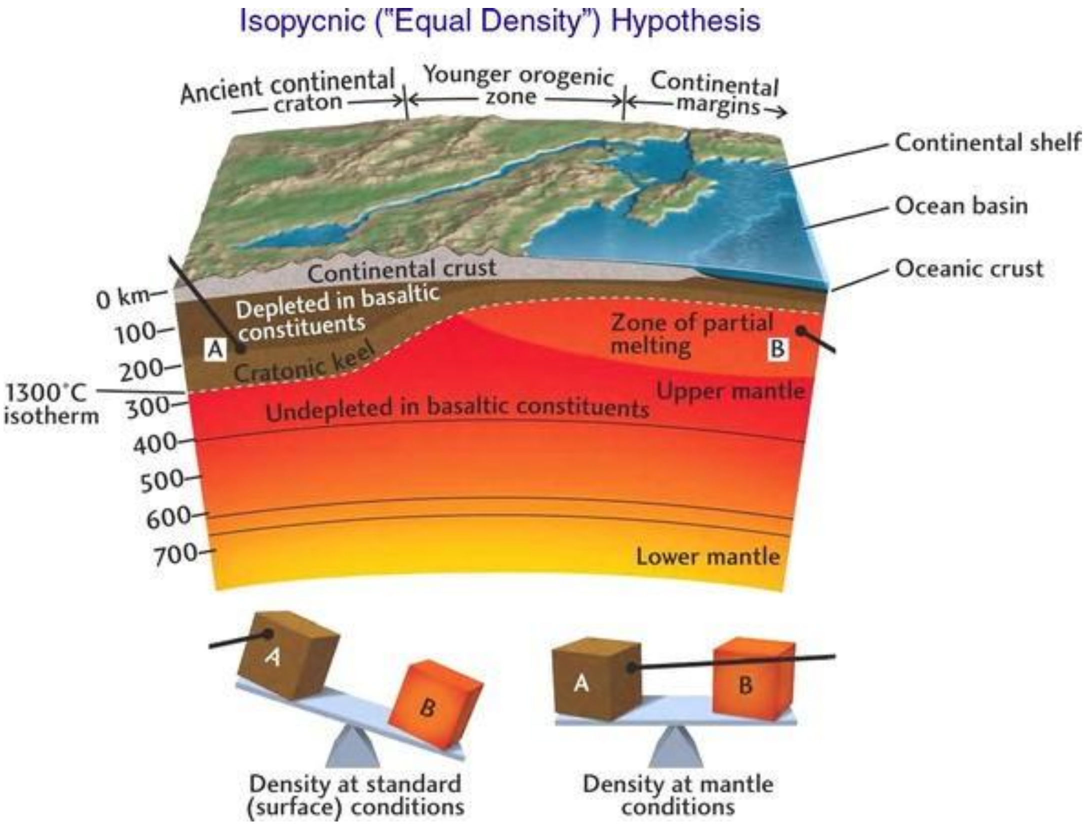
- most geochemical characteristics of peridotites are related to L-P melting origins
- A single step of high degree melting produces H-Mg lava (Komatiite) and we will need ca. 100 km of this lava to balance the a 150 km thick depleted lithospheric mantle

⇨ No worries, **WE HAVE A THEORY**!

(Or at least Carlson et al. 2005 have)



The density compensation hypothesis



Carlson et al. 2005 - Geochemical requirements:

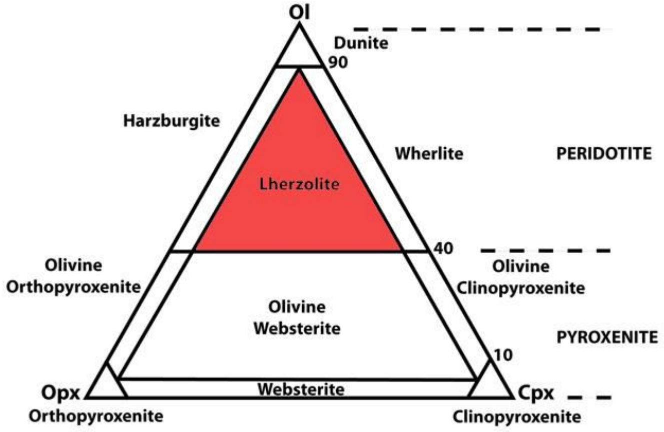
To have a buoyant (and thick) continental lithospheric mantle we need a **less dense and stiff layer** overlying the asthenosphere**.** How do you produce it?

1. The rocks must contain “**lighter minerals**”;
2. The layer must be **colder** (no heat producing **radioactive** minerals**);**
3. And **dry**

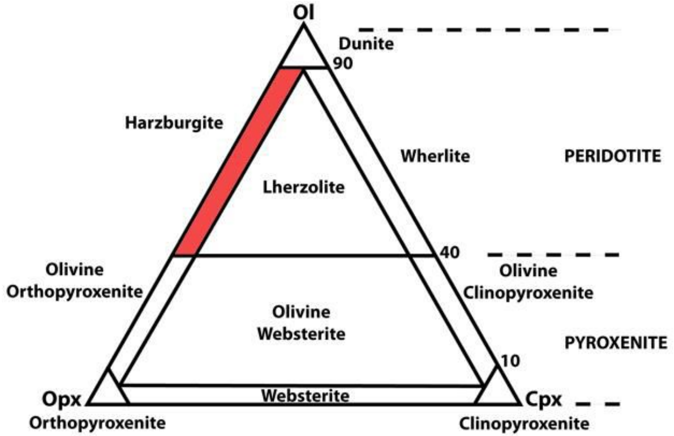
Carlson et al. 2005 - Geochemical requirements:

1. The rocks must contain **“lighter minerals”:**

Peridotites can be divided into **FERTILE** (Lherzolite) and **DEPLETED** (Hazburgite)



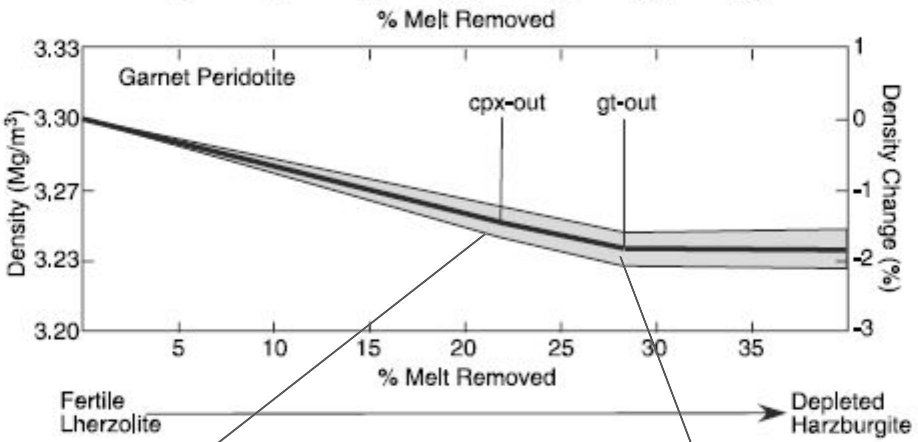
It contains Ol, Cpx,Grt, Opx



It contains Ol and Opx

Carlson et al. 2005 - Geochemical requirements:

1. The rocks must contain "**lighter minerals**":



Ol is 15% less dense than Gt; the rock is 2% lighter w/o Gt

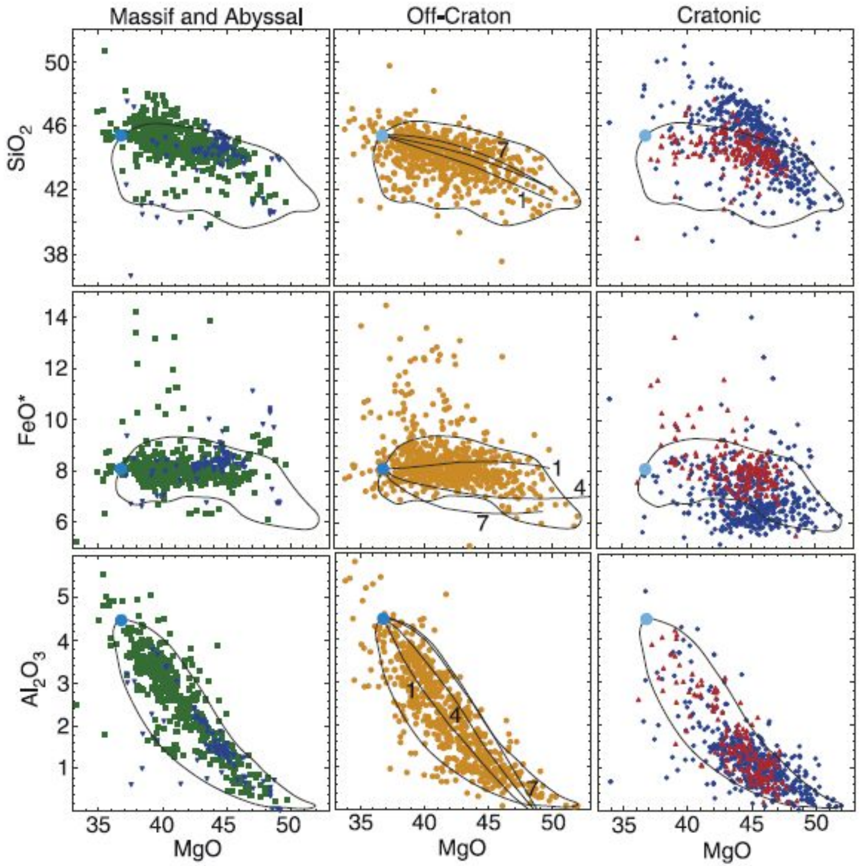
Cpx contains Ca, Al and Fe

Gt contains Ca, Al

Carlson et al. 2005 - Geochemical evidences:

Xenoliths analyses of major elements distribution for three different “geological settings”:

- Massif/abyssal
- Off-craton
- Cratonic



Carlson et al. 2005 - Geochemical evidences:

Xenoliths from different localities can be divided in:

- massif peridotites and off-craton peridotites → more fertile (and dense)
- xenoliths from cratonic areas → depleted (and less dense)

Does it make sense? I think so…where the lithosphere is thicker, the density is minor.

Carlson et al. 2005 - Geochemical requirements:

2. The layer must be **colder** (no heat producing **radioactive** minerals**)**:

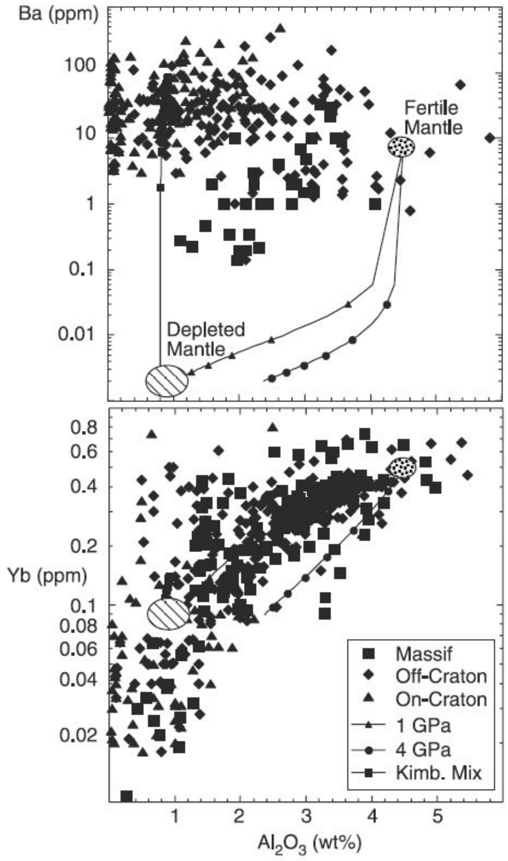
→**Incompatible trace elements** includes radioactive elements (such as Rb,K,U) that can produce heat.

A lithosphere that underwent (high) degree of partial melting will be naturally (**moderately) depleted** in all incompatible elements.

→ Unexpected high concentration of TC can be explained by refertilization or **infiltration** (in xenoliths)

Carlson et al. 2005 - Geochemical evidences:

- Oceanic and massif peridotites→ depleted in all incompatible elements (they are residue of partial melting)
- Cratonic peridotites → low abundance of moderately incompatible TC (Yb) (they are residue of larger degree of partial melting)

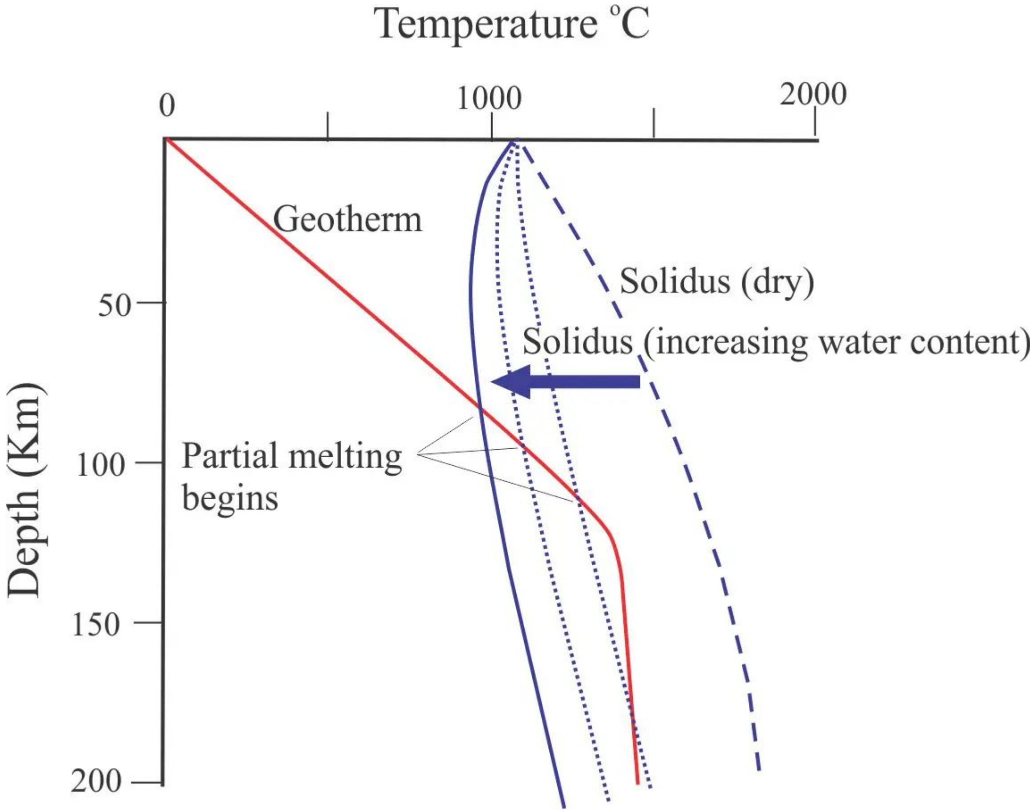


Carlson et al. 2005 - Geochemical requirements:

3. The layer must be **dry:**

Water can radically change the behavior of the mantle by:

- ❖ Lower the melting point
- ❖ Reduce the viscosity by a factor of 20-500



Carlson et al. 2005 - Chronology - problematics:

We study the mantle through **mantle xenoliths** (expression of residue of partial melting) where most of the incompatible elements are few.

BUT, most of the radiometric systems date the **incompatible elements** (Rb-Sr, Sm-Nd, Lu-Hf, U-Th-Pb).

→ **intrinsic error in the measurements**; perhaps we are measuring the refertilization event instead of the timing of formation

Re-Os system is one of the best,
→ Os is compatible during mantle melting

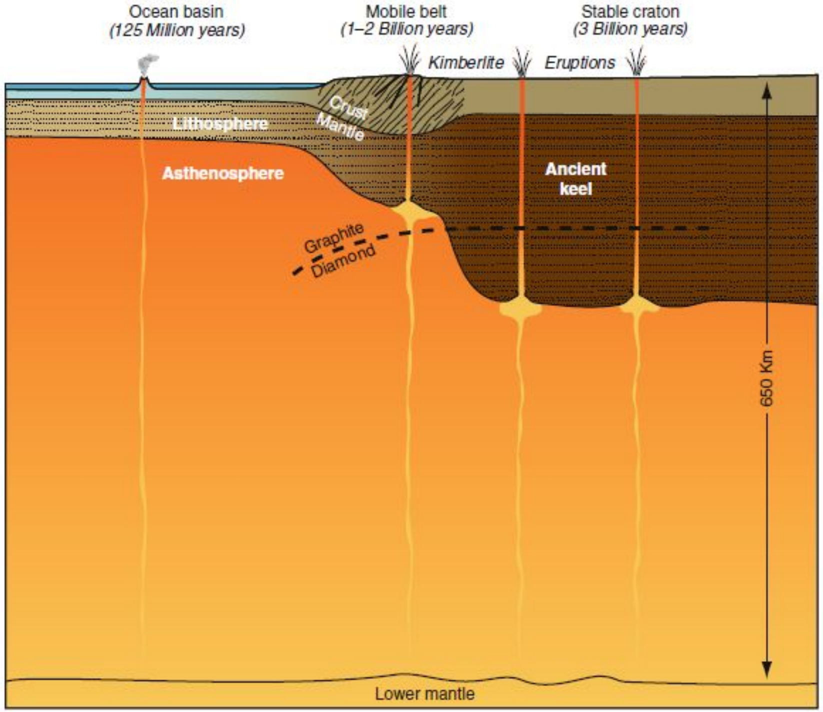
Carlson et al. 2005 - Chronology - evidences:

- There is general correspondence between the age of the crust and the age of the lithospheric mantle (S-Africa Craton)
- The Slave Craton is compositionally and temporally layered (Early archean h-depleted layer overlying a fertile younger mantle)

→ Lithospheres are not forever, and they can be lost/modified during major tectonomagmatic events affecting the continents

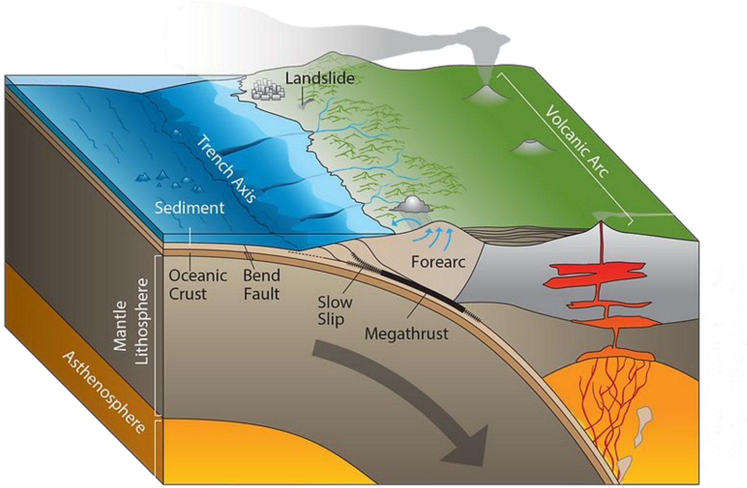
Density compensation hypothesis - chemical composition

- How much mantle need to be involved to create the crust?
- **Major elements**: 2%
- **Incompatible trace elements**: 30-50%
- This does not add up…



Density compensation hypothesis - chemical composition

- This does not add up…
- … unless we look at a subduction zone
- The **major elements** from melting of the mantle wedge
- **Incompatible trace elements** from subducting plate



Density compensation hypothesis - chemical composition

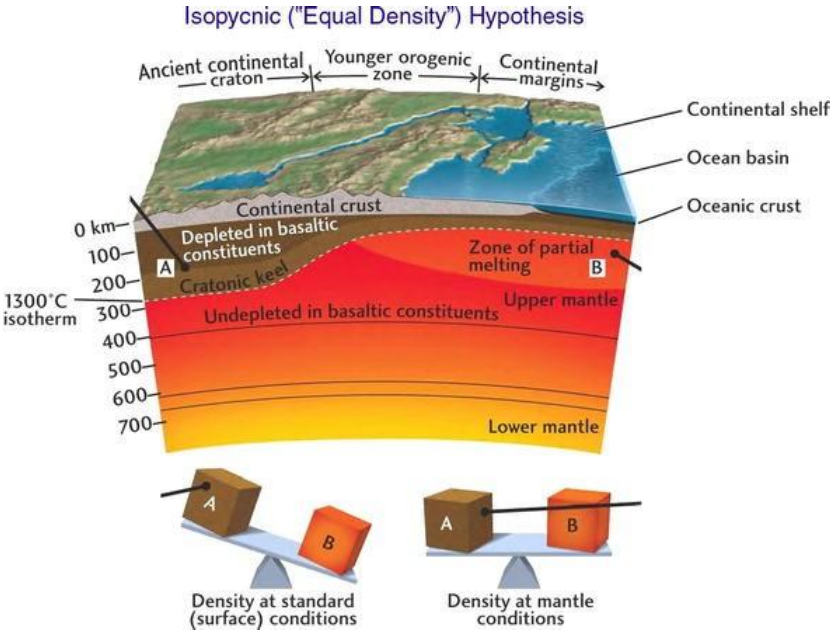
We do not know if convergent margin volcanism alone can create the composition found in continental crust, but it does explain:

- **High degree** of melting at low pressure
- **Silica enrichment** found in some peridotites – can be caused by Si-rich fluids form the slab
- Removes the problem of how much komatiite/lithosphere is needed to create the composition of the crust
- In modern mantle samples, only samples from island or continental arcs are close to the **degree of depletion** we see in **cratonic peridotites**

Density compensation hypothesis - buoyancy and strength

- Neutrally buoyant mantle is at risk to become involved in the circulation of the underlying convecting mantle
- But the SCM that underlies cratons can be very old…

- Melt depletion creates **compositional buoyancy** in residual mantle and leaves the mantle lithosphere depleted in **radioactive heat-producing elements and in water**
- Results in mantle that is cold and more viscous

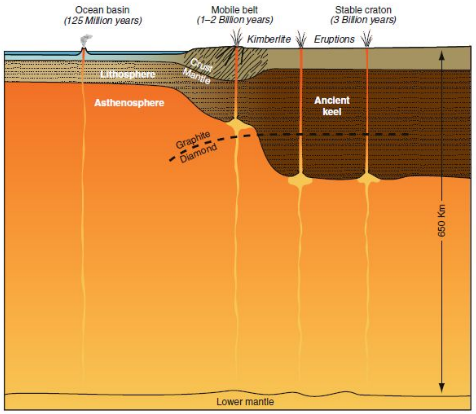


Density compensation hypothesis - buoyancy and strength

- This **compositional buoyancy** causes the lithospheric mantle to resist subduction and delamination (**decoupling** of mantle and crust where the lithospheric mantle sinks into the mantle below)

- The strength from cold temperatures and lack of water allows thick sections of mantle to **remain stable and stay attached to the overlying crust** of the same age (no delamination or subduction)
- SCLM acts together with overlying crust

Density compensation hypothesis - compositional buoyancy



SCLM:

- acts together with crust to **resist subsidence**
- creates a buffer from erosion from below
- **Adds strength** to the continent

If the compositional buoyancy of the SCLM becomes compromised:

- Insufficient melt removal or pervasive re-fertilisation → density stability
- SCLM enters mantle convection → magmatism → (different) ages in the crust

Why we think it is a good hypothesis:

1. The **geochemistry** requirements are **fulfilled** by the main analyses;
2. The difference in age of the lithospheric mantle and crust can be explained as an effect of a main **tectonomagmatic event** that refertilizes the mantle;
3. It explains the **heterogeneities** in seismic velocities;
4. It implies **subsidence** (when the plate becomes too heavy) and **uplift** (when the crust and the mantle detached) → can explain the sudden onset of intracontinental magmatism (flood basalt provinces)

→ It is exactly the opposite mechanism than the mantle plume (uplift and then subsidence)

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Ongoing discussions?