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Thermal- Compositional Structure of Cratonic Lithospheric Mantle: A Petrological View Part 3.

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Aims and Motivation for Part 3.

Cratonic Lithospheric Mantle: A Petrological View

- Understand what a craton is and where they occur on Earth
- Understand the importance of cratons (research, industry, hazards etc.)?
- Understand the basic geophysical and petrological properties of cratonic lithospheric mantle
- Understand how the unique physical and geochemical properties of cratons arise
- Age and timing of formation of cratons
- Understand different craton forming mechanisms
- Understand that cratons can be destroyed and modified

Recommended Reading:

- Lee, C., et al. "Geochemical/petrologic constraints on the origin of cratonic mantle." *Geophysical Monograph-American Geophysical Union* 164 (2006): 89.
- Lee, Cin-Ty A., Peter Luffi, and Emily J. Chin. "Building and destroying continental mantle." *Annual Review of Earth and Planetary Sciences* 39.1 (2011): 59-90.
- Pearson, D. Graham, et al. "Deep continental roots and cratons." *Nature* 596.7871 (2021): 199-210.

Cratonic Lithospheric Mantle: A Petrological View

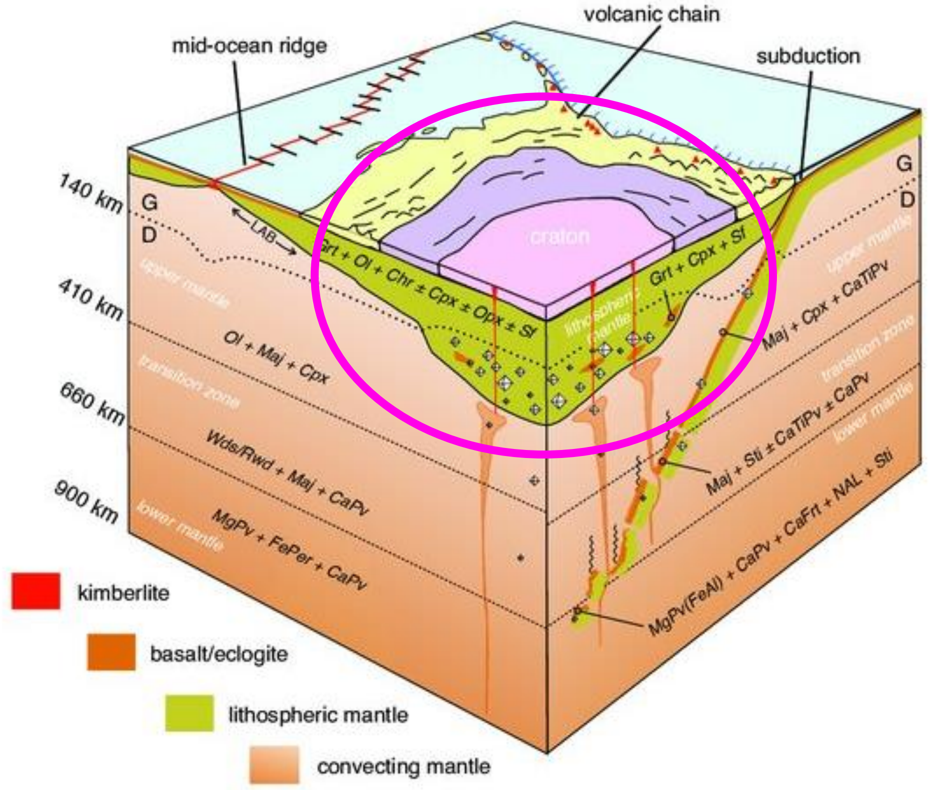
What are Cratons?

Cratons (*kratos* is Greek for strength) are coherent blocks of Precambrian (>500 Ma) lithosphere, typically stable for periods more than a billion years. They are supported by thick- buoyant lithospheric keels that are >150 km deep.

Almost all Archean crust is underlain by cratonic lithosphere. Some Proterozoic age crust is also underlain by cratonic lithosphere.

The distribution of cratonic lithosphere is debated however there are approximately 40 cratons on Earth

Cratons comprise between 40–60 per cent of the continental landmass



Cartoon illustration of cratonic lithospheric mantle. The craton is represented by the thickened (~200-250 km) portion of lithosphere (green). After Shirey et al. (2013).

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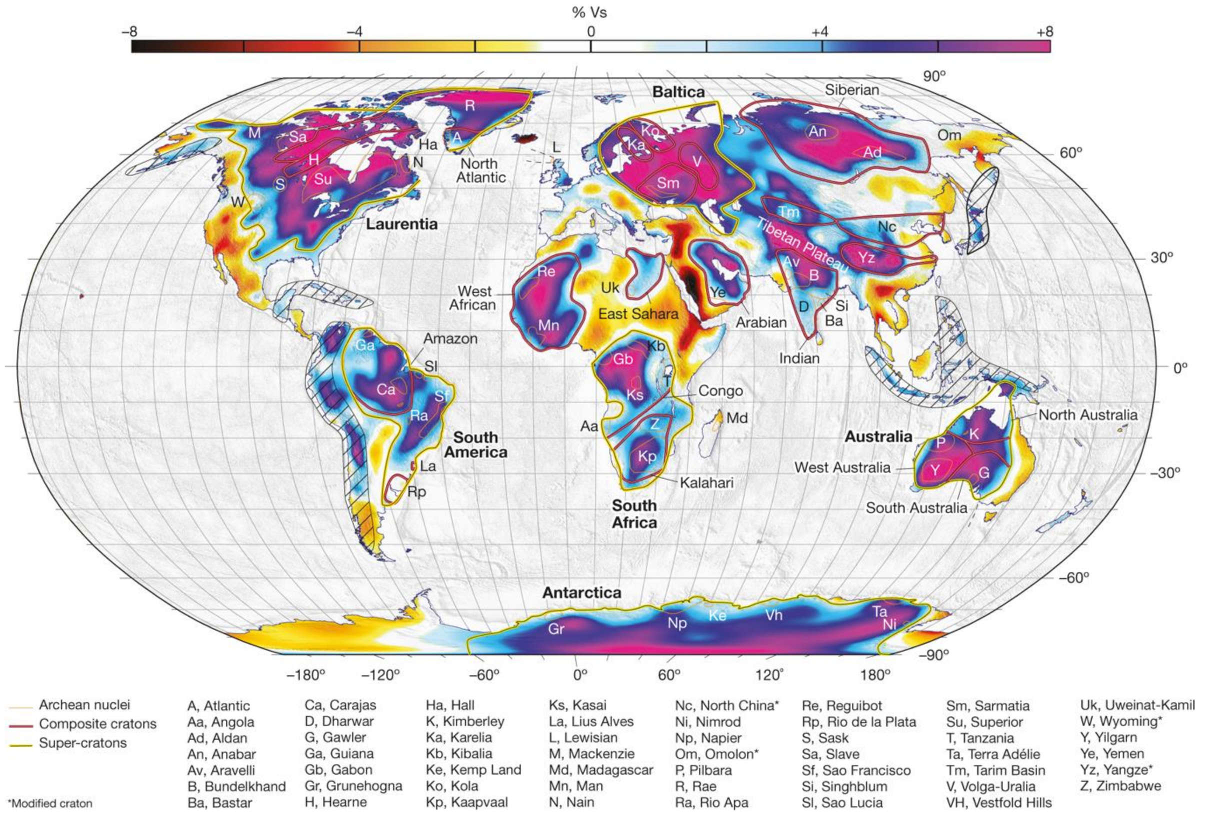
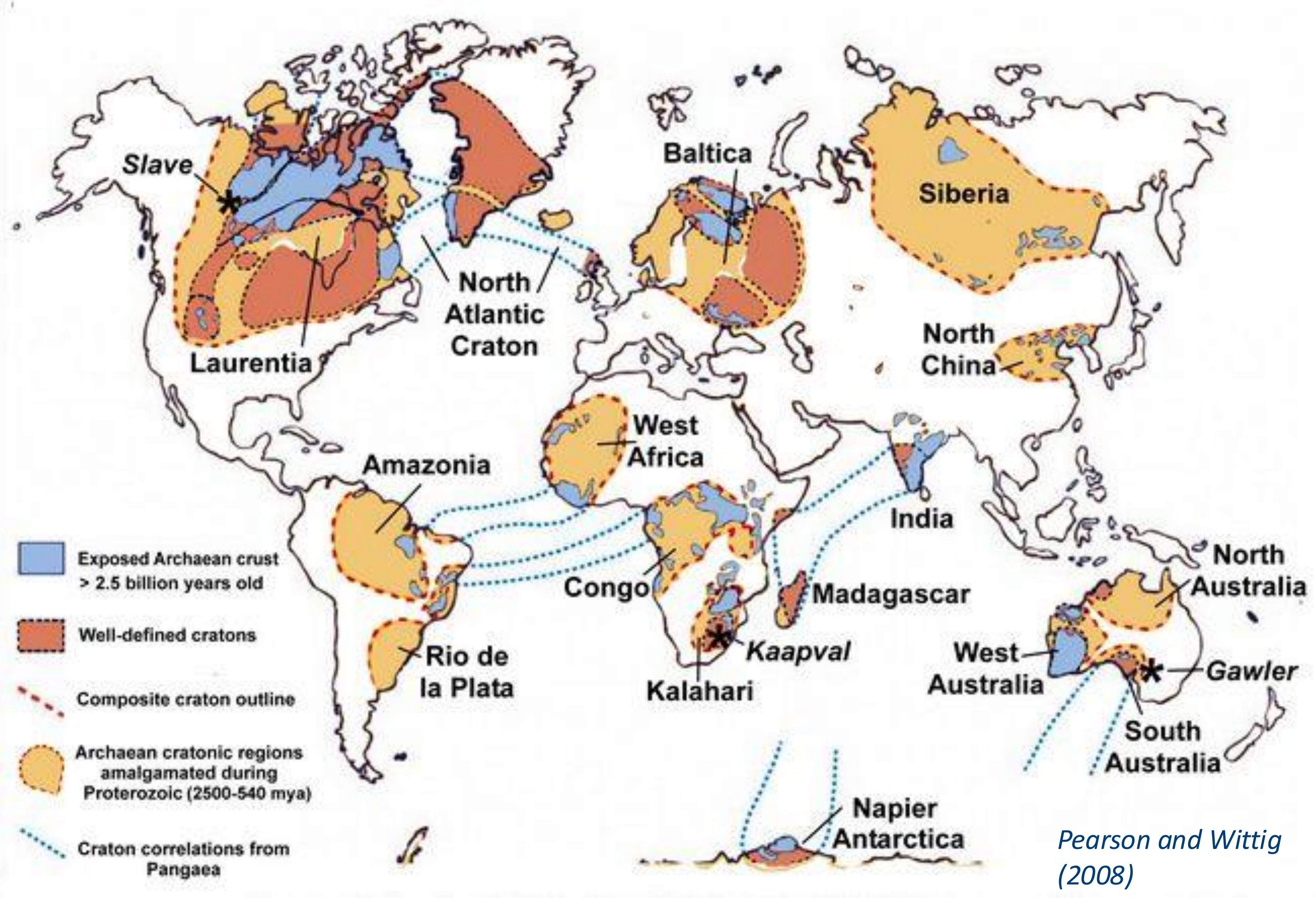


Distribution of Archean and Proterozoic cratonic lithosphere overlain on a global S-wave tomographic model. After Pearson et al. (2021). There are approximately 40 main cratons on Earth.



Pearson and Wittig (2008)

- Well studied cratons:
- Kaapvaal
- Siberia
- Slave
- Superior
- West Australia
- North China

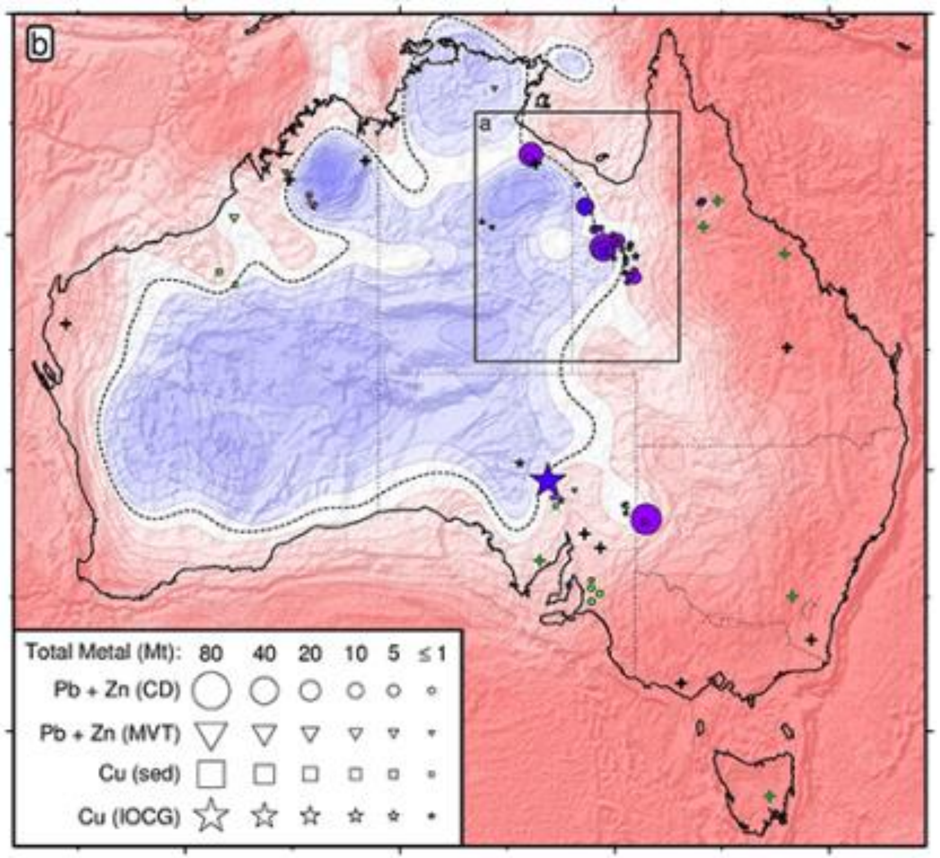
Less-well studied cratons:

- Baltica/Ferro-Scandinavia
- Amazonia
- West Africa
- Rio De Plata

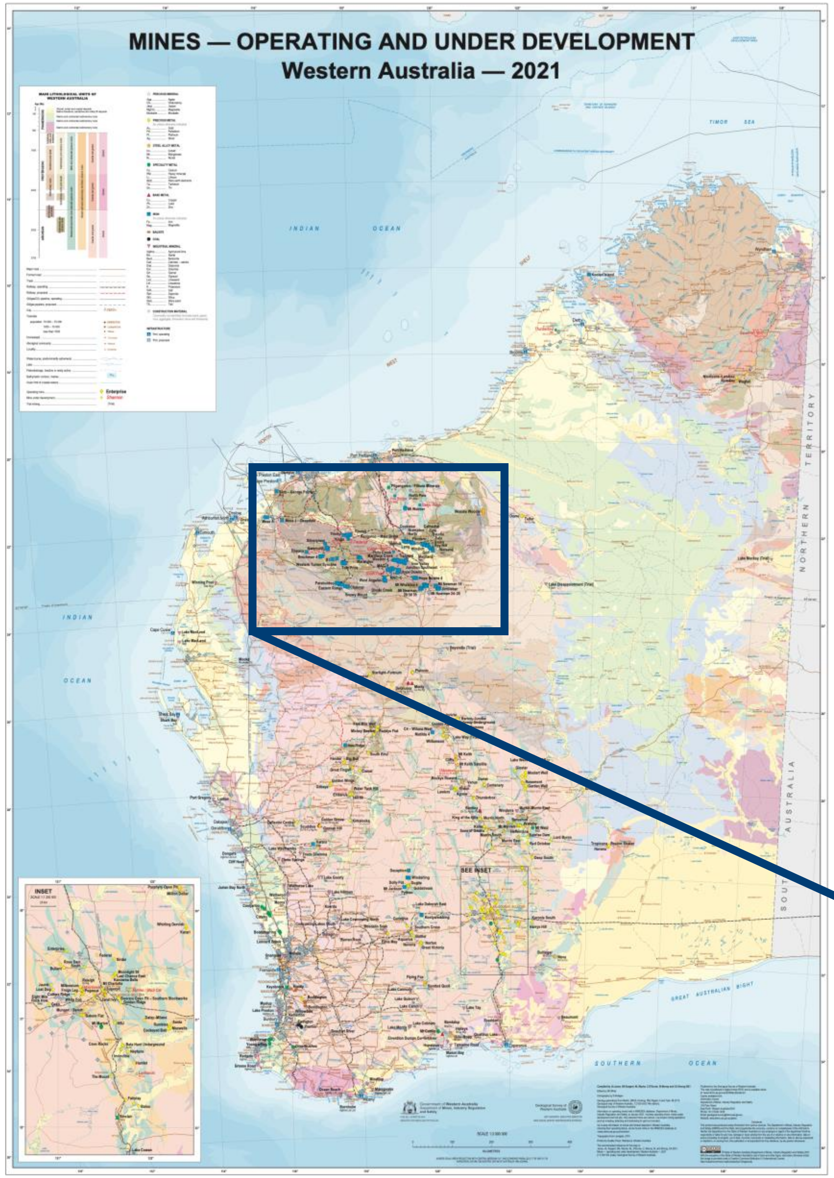
Cratonic Lithospheric Mantle: A Petrological View

The Importance of Cratons?

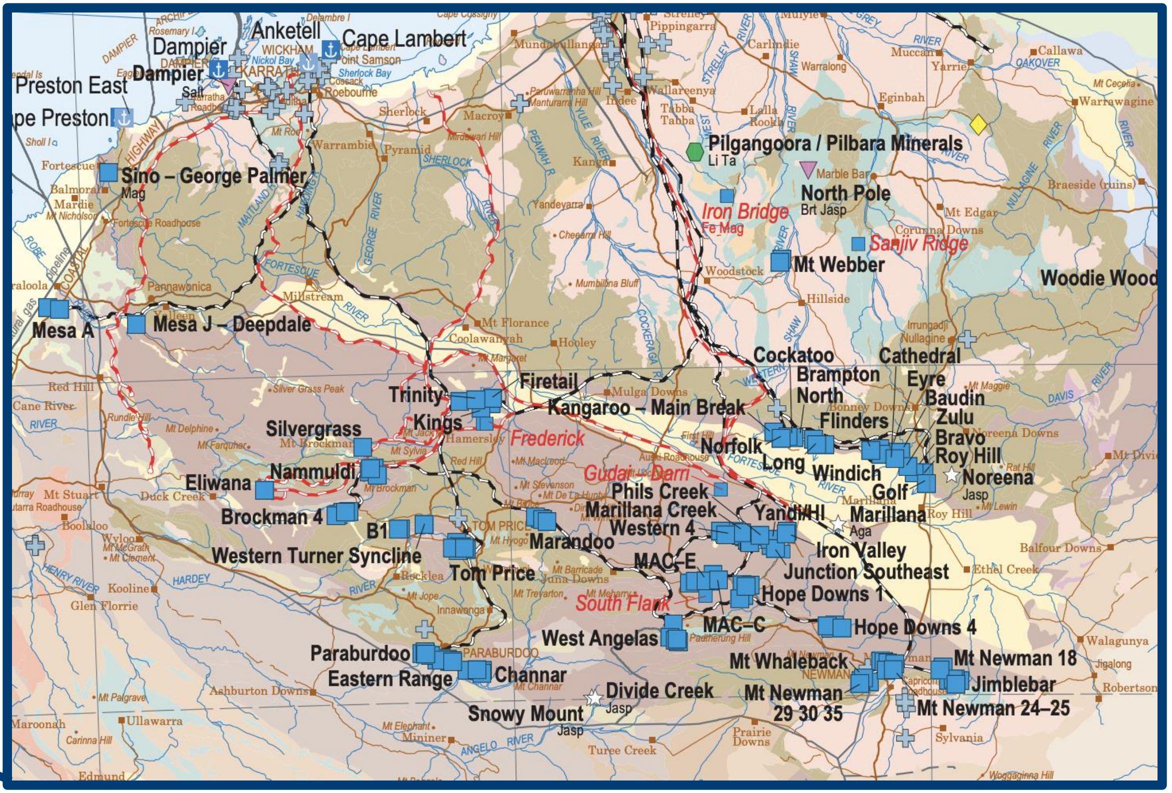
- **Cratons host most of Earth's geological resources, including Gold, Platinum, Diamond, Copper, Iron, Lead, Zinc and Silver**
- Cratons provide insights into the geodynamic processes that operated in the past
- Cratons are structurally stable and resistant to deformation, making them important for understanding long-term tectonic stability
- Cratons form the nuclei of many continents and provide insights into how continents grow and evolve



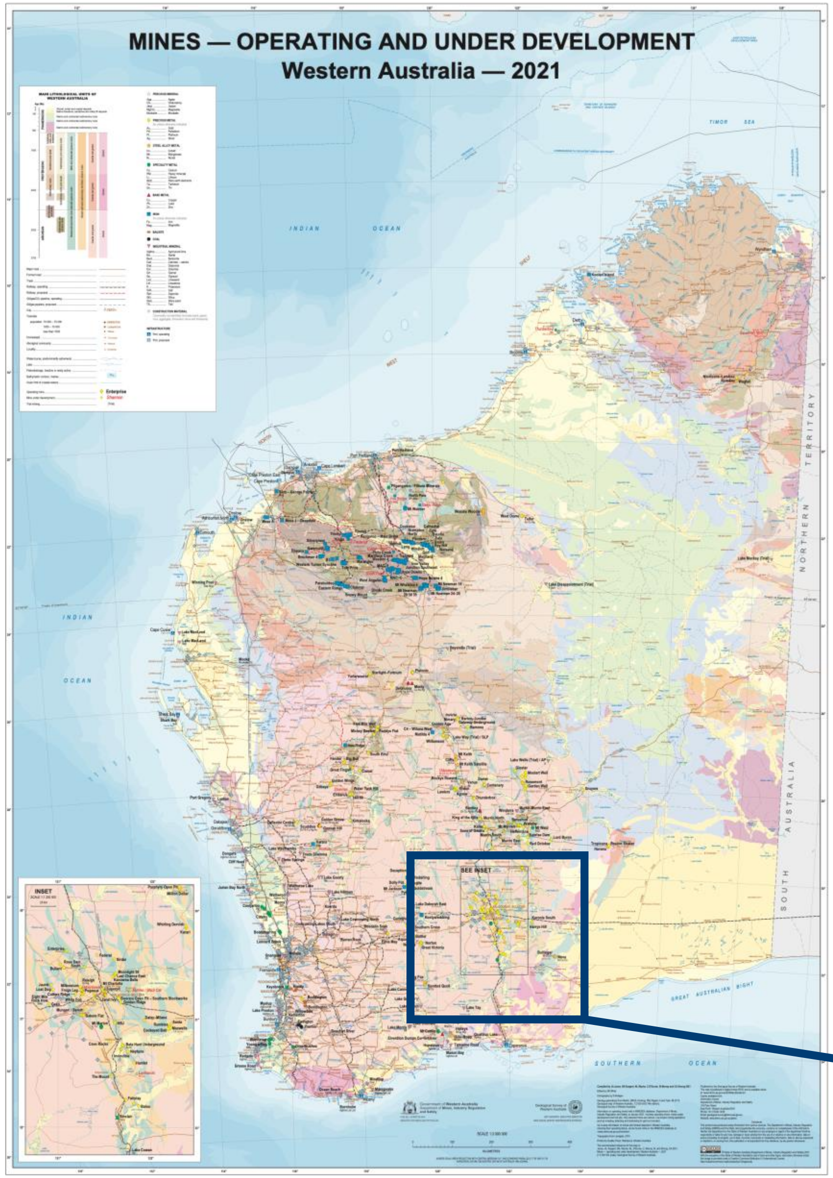
Many ore deposits are located within cratons, specifically their reworked margins. Figure shows location and size of ore deposits in Australia overlain on lithosphere thickness. After Hoggard et al. (2020)



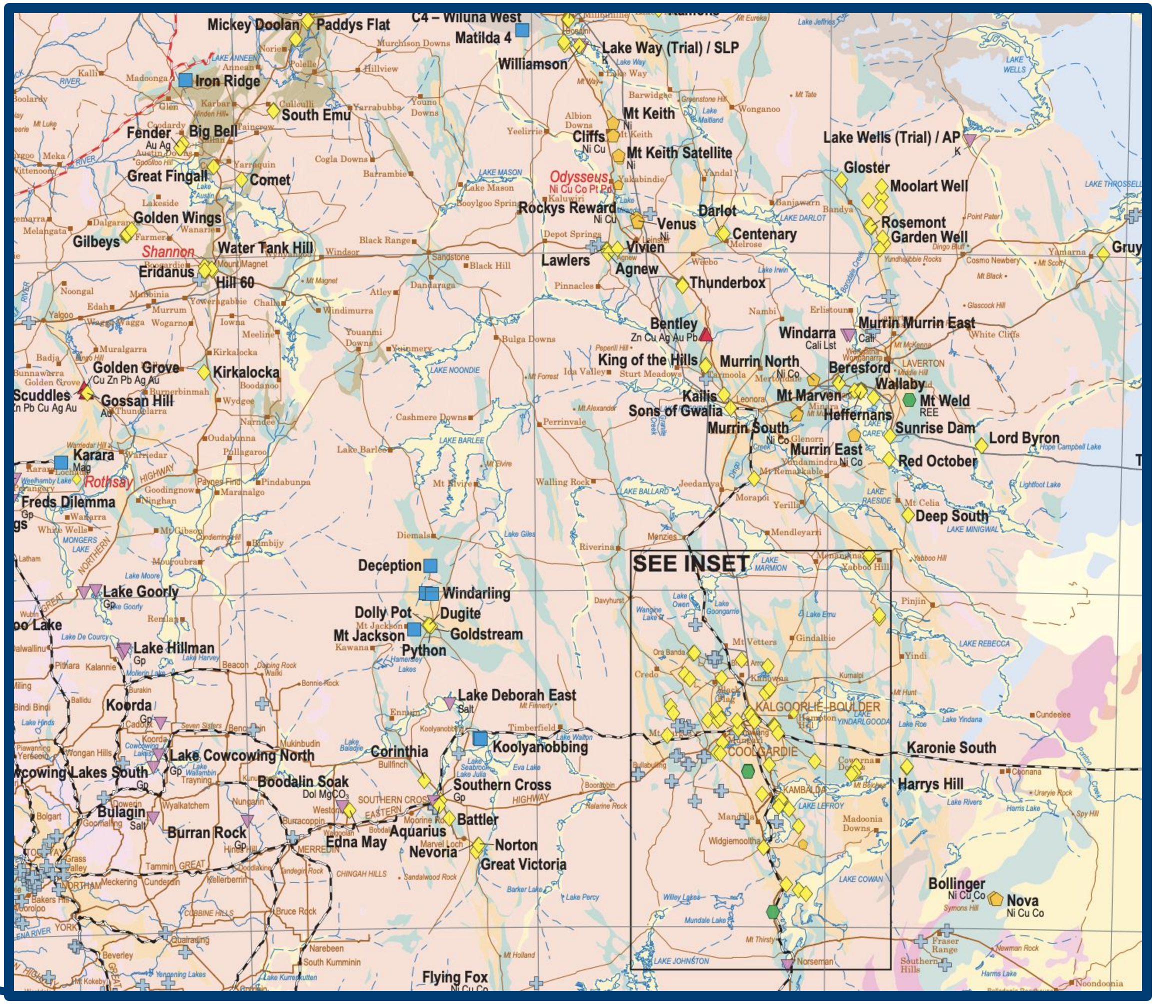
Pilbara Craton of Western Australia



Various Iron ore mine sites



Yilgarn Craton of Western Australia



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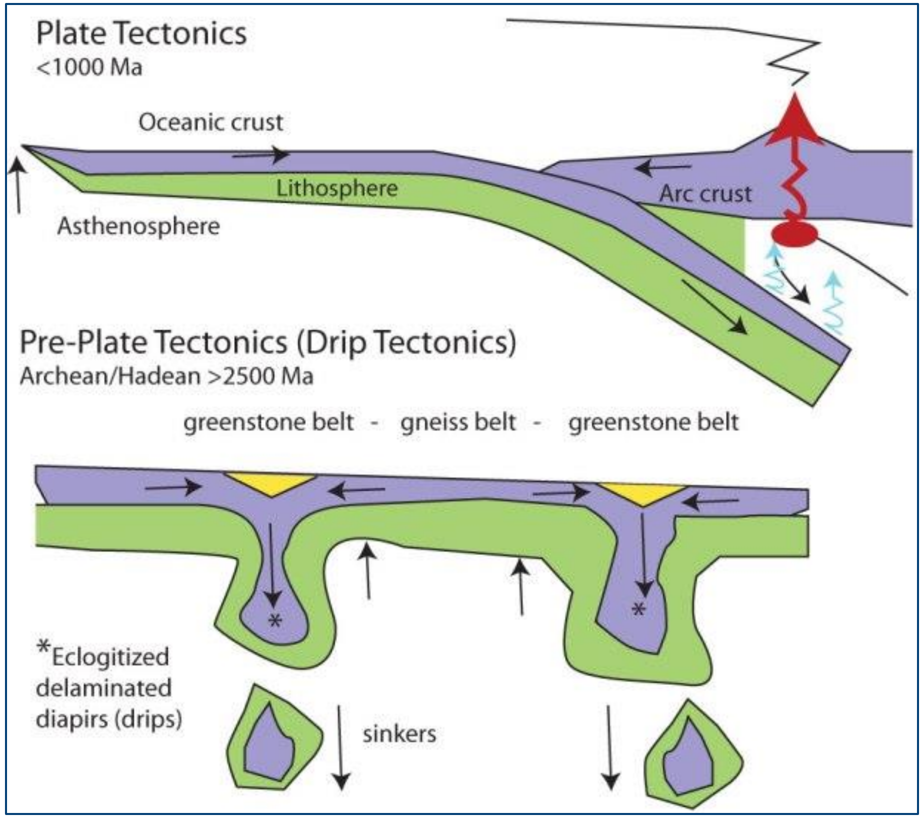

The tectonic mechanisms that operated during the Archean and Proterozoic are widely debated. Research into cratonic lithosphere has helped to fuel discussion on these topics. After Stern (2013).

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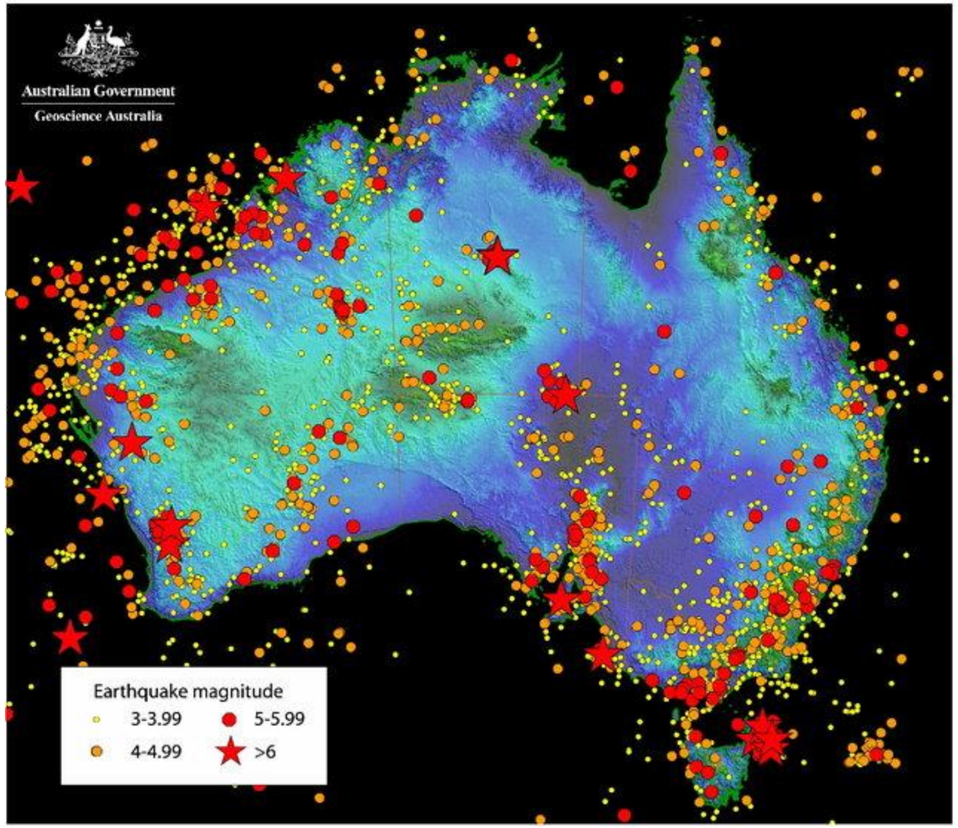

Distribution of Earthquakes throughout Australia. Note that there is very few earthquakes throughout central Western Australia (Yilgarn Craton). This region is a craton and is tectonically stable.

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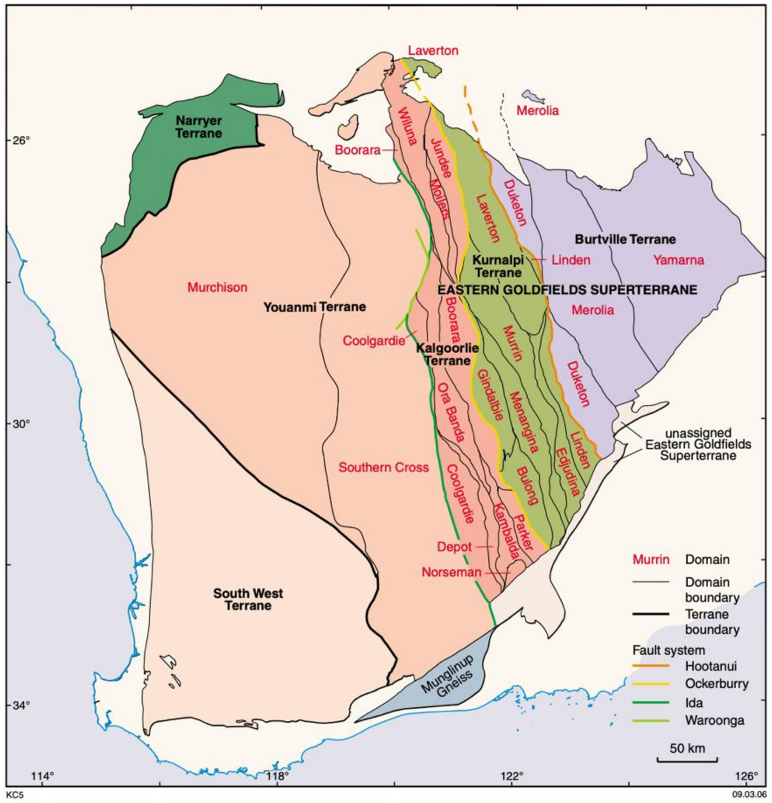

Many cratons are not just simple blocks of lithosphere, but rather several micro-continents or island arcs that were accreted together billions of years ago. The Yilgarn Craton is a classic example of several terranes forming a larger cratonic block.

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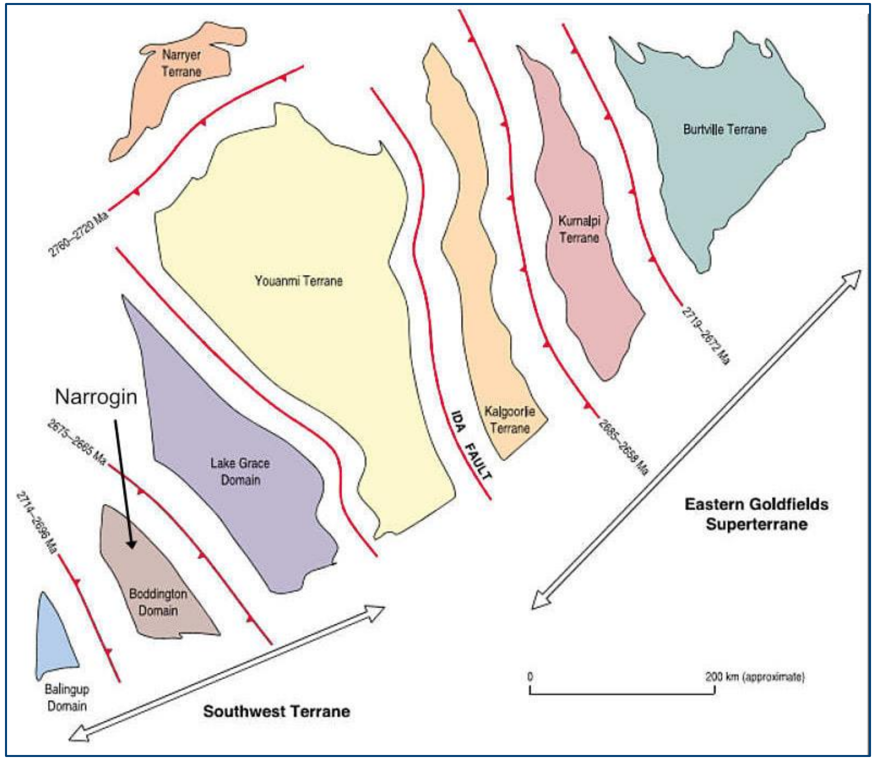

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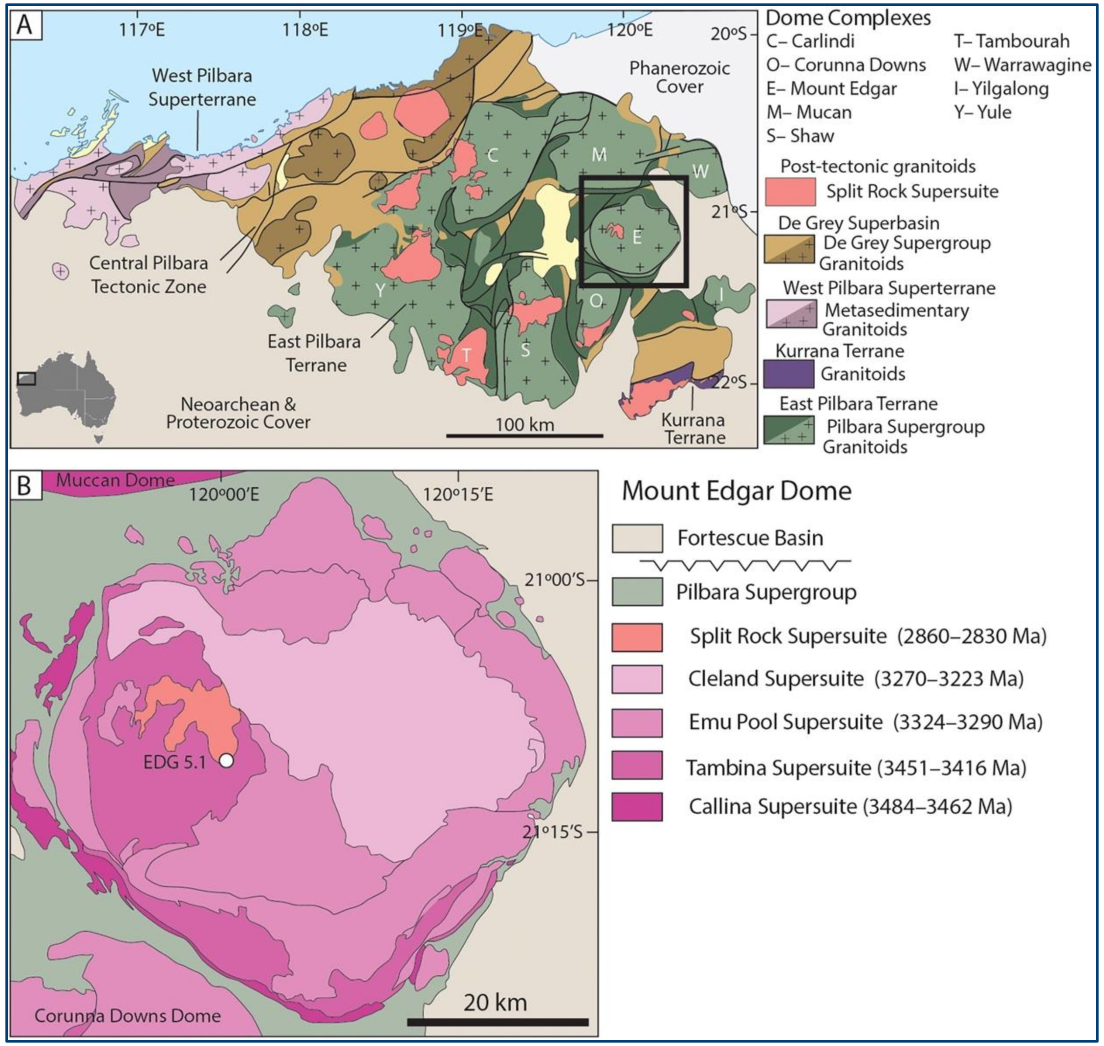

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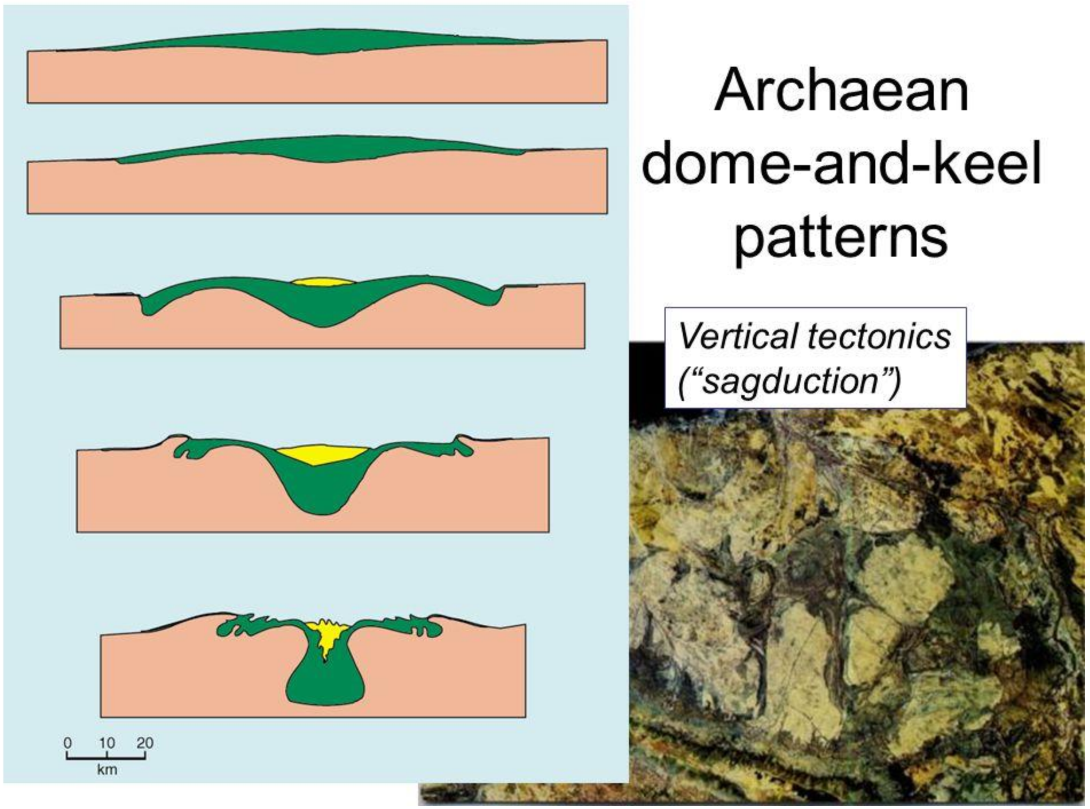


Cratonic Lithospheric Mantle

What are the properties of Cratons?

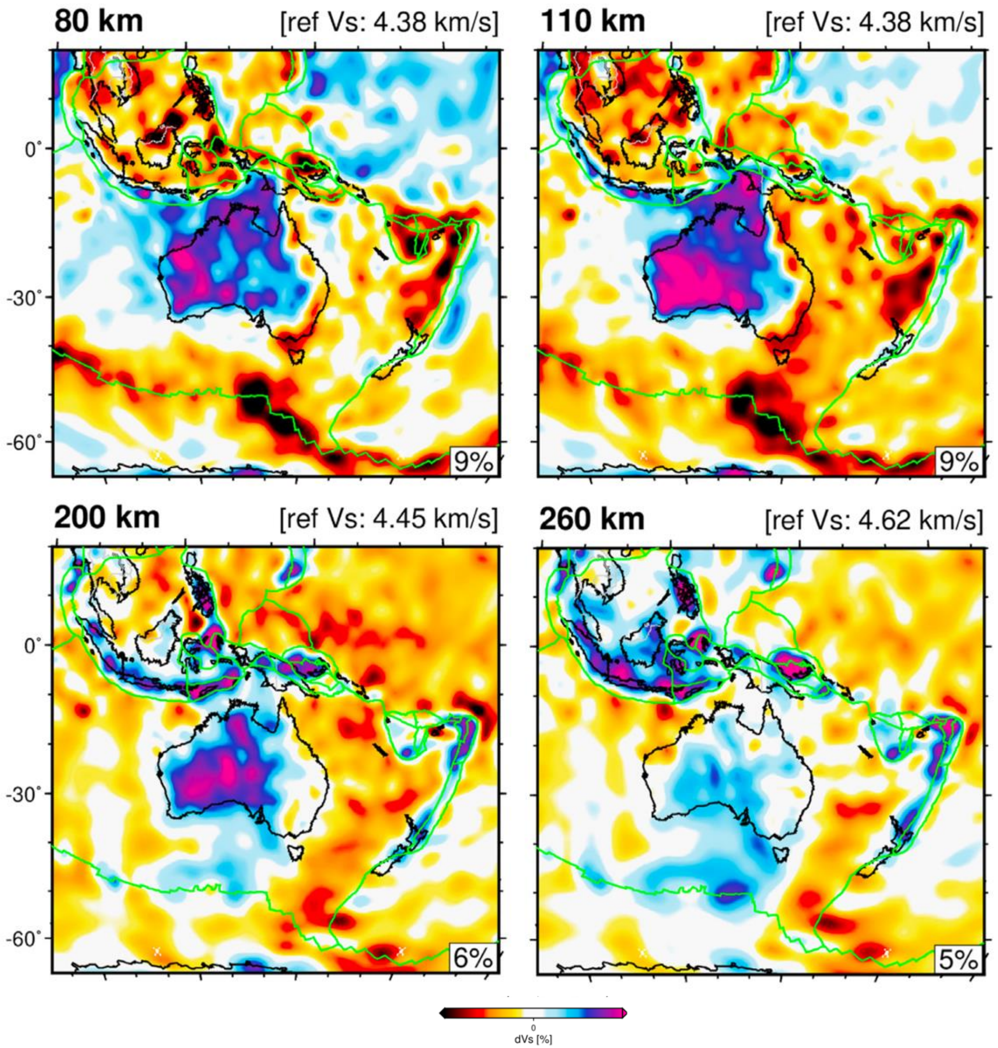
The geophysical properties of cratons are (relatively) well documented:

Surface Waves: Fasters Vs compared to non cratonic regions. Underlain by Lower Vs asthenosphere. Depth of asthenosphere usually >200 km

Receiver Functions: May contain a negative phase at 150–250 km interpreted as base of lithosphere

Surface Heat Flow: Low values (<40 mWm^{-2}) compared to oceans and off-craton continental lithosphere

Anisotropy: Layering in anisotropy with sharp change across the lithosphere-asthenosphere boundary



Depth-slices of the Aus22 S-wave tomography model (de Laat et al. 2023). Note change at 200 to 260 km.

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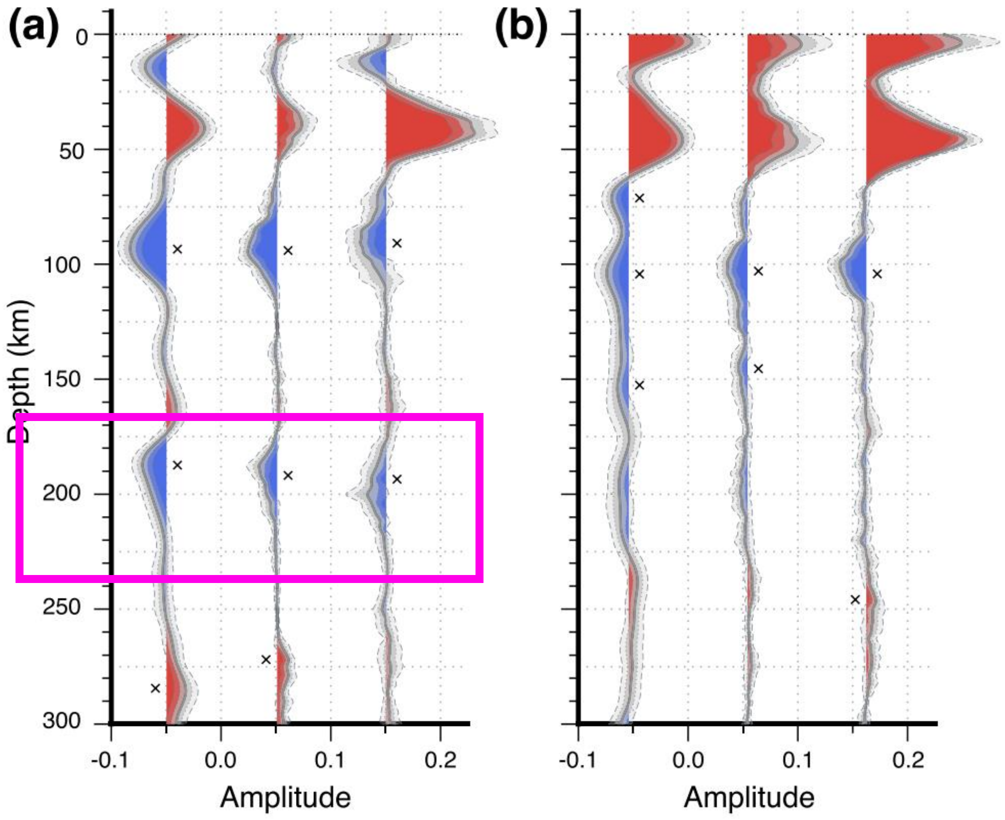

Examples of representative seismic receiver functions taken from Krueger et al. (2021). The negative phase at 200 km may be interpreted as the lithosphere-asthenosphere boundary

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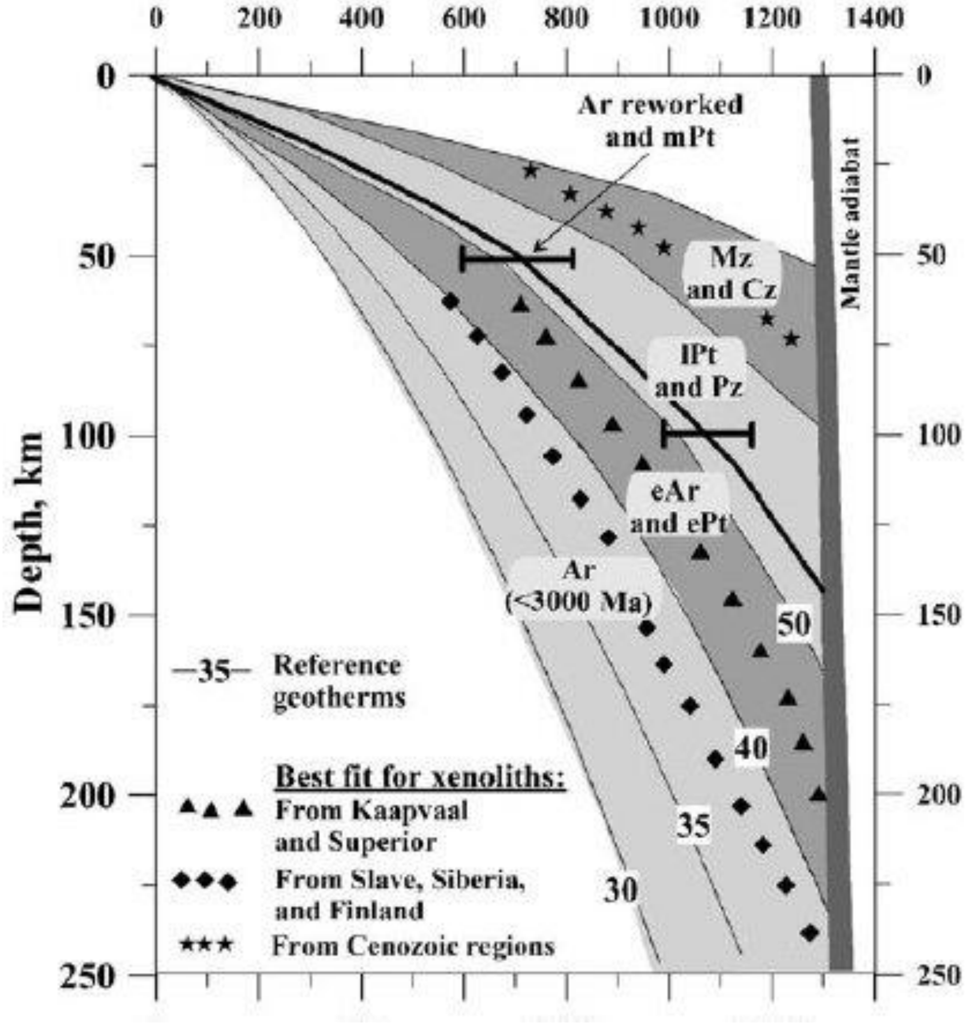

Typical continental geotherms constrained by heat flow data. Cratons typically have values of <40 mWm^{-2}. After Artemieva (2006)

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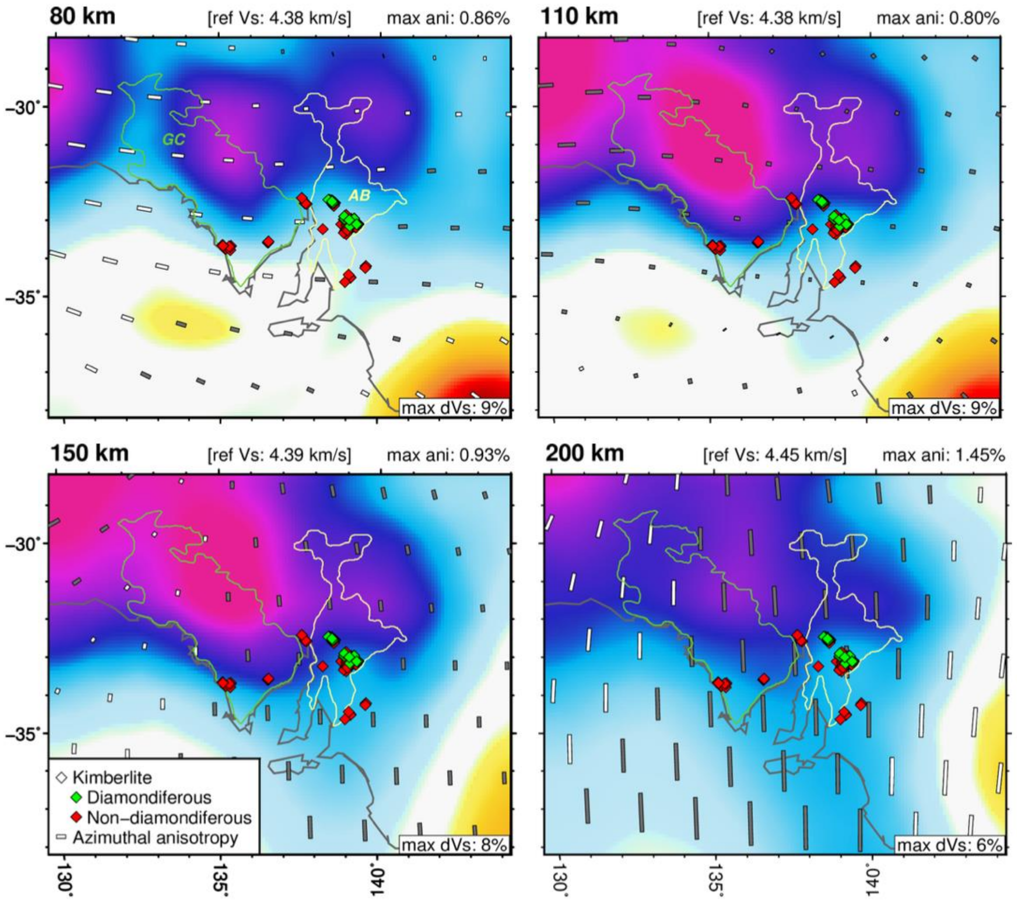
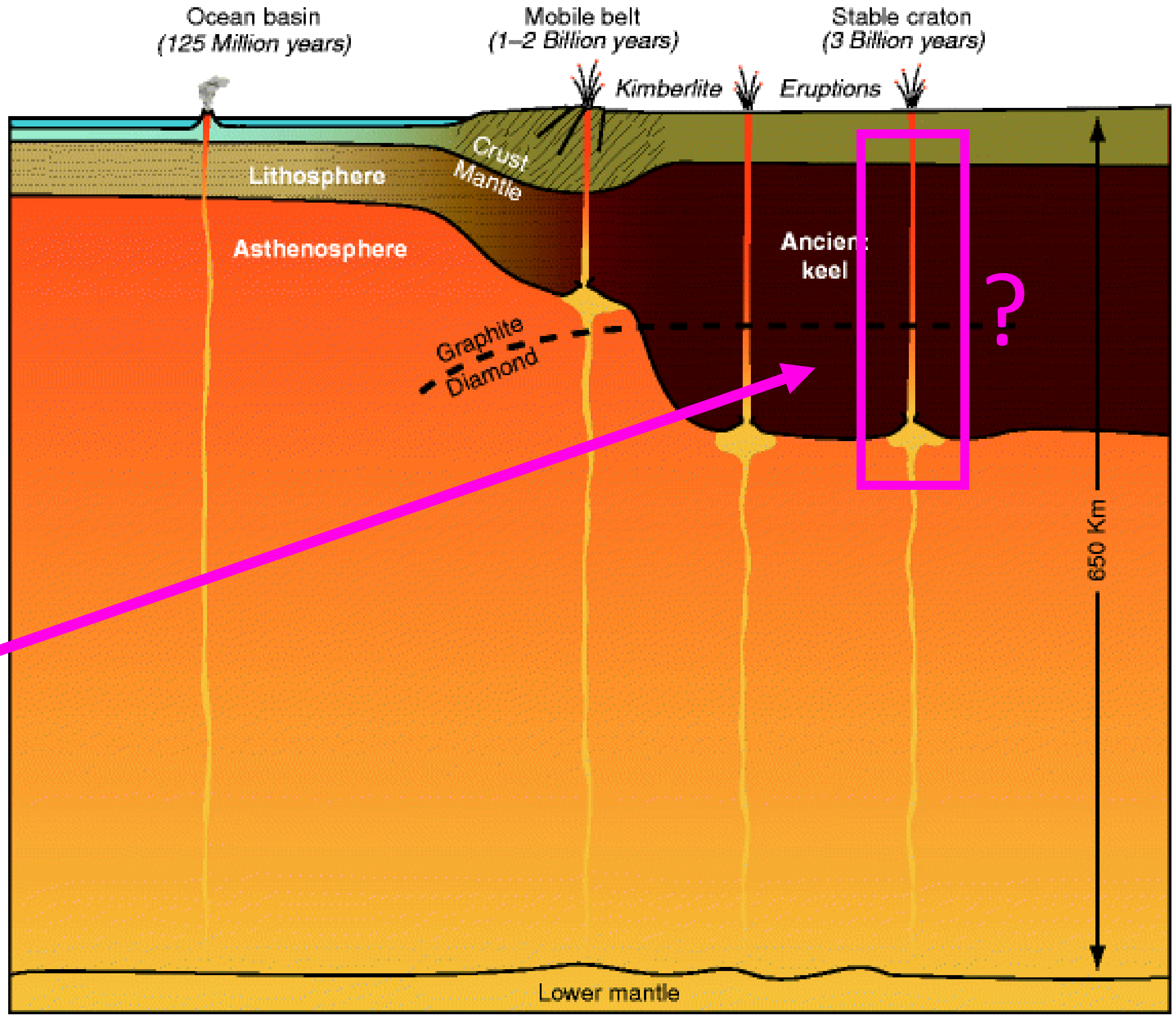


Azimuthal anisotropy around the Gawler Craton (S. Australia) taken from the Aus22 model (de Laat et al. 2023). Note change in azimuthal anisotropy at 150 km (corresponding to base of lithosphere).

Cratonic Lithospheric Mantle

What do rocks and minerals (synthetic and natural) tell us about the properties of the cratonic lithospheric mantle?



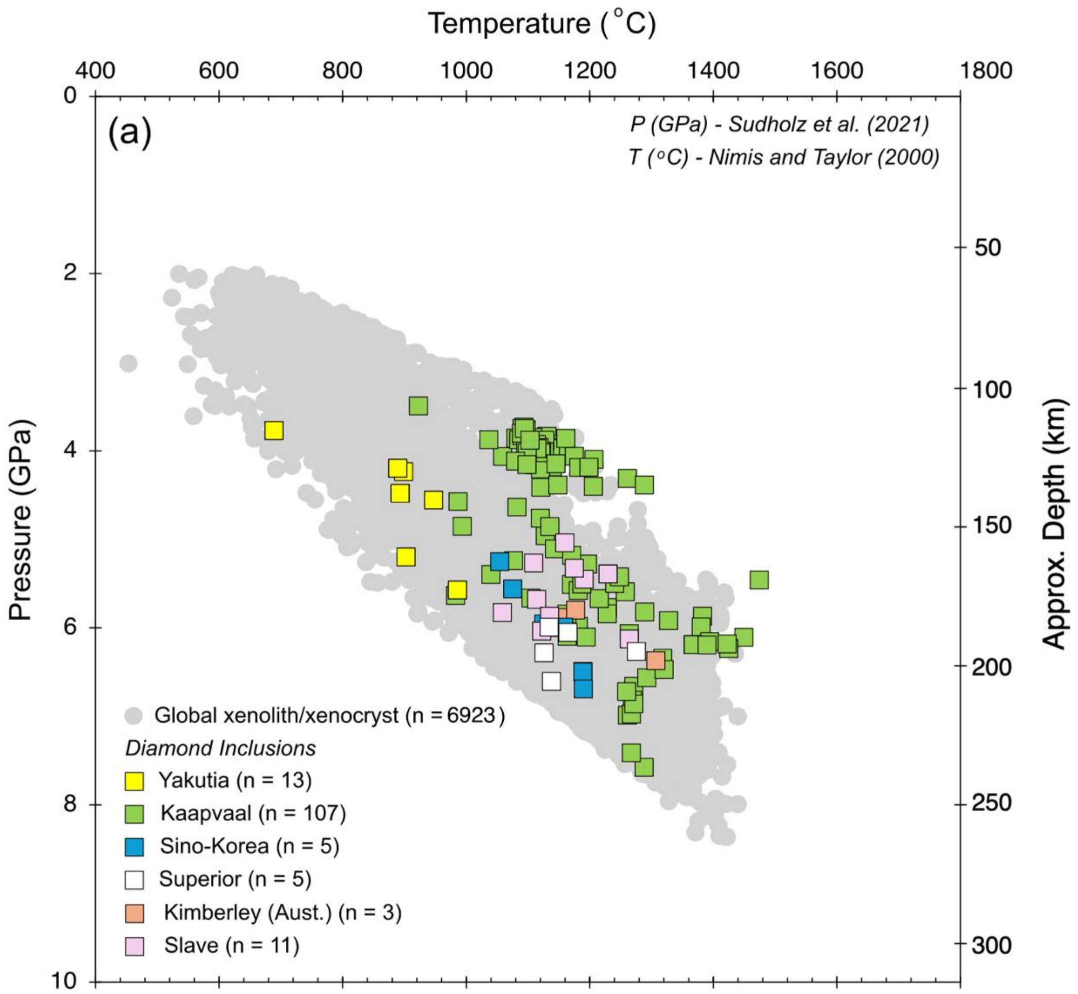
Cratonic Lithospheric Mantle

Petrological constraints on the properties of the cratonic lithosphere are also available:

Geothermobarometry PT estimates on mantle xenoliths/xenocrysts from kimberlites erupted in cratons range between 2–8 GPa and 600–1450 ℃ (50–250 km)

These values are <u>much greater</u> compared to non-cratonic samples (owning to thicker lithosphere for cratons)

Paleogeotherm modelling of PT estimates for individual xenolith/xenocryst suites typically yields lithospheric thickness between 150–250 km (Tp = 1330 ℃)



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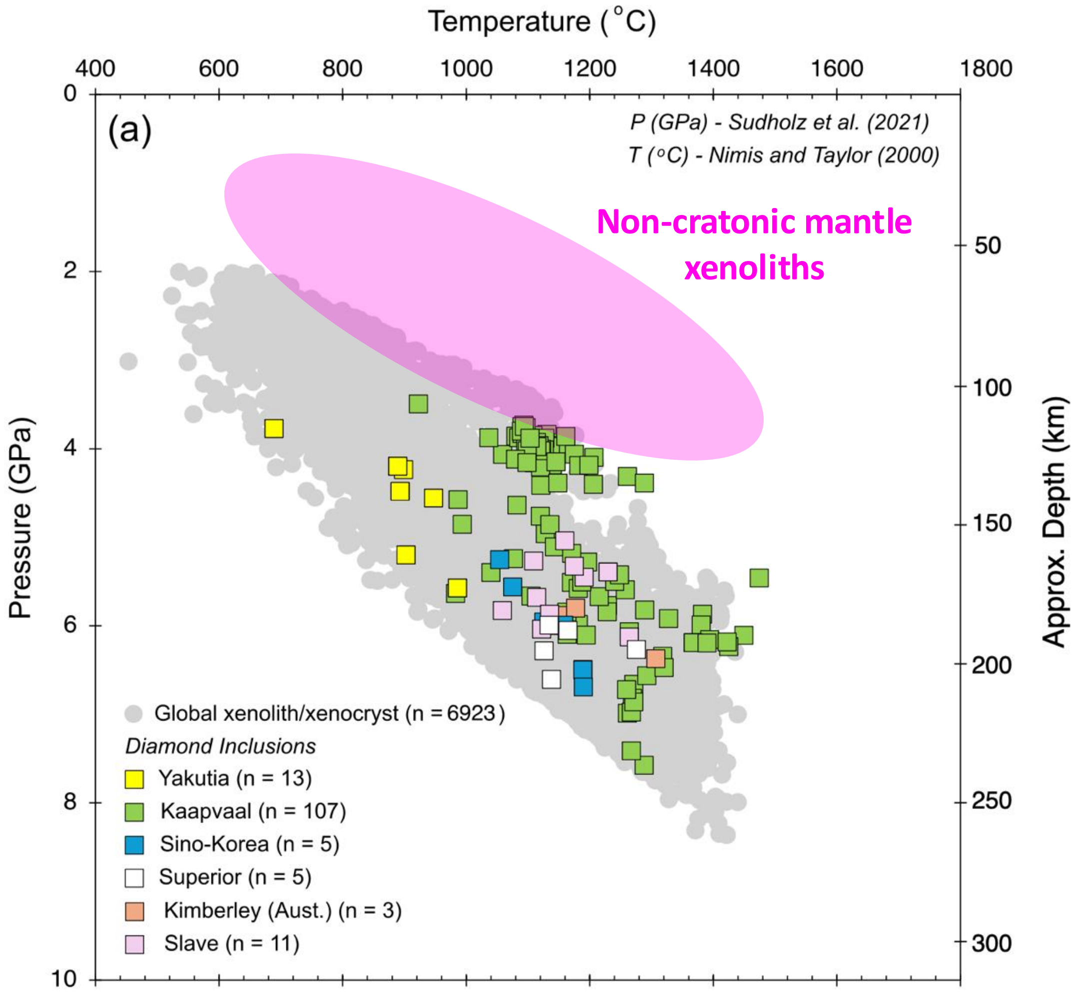

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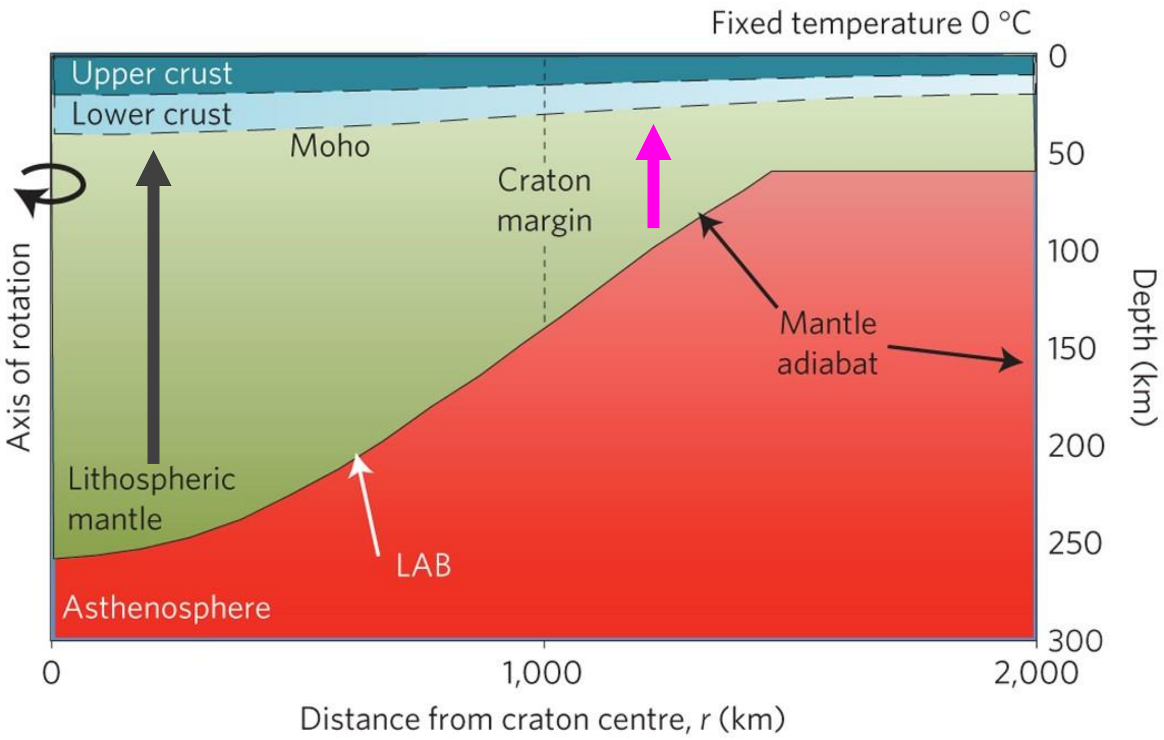
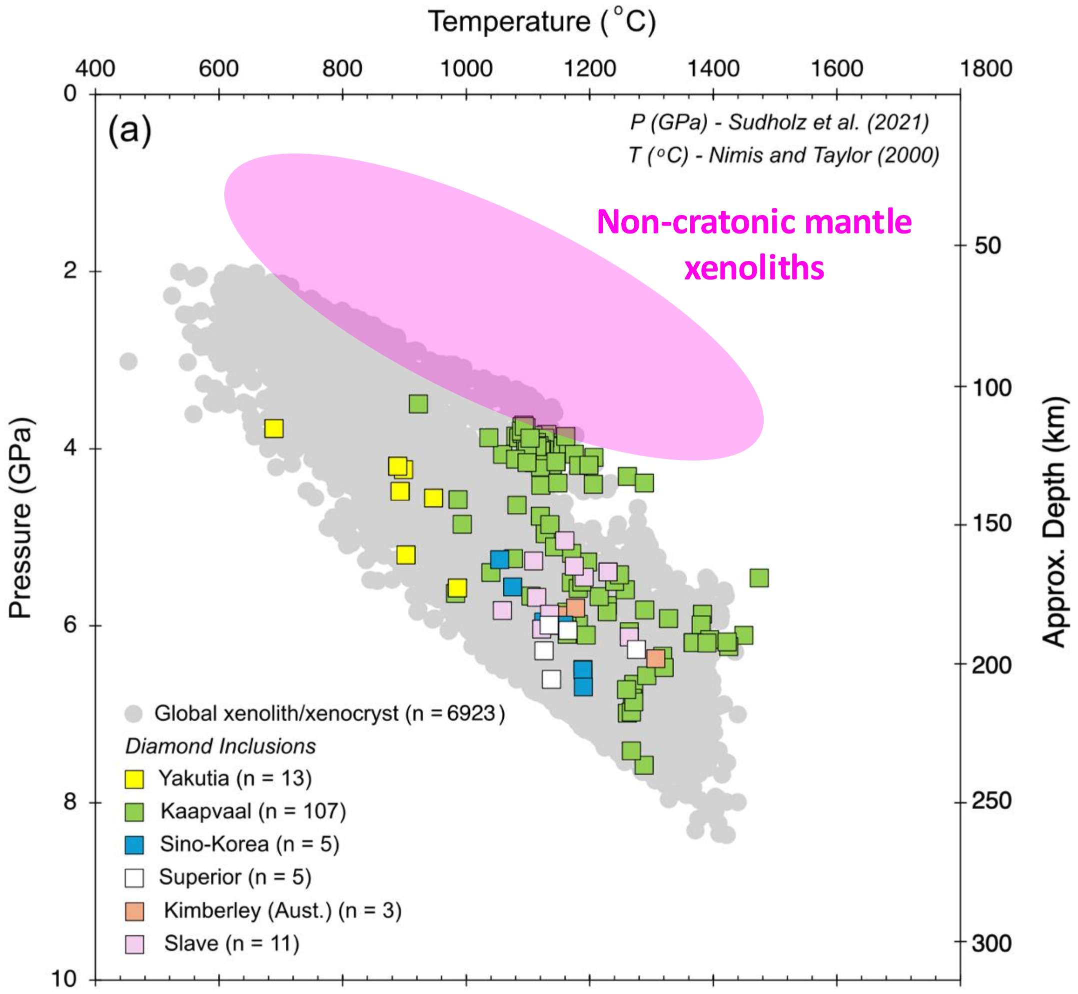


Cartoon of the continental lithospheric mantle. Eaton and Perry (2013)



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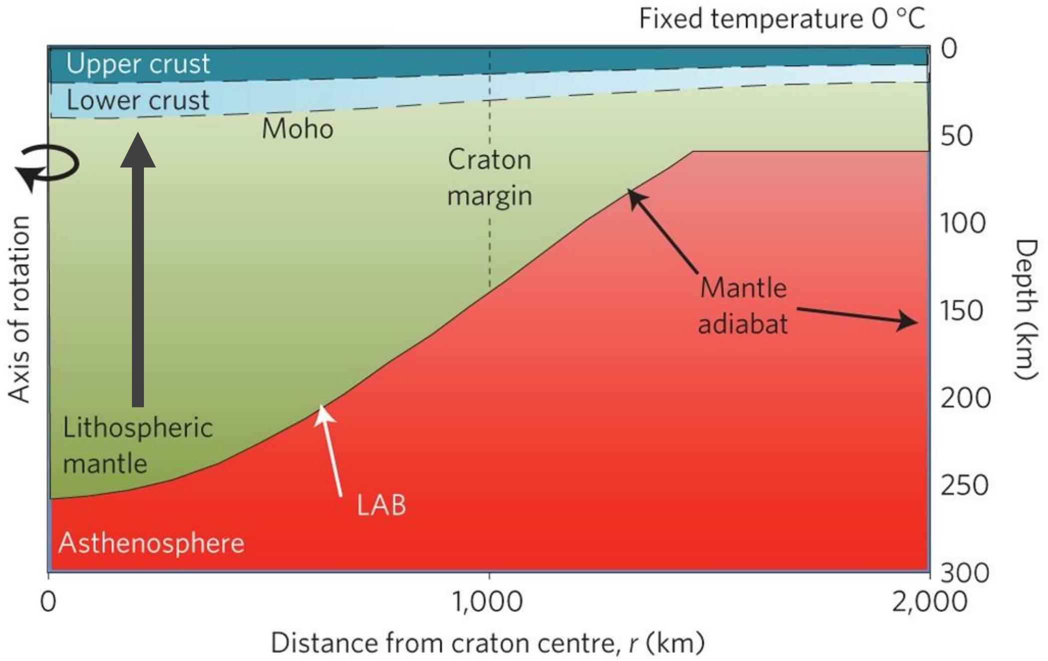

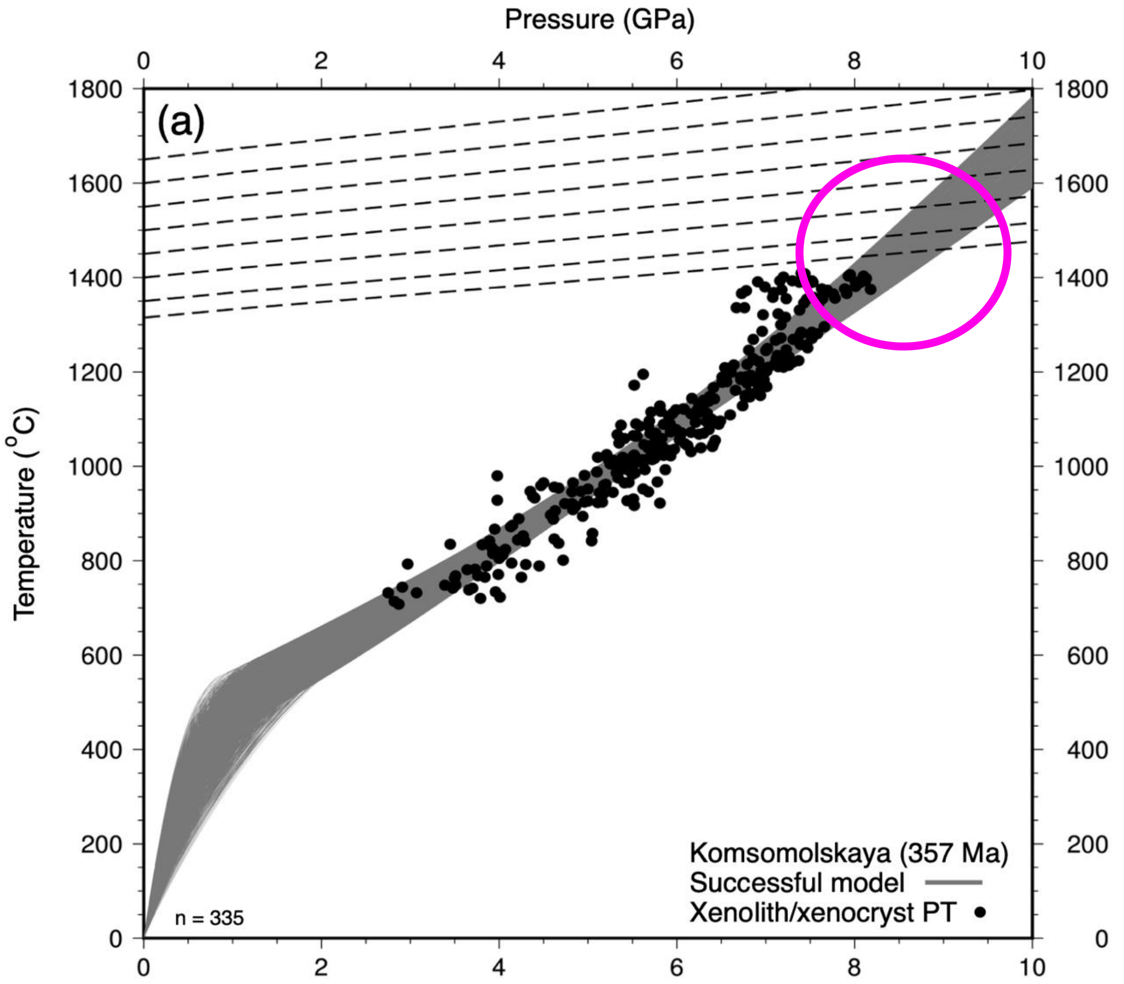

Representative paleogeotherms fit to xenolith/xenocryst PT data from the Komsomolskaya kimberlite. Paleogeotherms intersect the 1330 ℃ adiabat at ~8 GPa.

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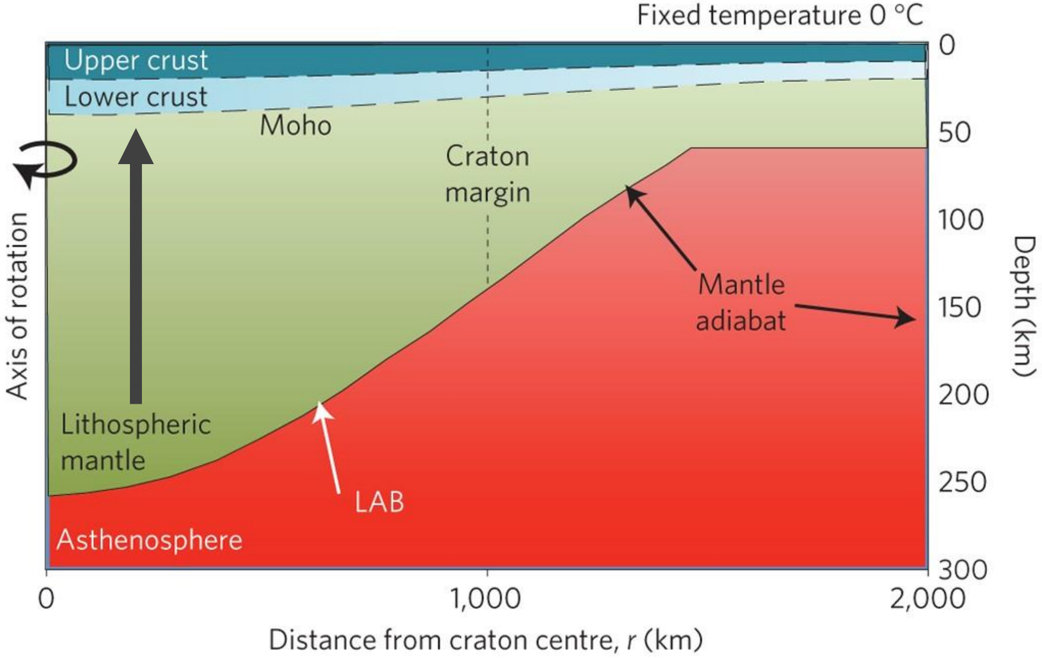

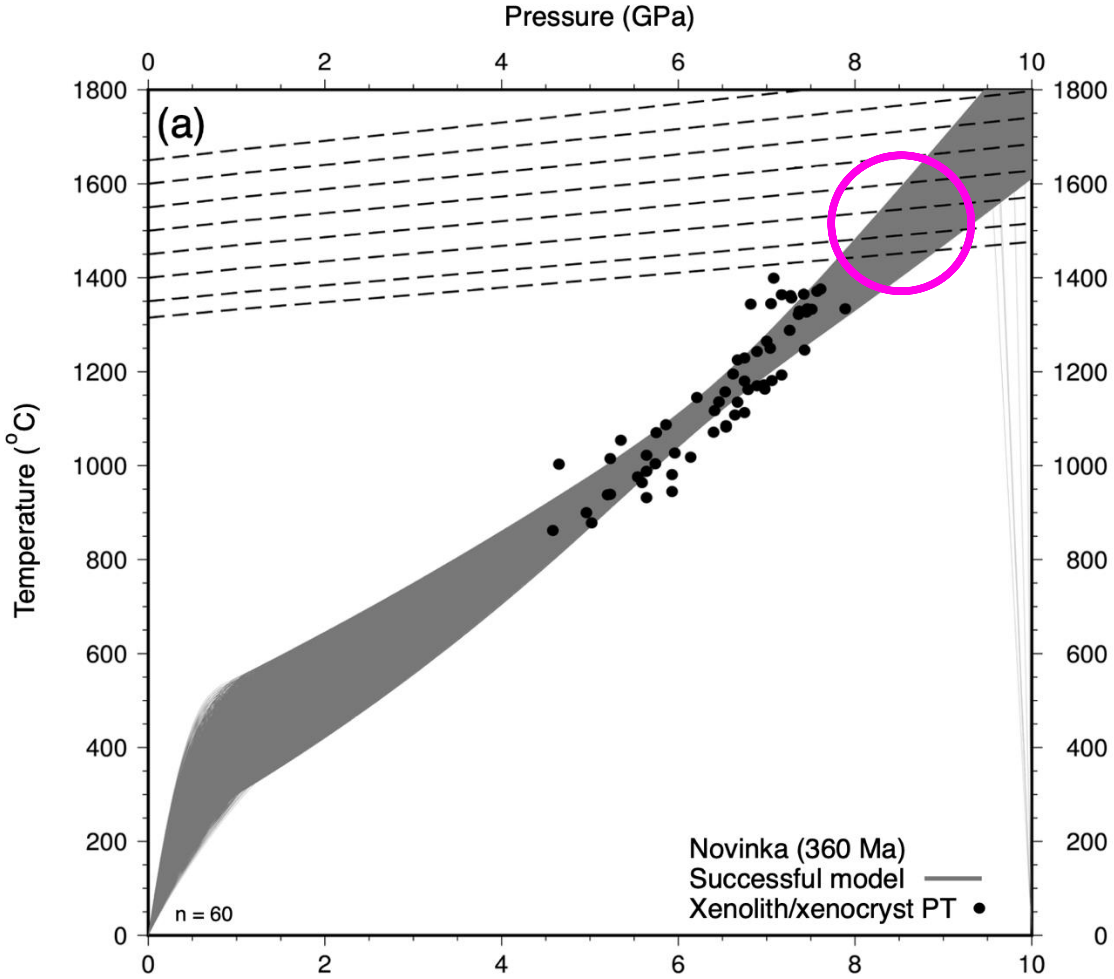

Representative paleogeotherms fit to xenolith/xenocryst PT data from the Novinka kimberlite. Paleogeotherms intersect the 1330 ℃ adiabat at ~8 GPa.

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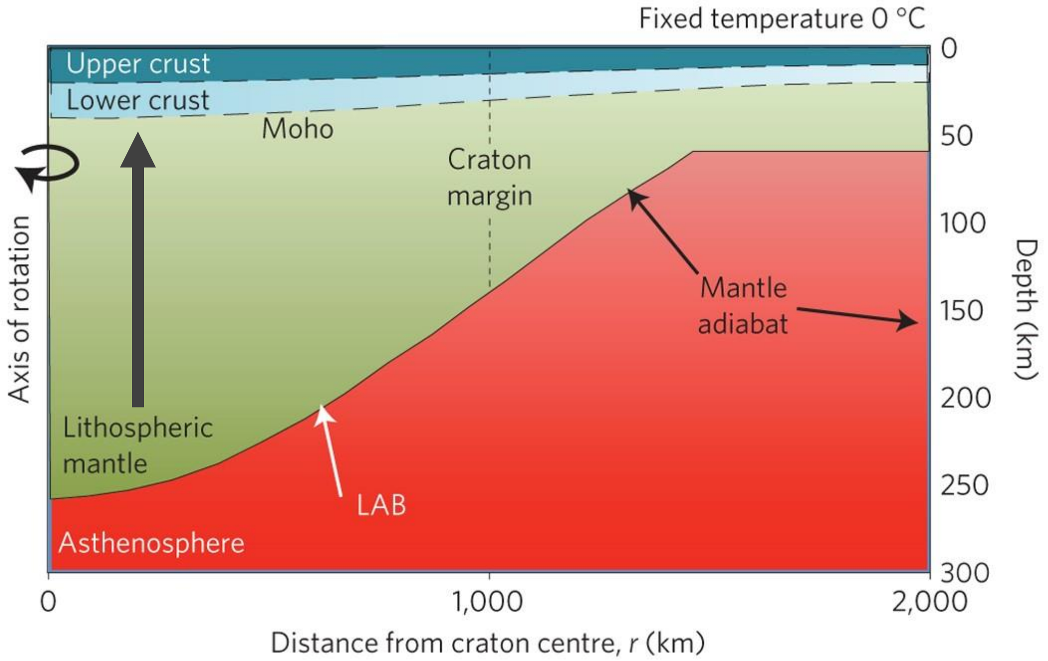

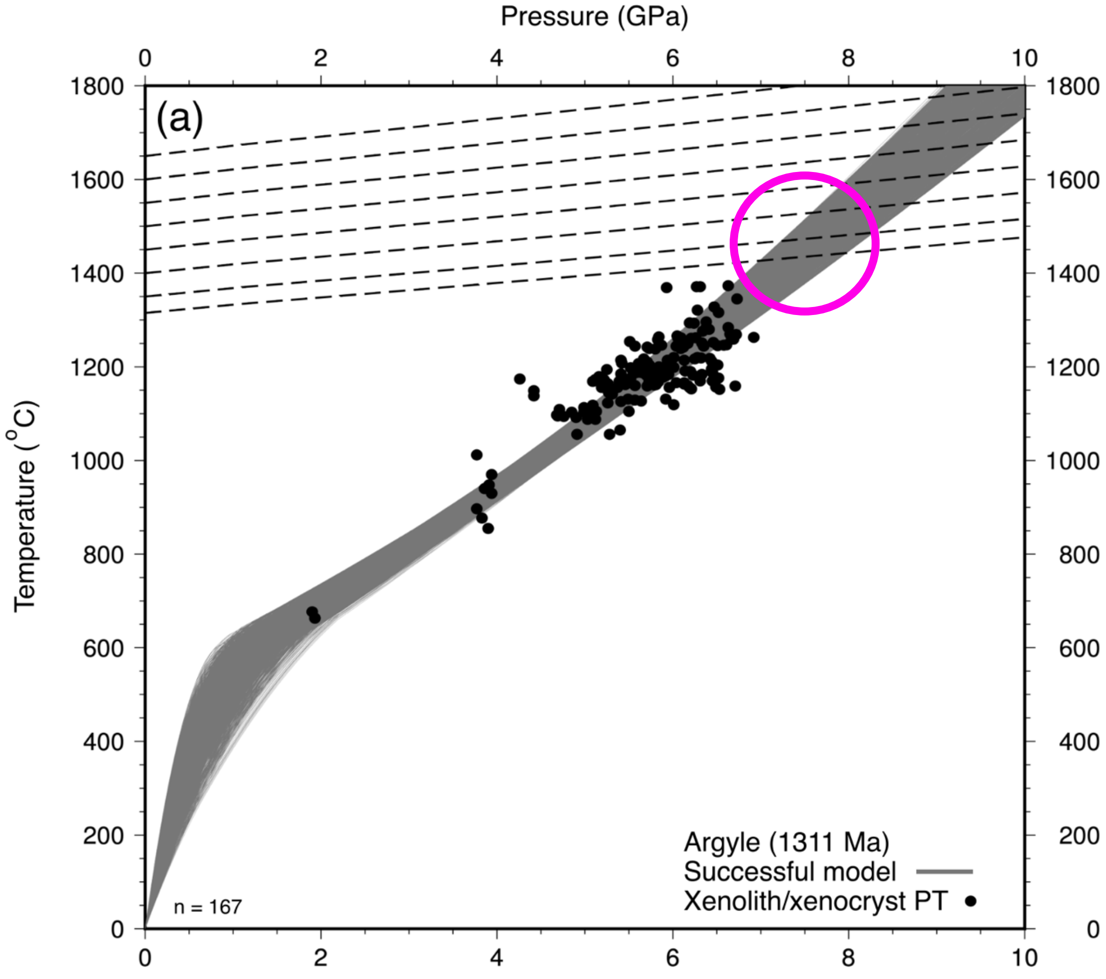

Representative paleogeotherms fit to xenolith/xenocryst PT data from the Argyle lamproite. Paleogeotherms intersect the 1330 ℃ adiabat at ~7.5 GPa.

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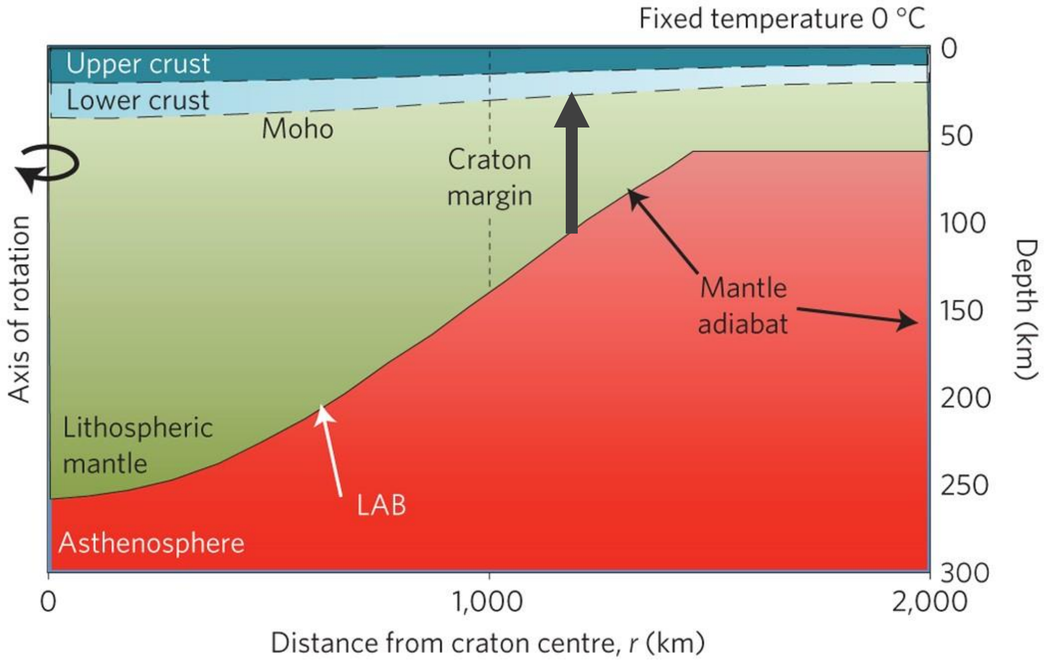
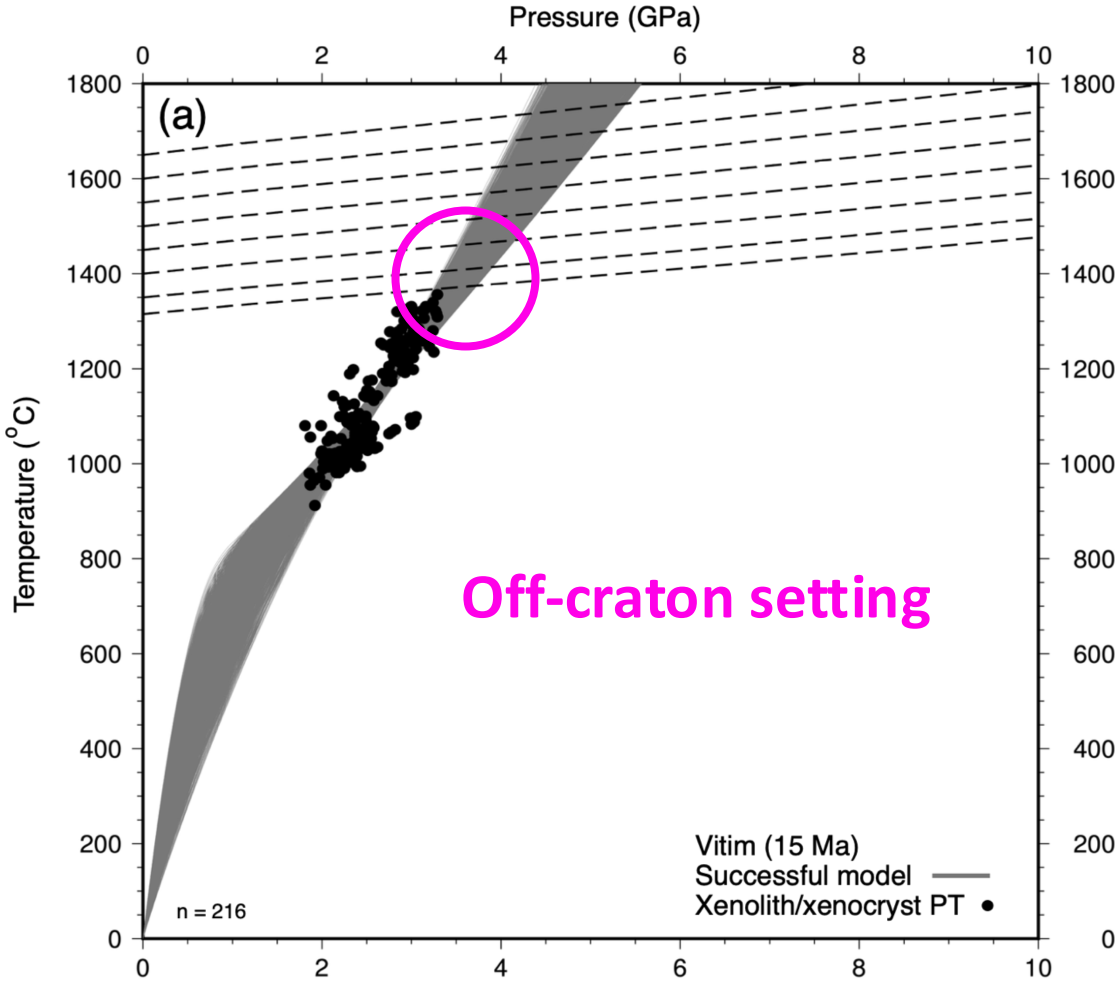




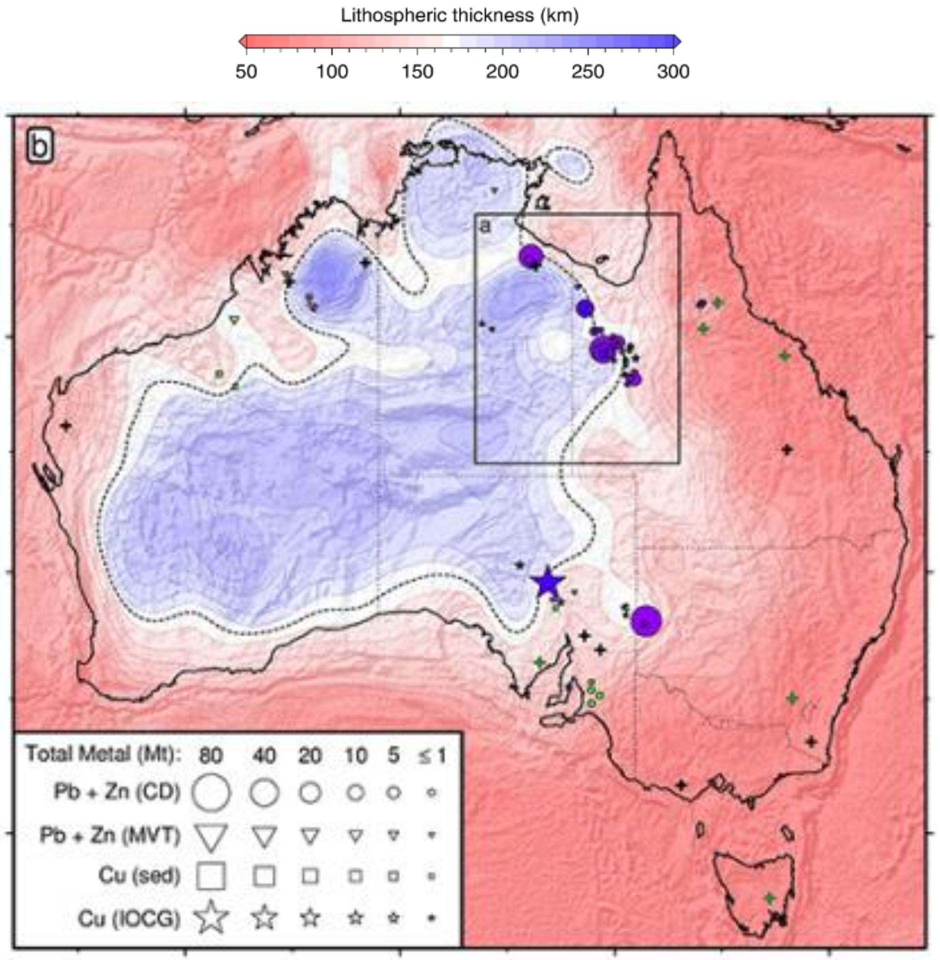
Representative paleogeotherms fit to xenolith/xenocryst PT data from the Vitim basalt. Paleogeotherms intersect the 1330 °C adiabat at ~3.5 GPa.

Cratonic Lithospheric Mantle

Petrological constraints on the properties of the cratonic lithosphere are also available:

Petrological (paleogeotherms) and seismological estimates for lithospheric thickness of cratons yields similar results (150–250 km) for the same location

Because petrological estimates of cratonic lithosphere thickness are for the time of eruption – the similarity between both methods suggests that there has been negligible change in the lithospheric thicknesses of cratons over the interval which we have available xenolith/xenocryst data



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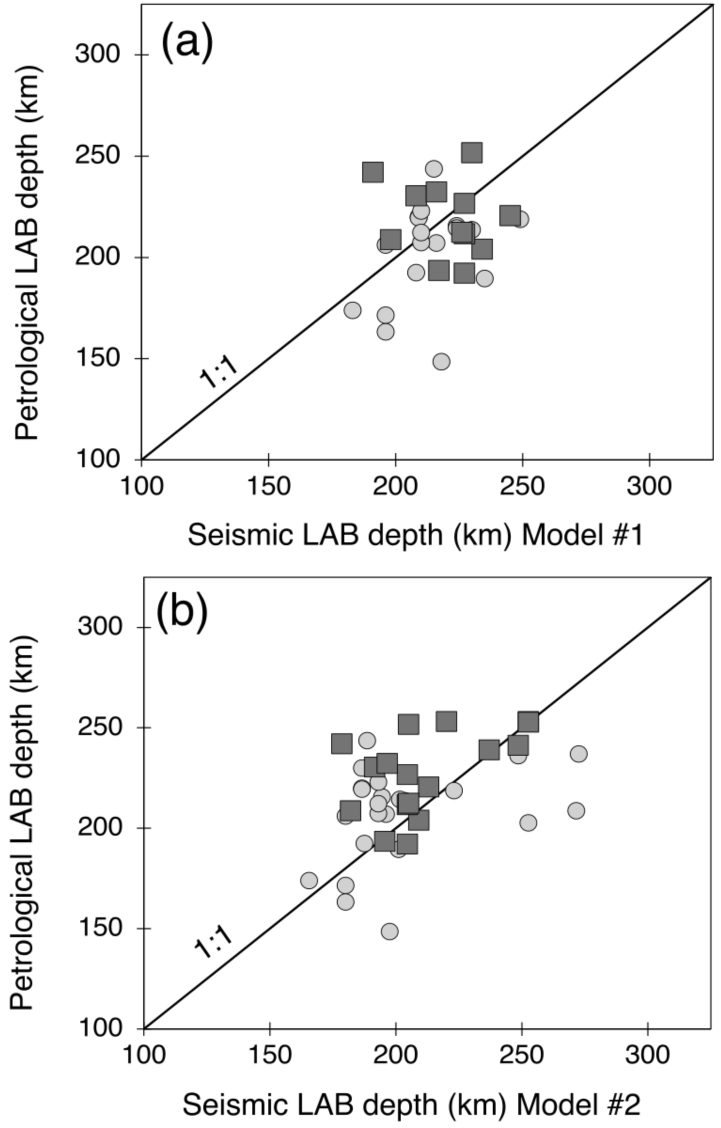

Cratonic Lithospheric Mantle

The rocks that make up cratonic lithosphere have different modal mineralogies compared to non-cratonic regions. These contribute to the physical properties of cratons:

Mantle xenoliths from cratons have higher olivine (olv) and lower clinopyroxene (cpx)

The lower modal clinopyroxene in cratonic peridotites requires very high temperatures and large amounts of melt extraction. These processes closely link to craton formation (coming soon!)

The cpx-free rock is essentially a melt-depleted peridotite residue (left-over rock after melt was extracted)

Modal abundances of mantle minerals in cratonic and non-cratonic settings

Table 3 Mean and median modal mineralogy of xenoliths

	ol	*opx*	*cpx*	*sp*	*gt*
Off-craton	($n = 98$)				
Average	63.7	21.5	11.7	1.8	9.6
Median	62.9	21.8	12.9	1.7	11.4
1σ	8.4	6.6	5.2	0.8	6.1
On-craton	($n = 210$)				
Average	71.9	20.8	3.3	1.1	6.2
Median	72.0	20.6	2.0	0.8	5.3
1σ	11.6	10.3	4.5	1.0	3.8

Table of the representative modal mineralogy (%) of mantle xenoliths from cratonic and non-cratonic settings. After Pearson et al. (2003). Note the lower amounts of of clinopyroxene (cpx) in mantle xenoliths from cratons.

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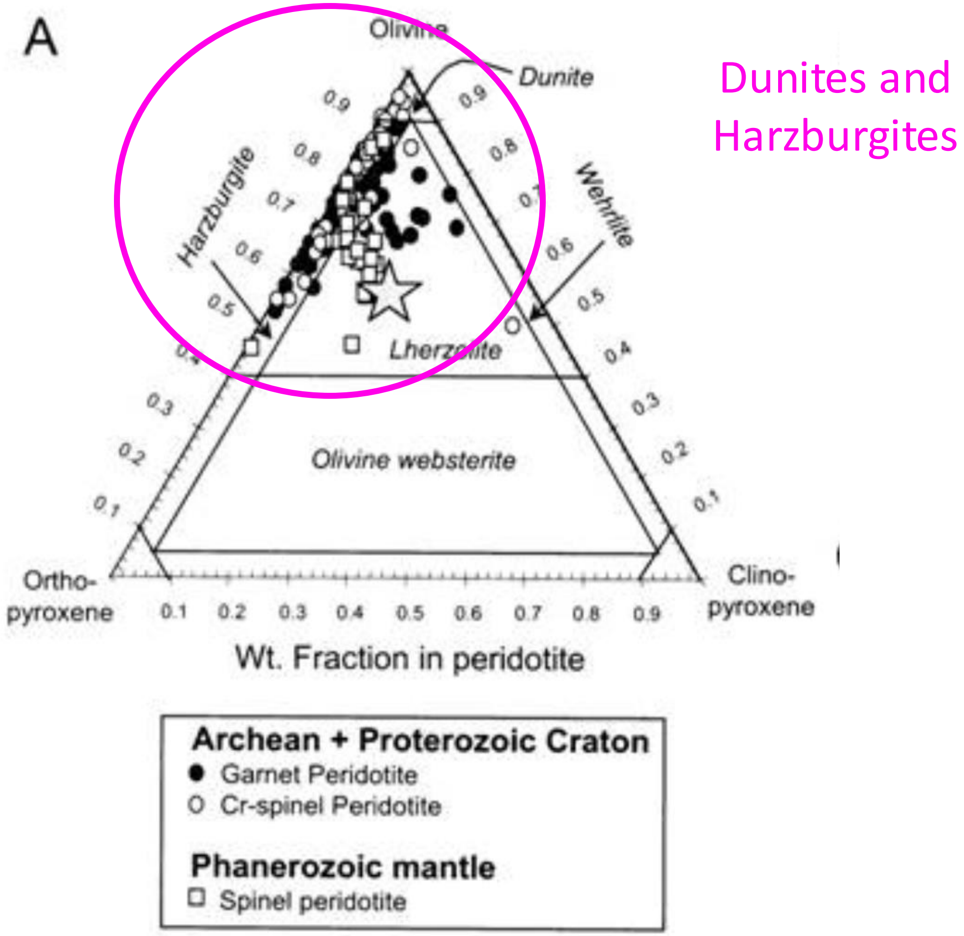

Ternary diagram of the typical modal mineralogy of peridotites from cratonic and non-cratonic peridotite xenoliths. Note that cratonic xenoliths are commonly harzburgites and dunites. After Lee (2006).

Re-cap from first lecture:

What is the significance dunite and harzburgite?

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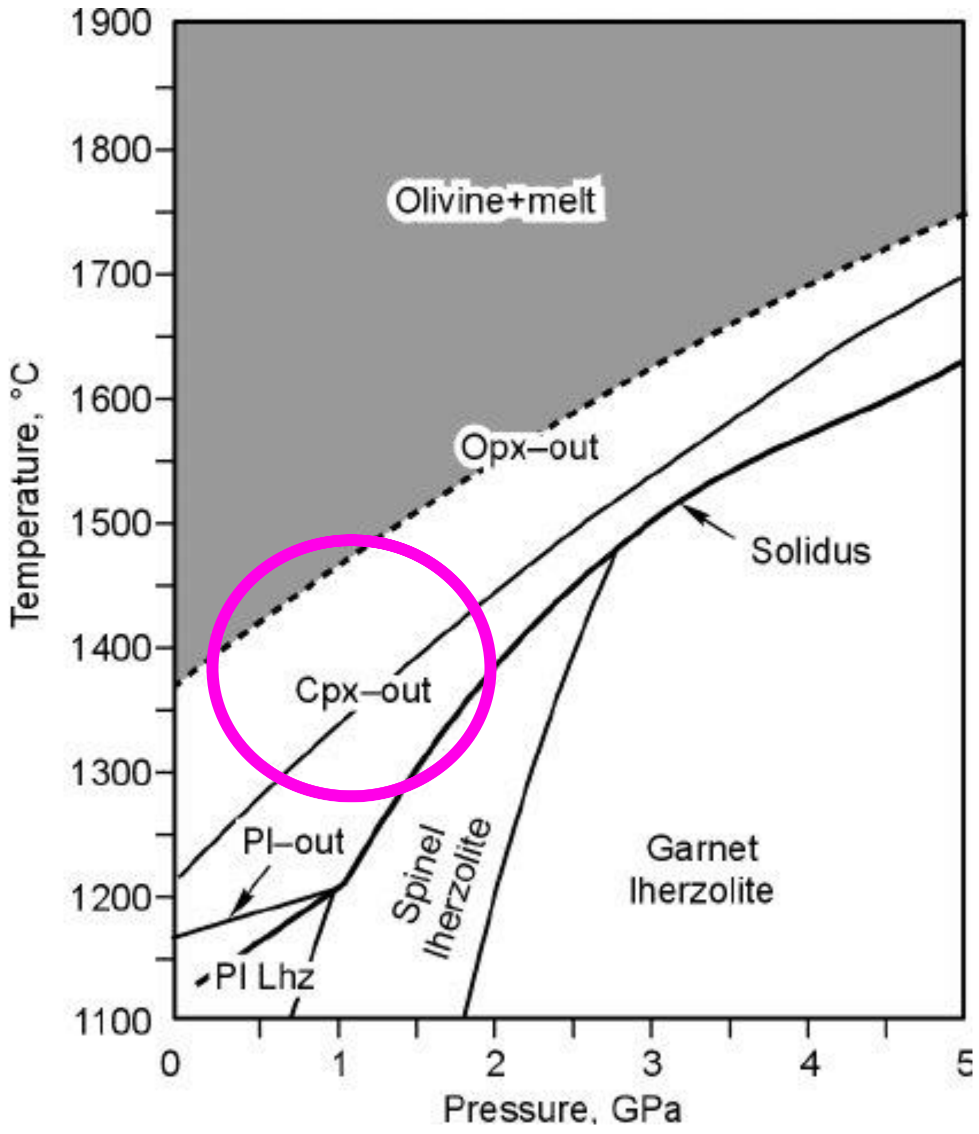
The rocks that make up cratonic lithosphere have different modal mineralogies compared to non-cratonic regions. These contribute to the physical properties of cratons:

Mantle xenoliths from cratons have higher olivine (olv) and lower clinopyroxene (cpx)

The lower modal clinopyroxene in cratonic peridotites requires very high temperatures and large amounts of melt extraction. These processes closely link to craton formation

The cpx-free rocks that make up the cratons are essentially melt-depleted peridotite residue (left-over rock after melt was extracted)

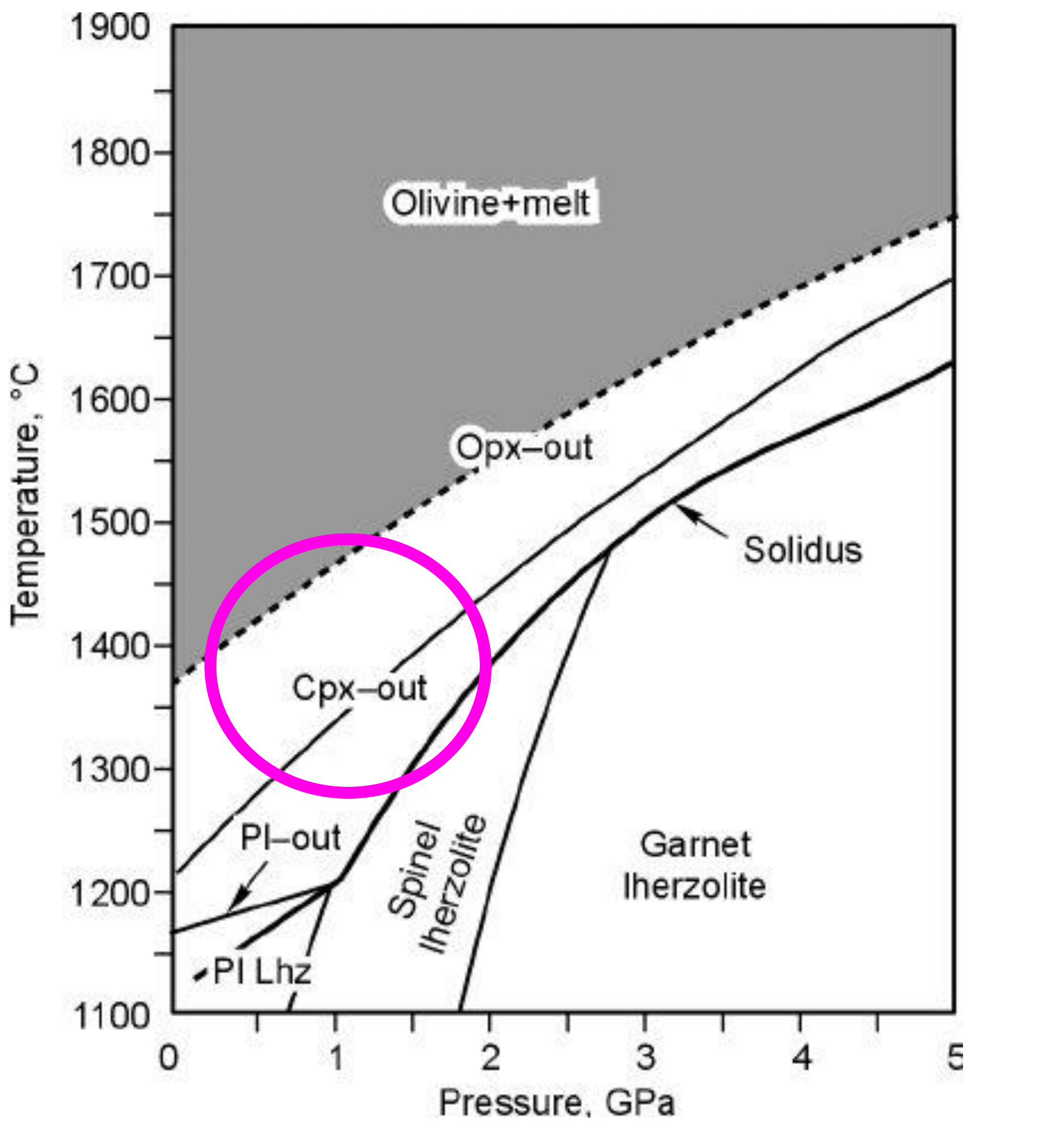


Cratonic Lithospheric Mantle

The lower modal clinopyroxene in cratonic peridotites requires very high temperatures and large amounts of melt extraction. These processes closely link to craton formation

The presence of harzburgite (cpx-free lherzolite) is uncommon in most other mantle settings outside of cratons because they did not reach the conditions for cpx to breakdown and melt

Most off-craton rocks are either spinel lherzolites and/or garnet lherzolites. These rocks have higher densities than harzburgites. This greatly influences the physical properties of the lithospheric mantle and its capacity to act as a buoyant keel that resists further melting and deformation

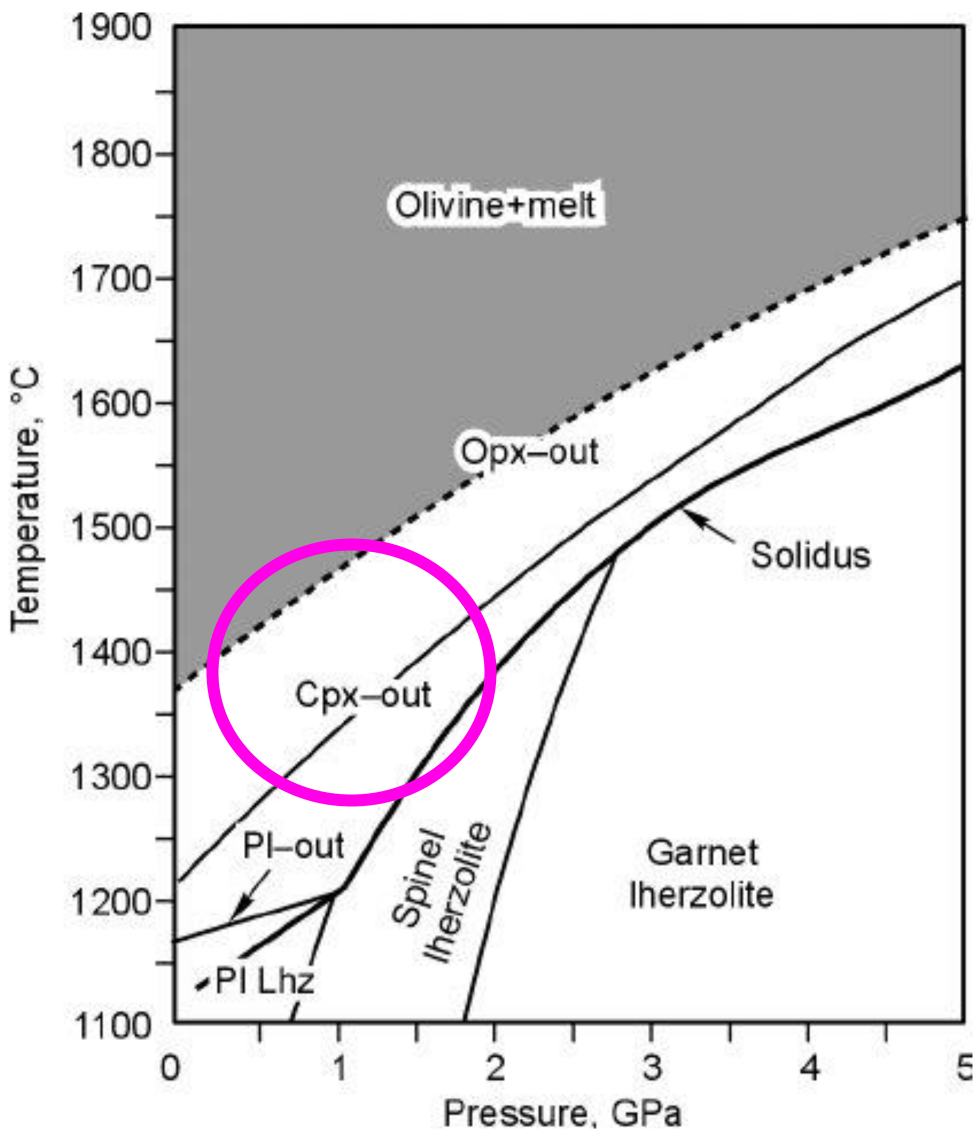


Cratonic Lithospheric Mantle

We will discuss the geodynamic mechanisms for reaching such high temperatures and pressures later in the lecture (i.e., mantle plume);

The series of events for forming the cpx-free rocks (harzburgites and dunites) in cratons was likely as follows:

- The shallow lithospheric mantle was exposed to very high temperatures
- The temperature exceeded the cpx-out reaction resulting in cpx melting
- The melt segregated and ascended to the surface and left behind a melt-depleted residue with slightly higher volume



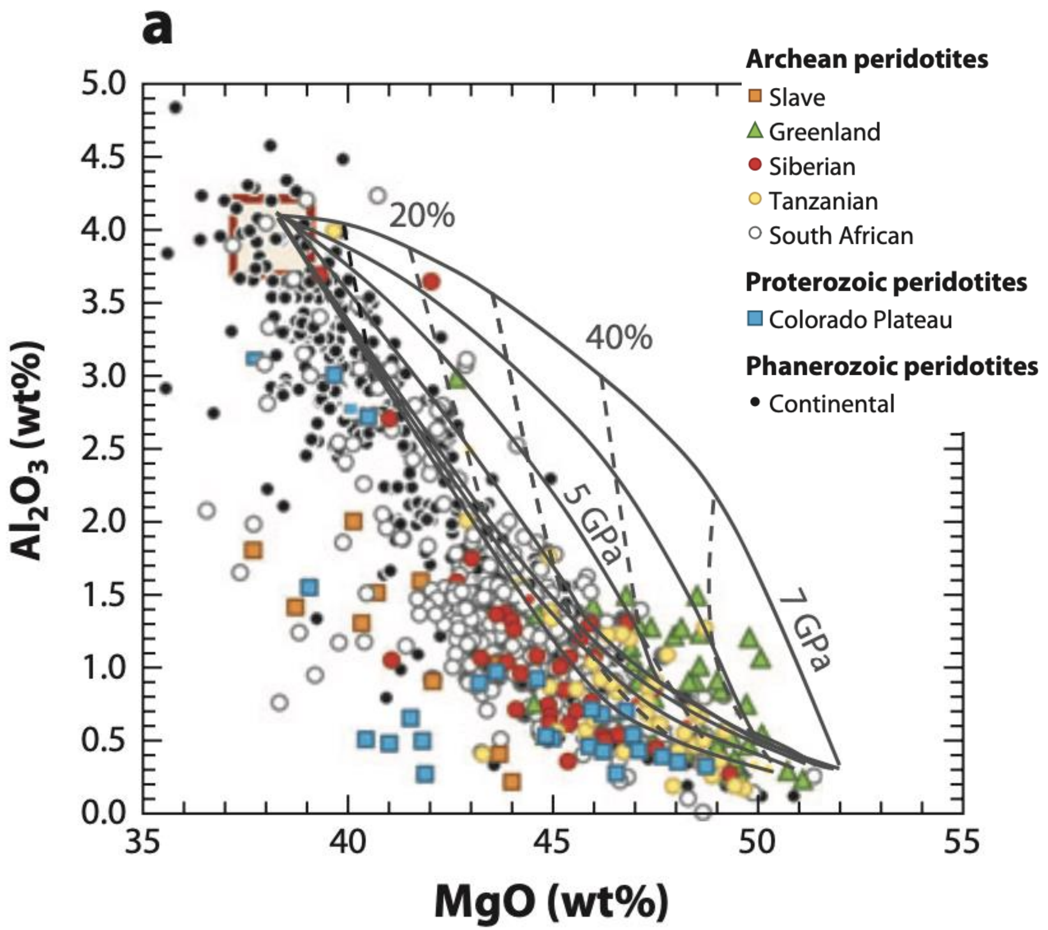
Cratonic Lithospheric Mantle

Peridotites from the cratonic lithospheric mantle also have different chemical compositions compared to non-cratonic varieties. **The different compositions are also related to melt extraction at high temperatures**

Peridotites from cratonic lithospheric mantle have **higher MgO and lower Al_2O_3 and FeO** compared with most other settings due to the extraction

The removal of FeO from peridotite is also due to melt extraction at high temperature. The FeO (and other elements) enter the melt and leave behind a 'melt-depleted' peridotite residue. **The residue has much lower density.**

Covariation in whole-rock concentration of Al2O3 and MgO (wt%) for peridotite mantle xenoliths from different settings (cratonic settings in colour). After Lee et al. (2011)



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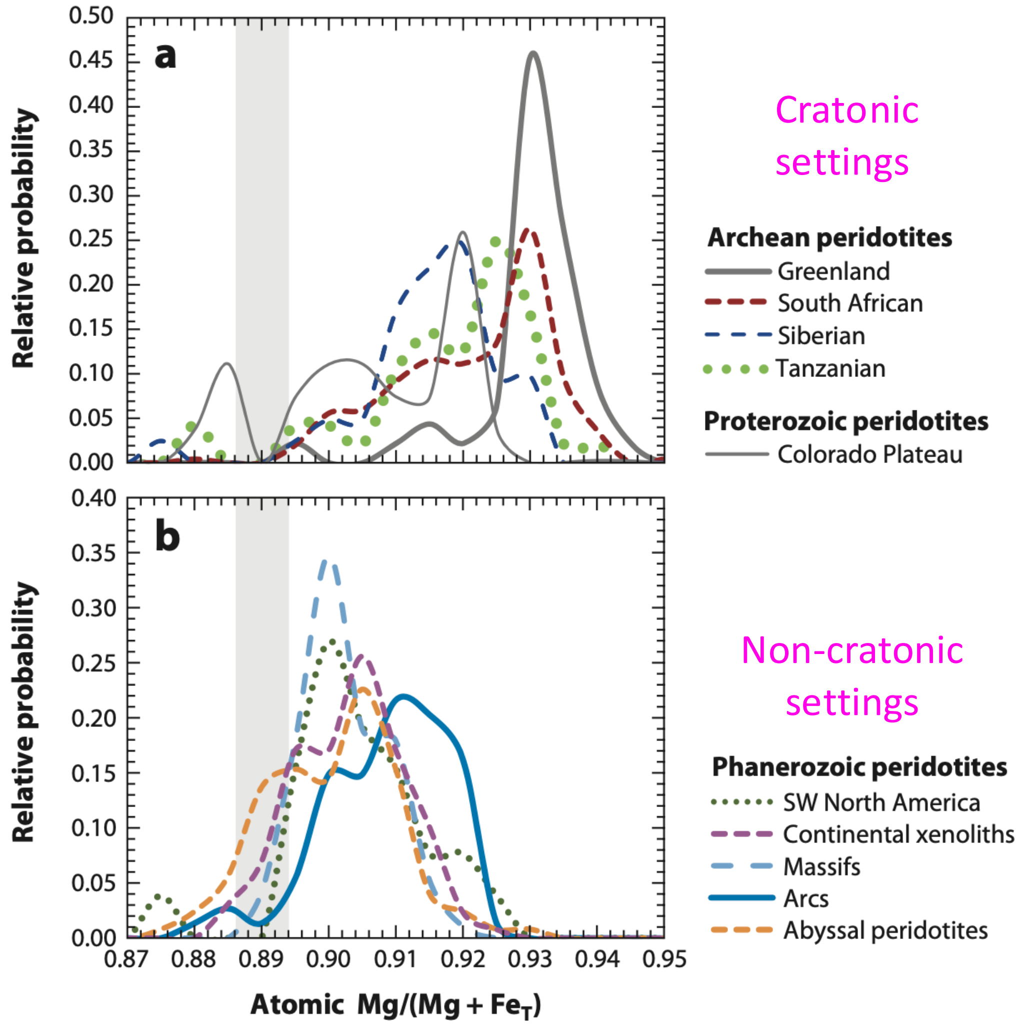

Kernel density estimate plot of whole-rock concentration of Mg/(Mg+Fe) in peridotites from different settings. After Lee et al. (2011)

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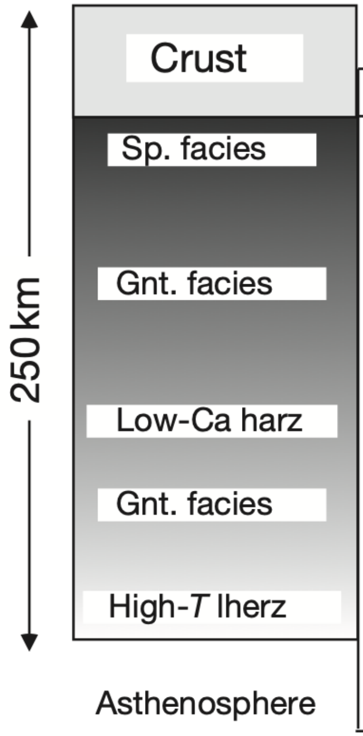
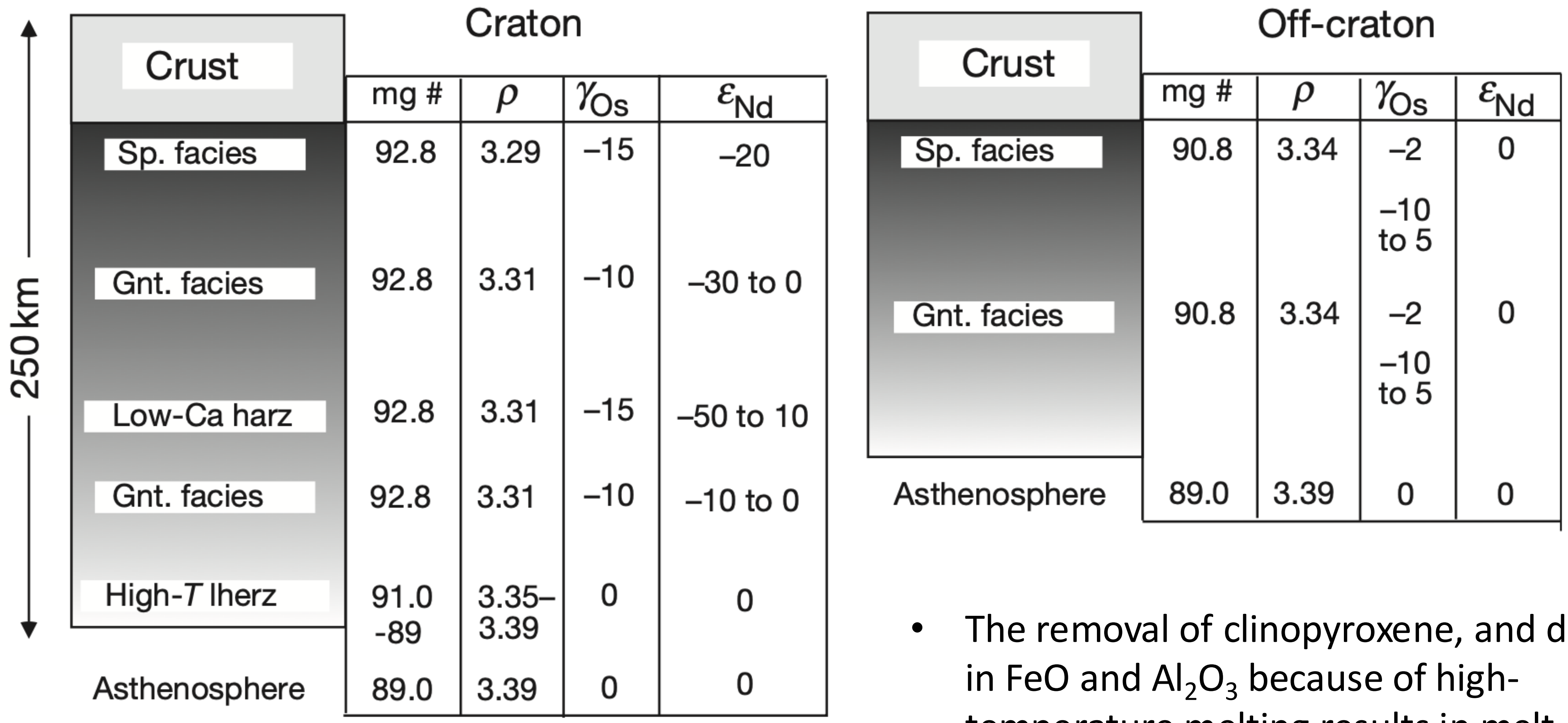


Craton

	mg #	ρ	γ_{Os}	ε_{Nd}
Sp. facies	92.8	3.29	–15	–20
Gnt. facies	92.8	3.31	–10	–30 to 0
Low-Ca harz	92.8	3.31	–15	–50 to 10
Gnt. facies	92.8	3.31	–10	–10 to 0
High-*T* lherz	91.0 -89	3.35–3.39	0	0
Asthenosphere	89.0	3.39	0	0

Due to melt extraction and depletion in highly dense elements (i.e., FeO), cratonic peridotites are less dense in comparison to the underlying lithosphere and in comparison, to non-cratonic peridotites. These properties affect the buoyancy of cratons. After Pearson et al. (2003). Typical non-cratonic peridotite has a dense of 3.34 g/cm3.



- The removal of clinopyroxene, and depletion in FeO and Al_2O_3 because of high-temperature melting results in melt-depleted residue that has a lower relative density.

Cratonic Lithospheric Mantle

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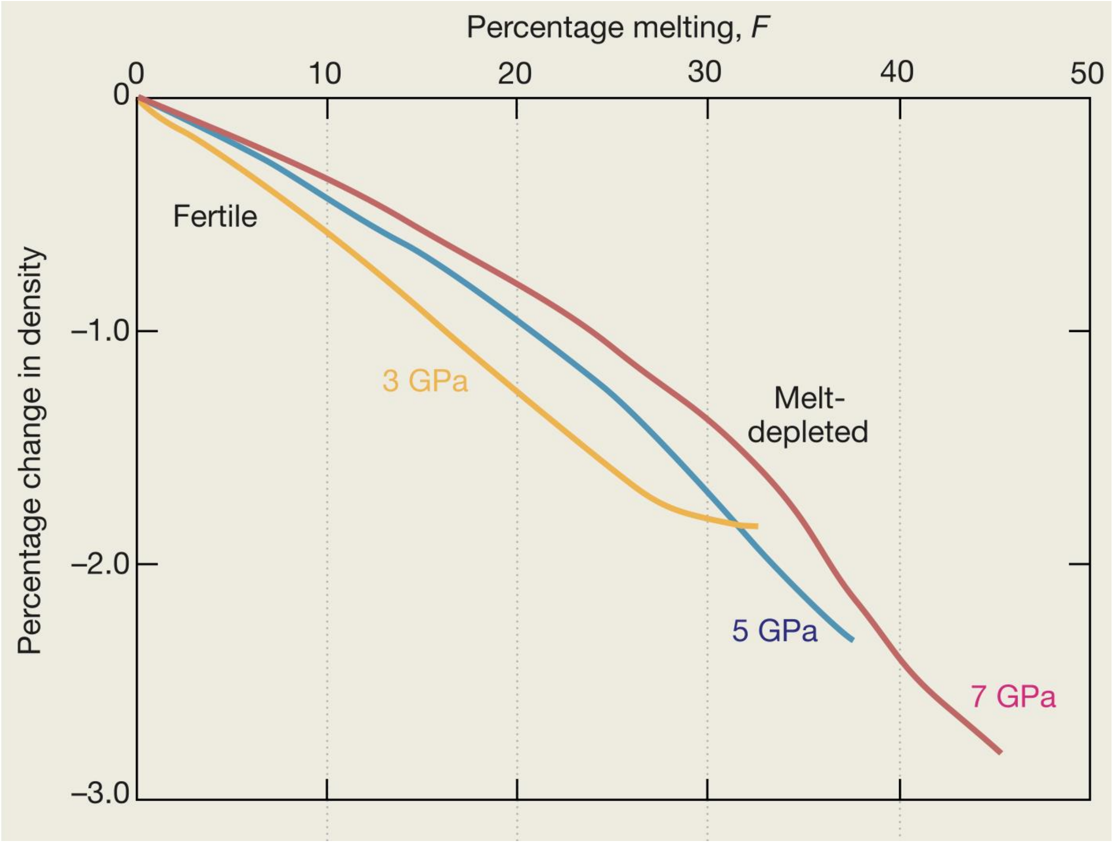


The decrease in density of cratonic peridotites due to melt extraction is directly proportion to the amount of melt being extracted (i.e., more melt extracted results in a greater depletion in FeO). Figure after Pearson et al. (2021).

Quick break for Questions…..

- What is the significance of harzburgites and dunites within the lithospheric mantle of cratons and what do they represent?
- How has the formation of dunites and harzburgite influenced the physical properties of cratons, such as their thickness and resistance to subduction?
- Why is it unlikely that the cratonic lithospheric mantle will re-melt again in the future?

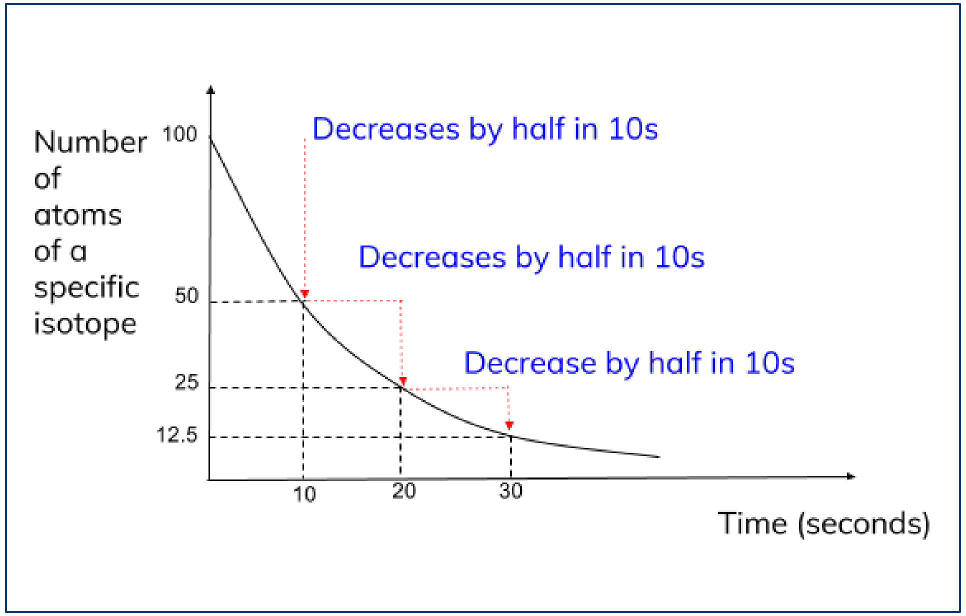
How old is cratonic lithospheric mantle?

The age of cratonic lithospheric mantle can be determined by Re-Os dating peridotite xenoliths.

^{187}Re decays to ^{187}Os with half-life of 42 billion years. The radioactive decay forms the basis of isotopic dating

Re is moderately incompatible (it will enter a melt rather than stay in solid) and Os is compatible (it will stay in solid rather than enter melt)

When the mantle underwent partial melting to form the harzburgites and dunites, a significant portion of Re was extracted into the melt (which later forms crustal rocks like basalt), while Os remains in the residue. This process leads to **Re depletion** in the mantle residue.



Re and Os are both in mantle rock
Mantle rock melts
Most Re enters melt
Most Os stays in mantle rock
The Re/Os ratio will be different before/after melting

How old is cratonic lithospheric mantle?

After mantle depletion (partial melting), the Re-Os ratio of the depleted mantle is lowered, meaning that over time, less new ^{187}Os is generated from the decay of ^{187}Re in the residual mantle.

The $^{187}Os/^{188}Os$ ratio in the residue increases much more slowly than it would in a system with higher Re concentrations. By measuring the current $^{187}Os/^{188}Os$ ratio in mantle-derived rocks and comparing it to the known $^{187}Os/^{188}Os$ ratio, geologists can back-calculate the time of Re depletion, **which corresponds to the last major melting event in the mantle rock's history.**

When did the last major melting event typically occur for most cratons?

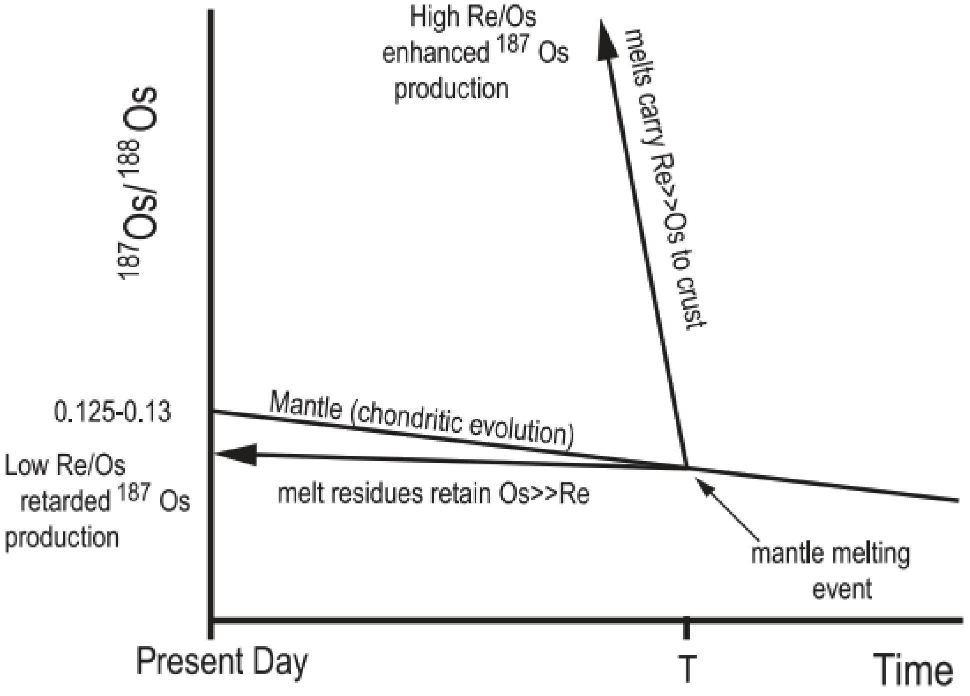


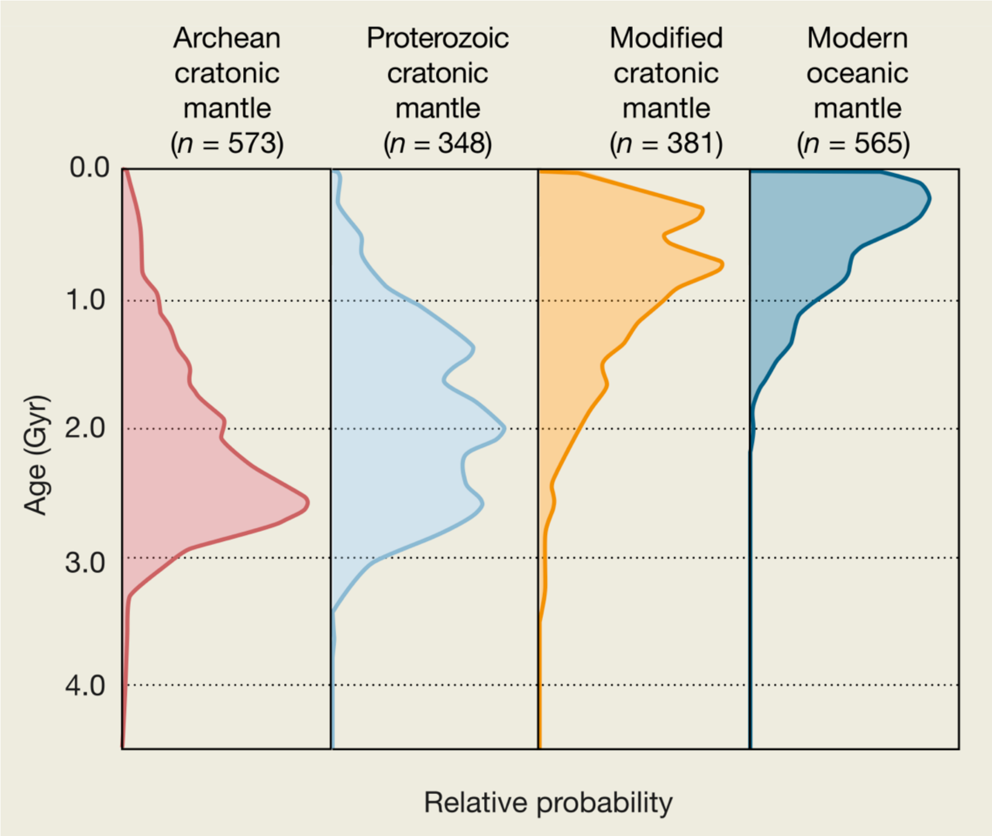
Figure 2. Schematic diagram of the evolution of crust and mantle components for a melting event at time T. The $^{187}Os/^{188}Os$ = 0.1296 (Meisel et al., 2001) is the present day isotopic composition of the fertile convecting upper mantle.

How old is cratonic lithospheric mantle?

The analysis of several hundred peridotite xenoliths from different geological settings (cratons, oceanic lithosphere etc.) shows variation in the age of Re depletion (the last major melting event):

Peridotites from cratonic settings have Archean and Proterozoic Re depletion ages. This indicates that the extraction of Re during the last major melting event in the mantle took place during the Proterozoic and Archean

This agrees with the surface geology for cratons which are typically also comprised of very old rocks of similar or slightly younger ages



Probability density plots of Re depletion ages (billions of years) for peridotite samples from different settings. Note that cratonic peridotites have typically older Re depletion ages. After Pearson et al. (2021).

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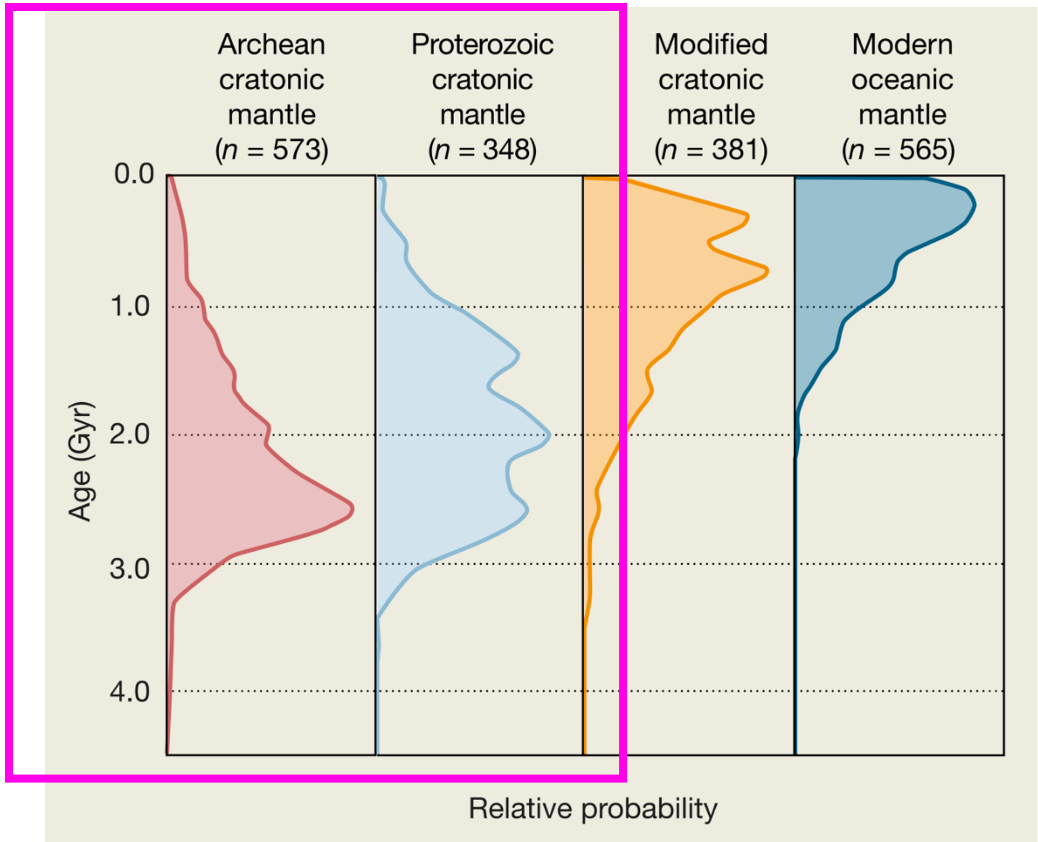

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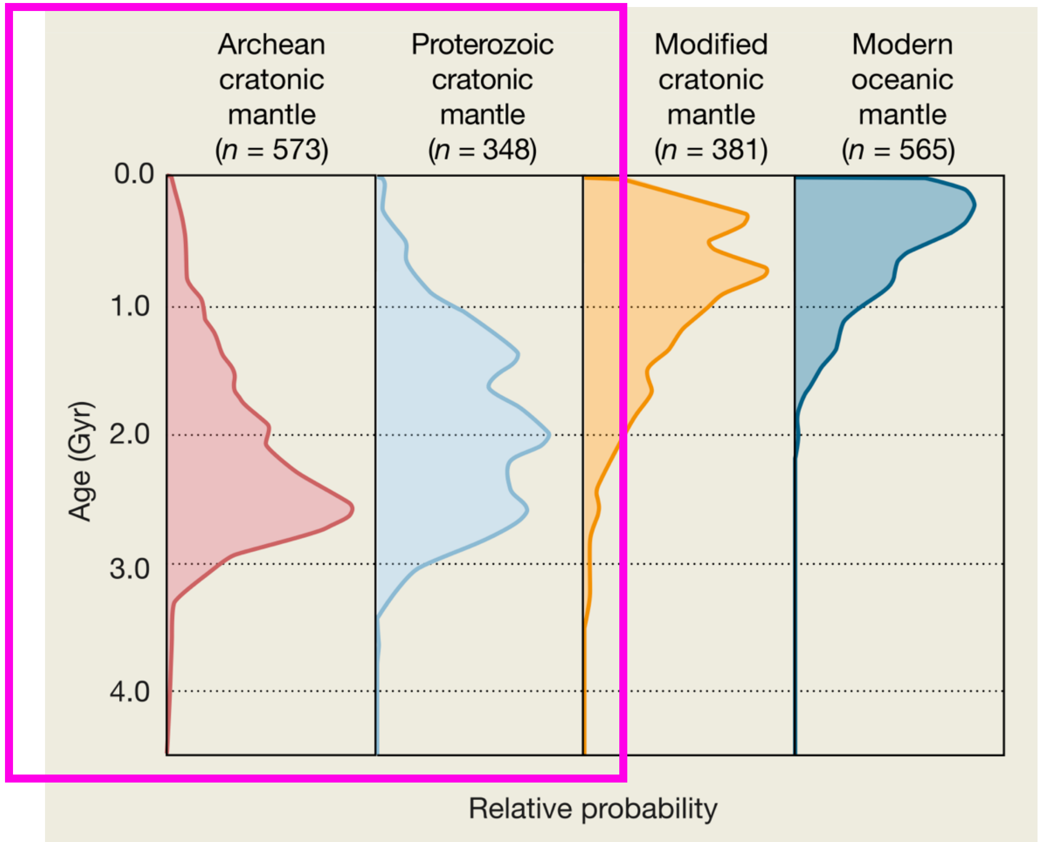

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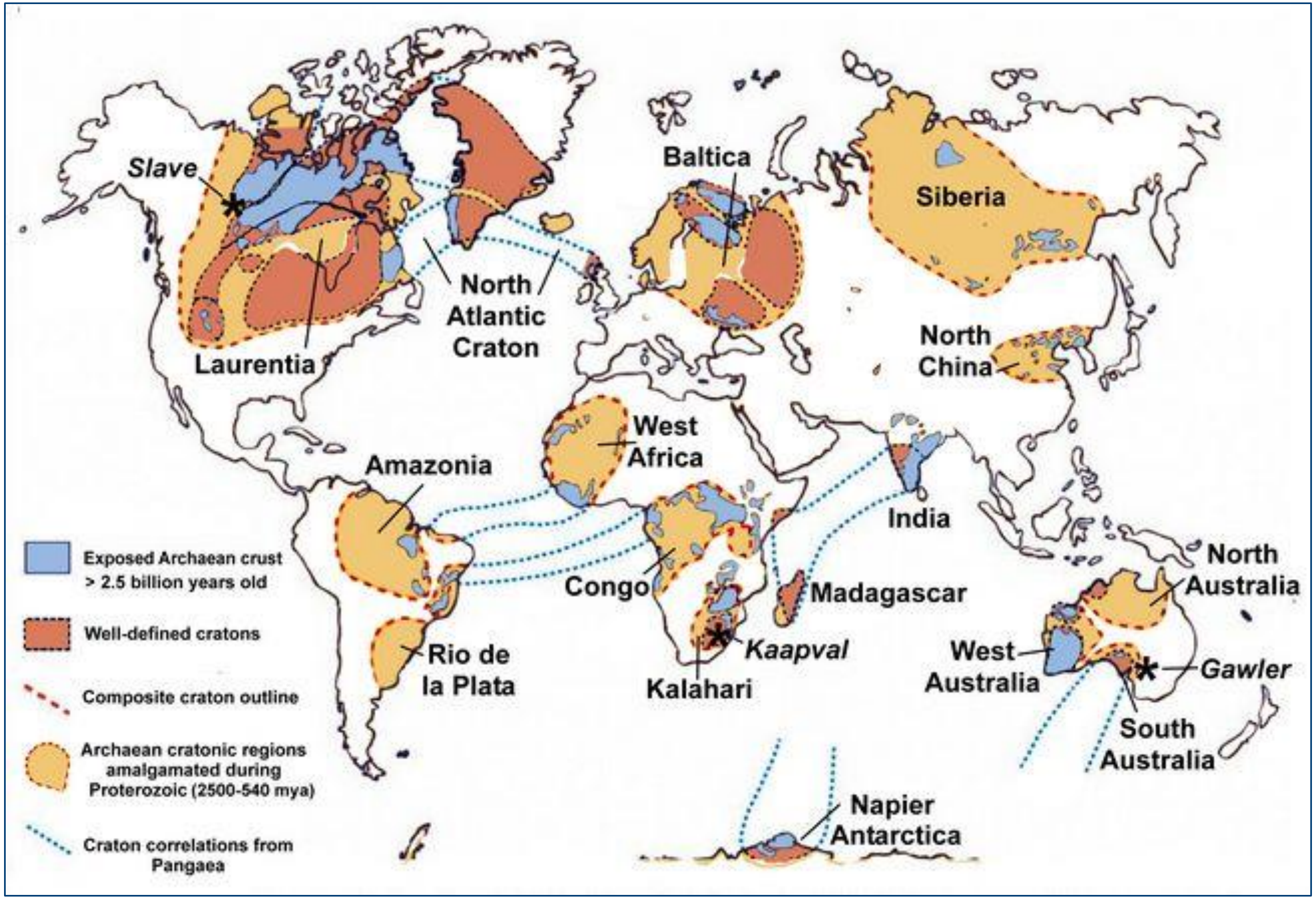
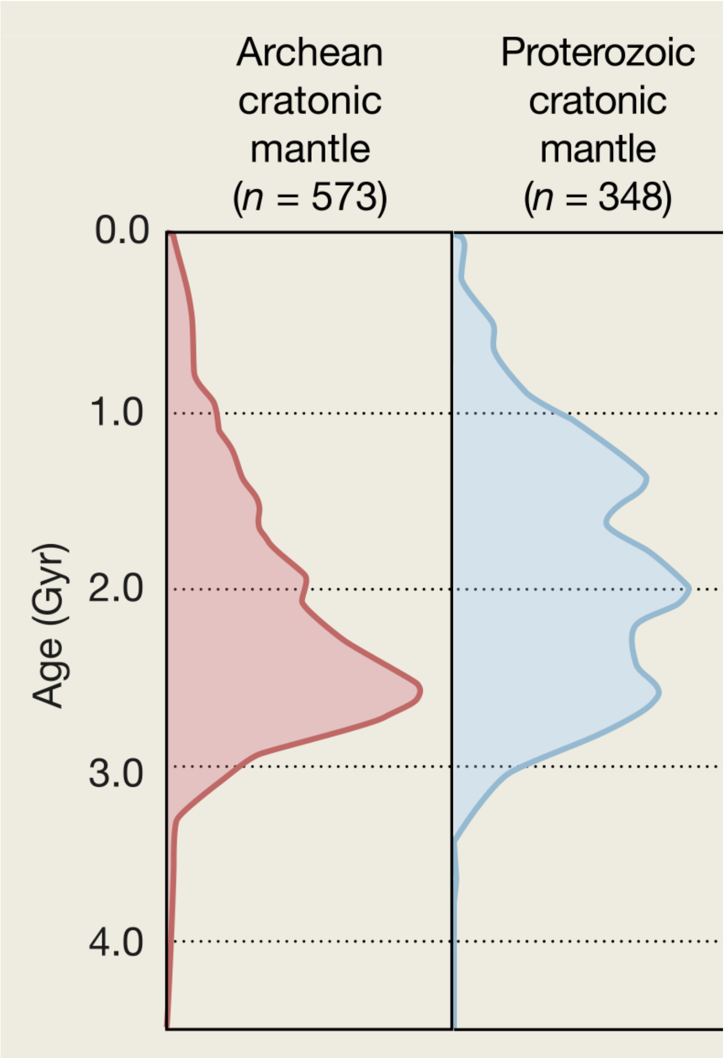
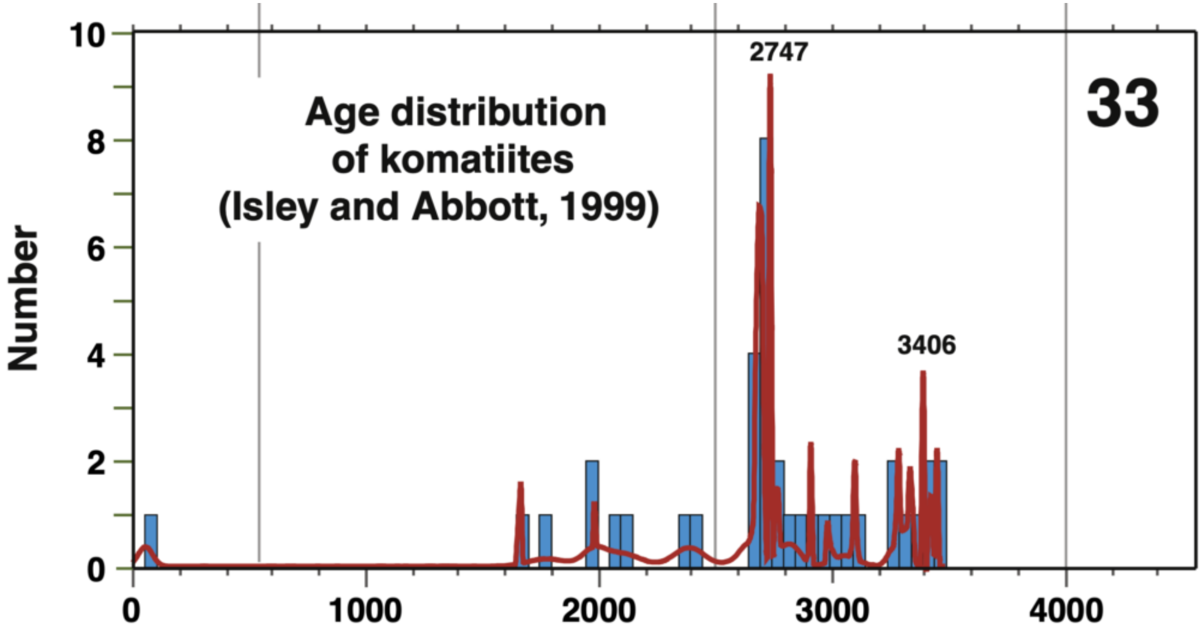
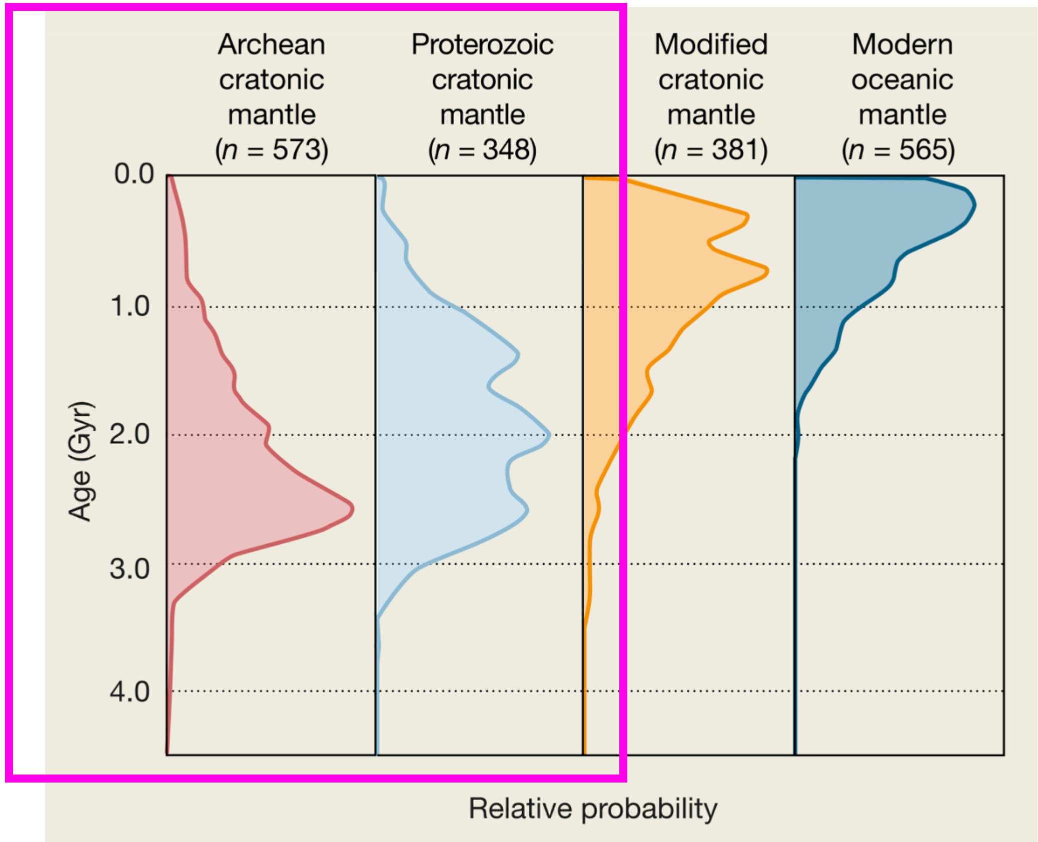

Slave
Laurentia
North Atlantic Craton
Baltica
Siberia
North China
West Africa
Amazonia
India
Congo
Madagascar
North Australia
Kaapval
Kalahari
Rio de la Plata
West Australia
Gawler
South Australia
Napier Antarctica
Exposed Archaean crust > 2.5 billion years old
Well-defined cratons
Composite craton outline
Archaean cratonic regions amalgamated during Proterozoic (2500-540 mya)
Craton correlations from Pangaea


Archean cratonic mantle (n = 573)
Proterozoic cratonic mantle (n = 348)
Age (Gyr)
0.0
1.0
2.0
3.0
4.0

How old is cratonic lithospheric mantle?



The age distribution of komatiites. Modified after Isley and Abbott (1999). Note that most global komatiites were emplaced between 2500 and 3000 Myr. This time interval ALSO overlaps with the Re-Os depletion ages of many cratonic peridotite mantle xenoliths. The Re-Os ages typically represent the age that the mantle last experienced a major melt extraction event.



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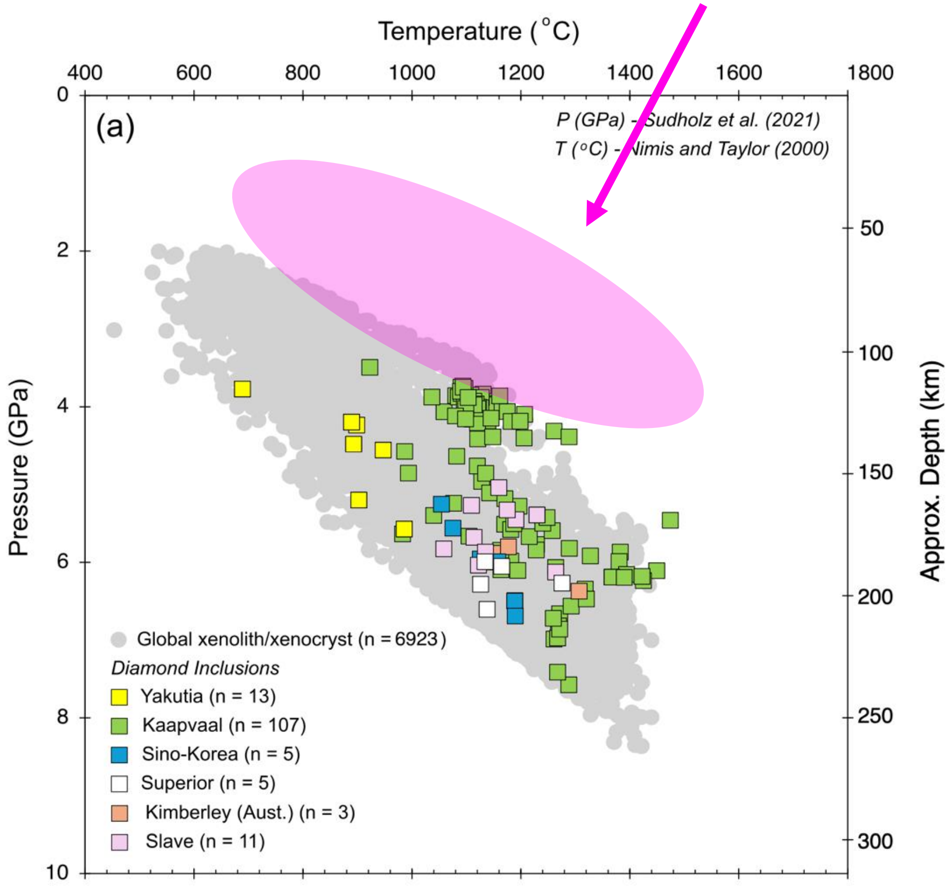
Cratonic Lithospheric Mantle: Quick Summary

- **The PT of mantle xenoliths from cratons are between 2 –8 and 600–1450 °C. These values are much greater than non-cratonic samples**
- Paleogeotherms calculated from these values results in lithosphere thicknesses between 150 –250 km. These estimates are comparable to most seismic estimates
- The lithology of the cratonic lithospheric mantle is depleted in clinopyroxene. The absence of the mineral requires that temperature of the mantle reached >1500 °C and high-degree partial melting
- As a result of depletion in clinopyroxene most rocks within the cratonic lithospheric mantle are harzburgites and dunites (the left-over residue)

Non-cratonic mantle xenoliths



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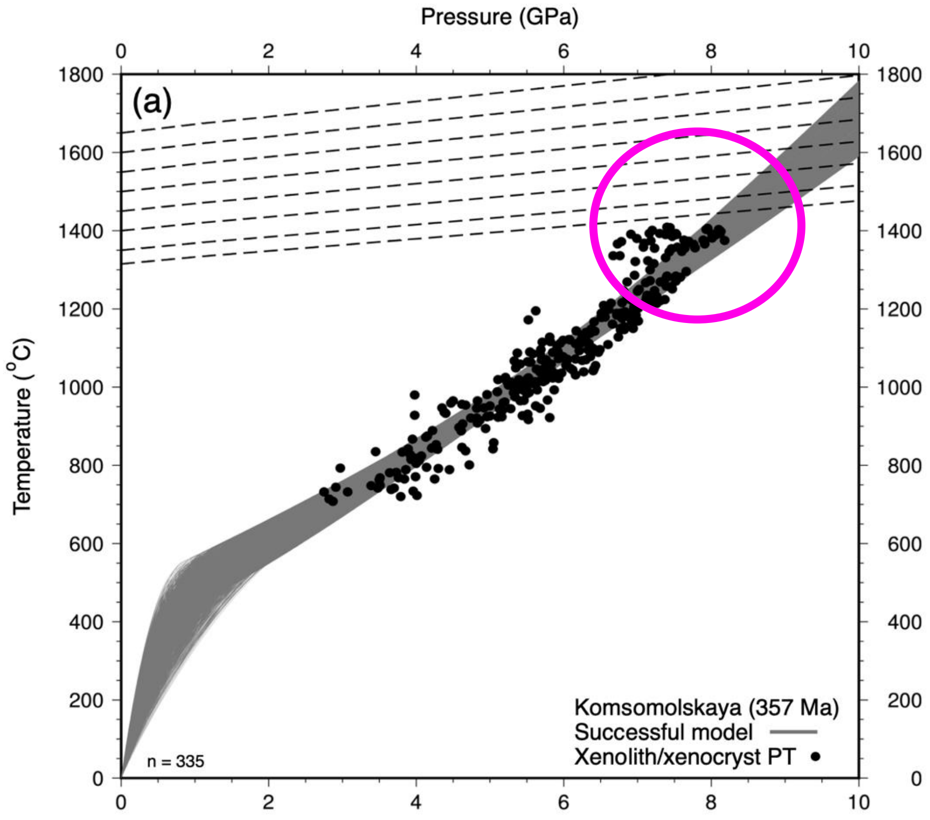

Representative paleogeotherm for a cratonic setting constructed from a large suite of PT estimates on mantle xenoliths and xenocrysts.

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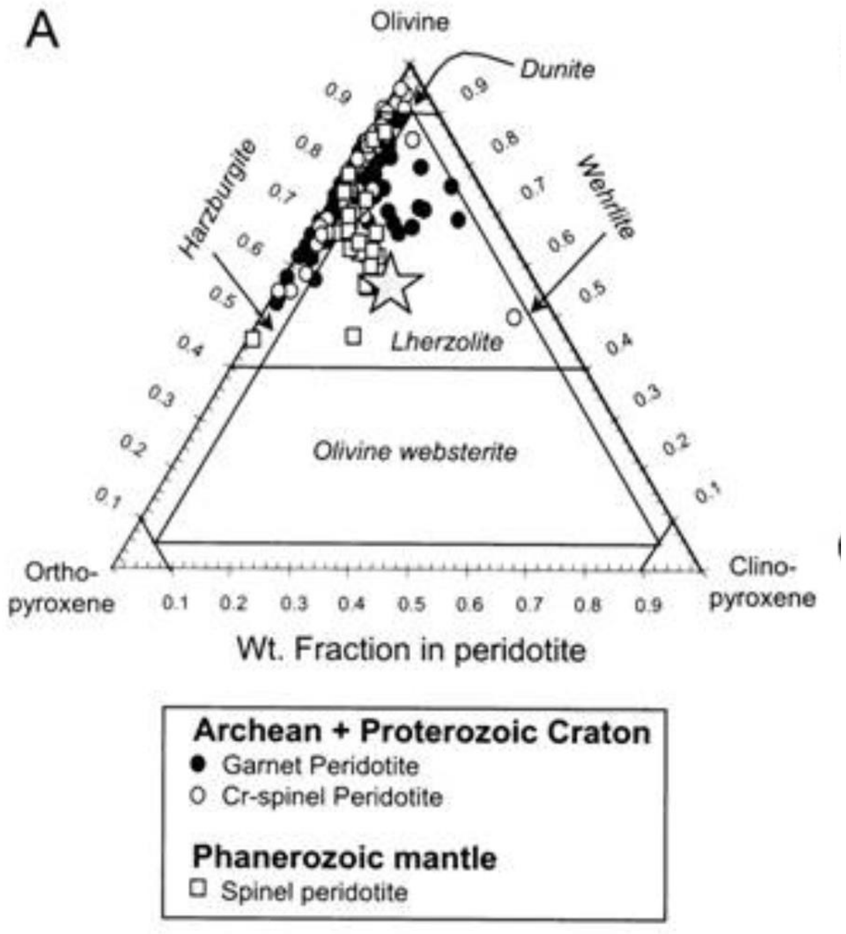

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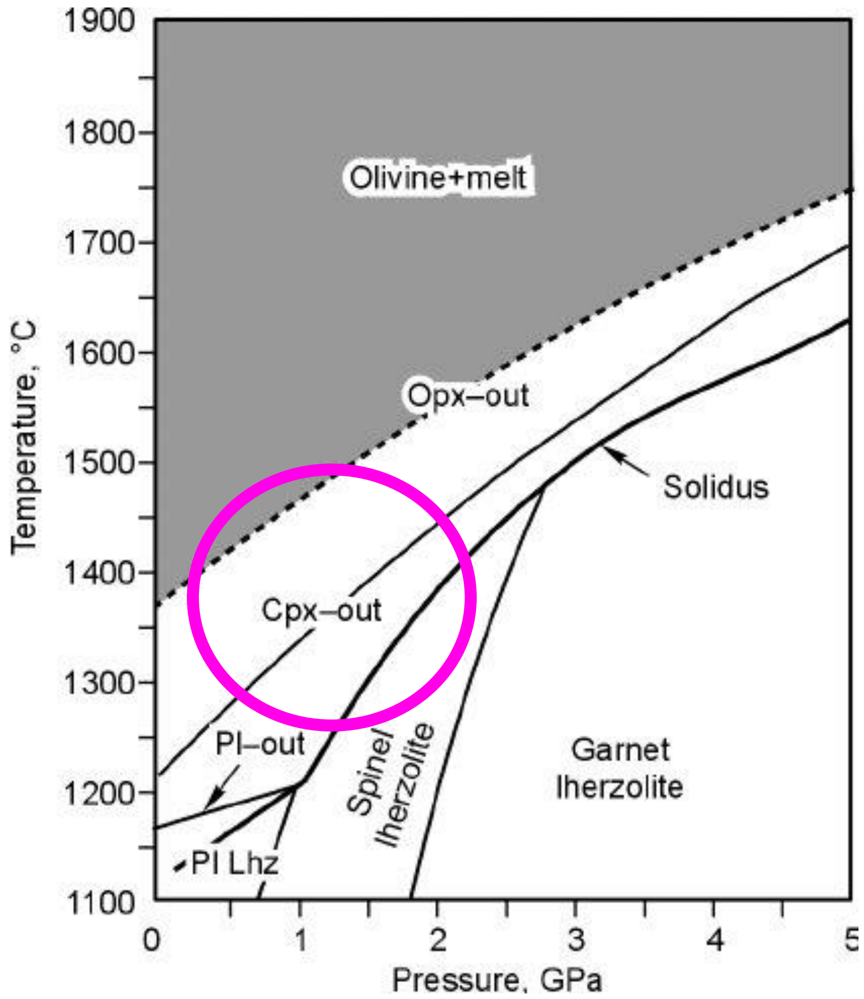
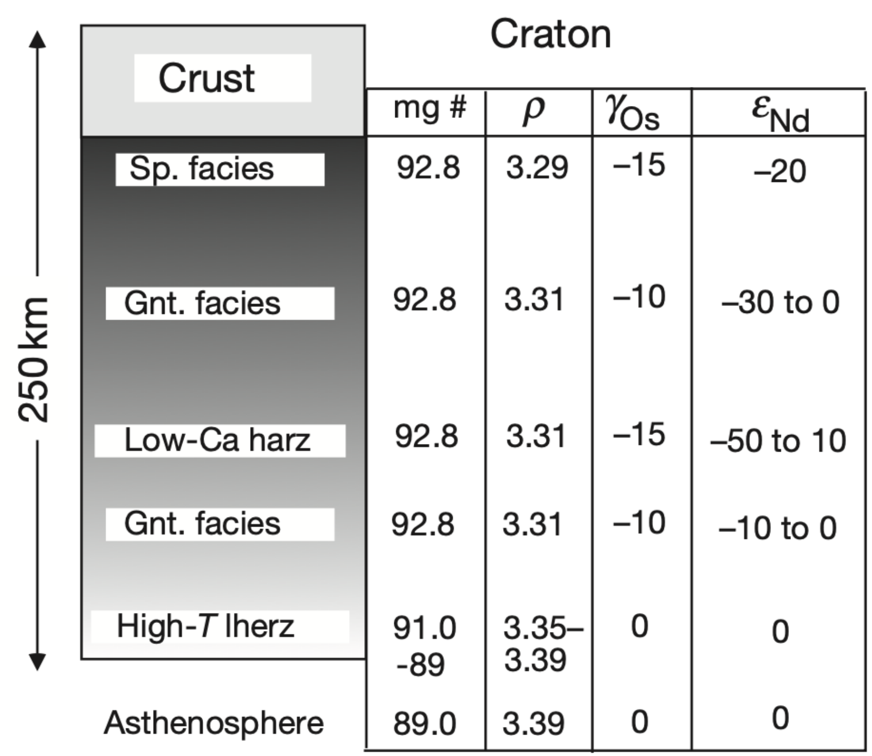


Cratonic Lithospheric Mantle: Quick Summary

- **The harzburgite and dunite residue is also depleted in FeO and Al2O3 (went into melt) and richer in MgO. These properties in part give cratons their unique buoyancy (low density of residue) and relatively faster surface wave velocities compared with non-cratonic regions**
- The melt extraction of cratons can be directly dated using Re-Os geochronology. This method has shown that peridotite residues within cratons (which formed by high-degree partial melting) formed during the Proterozoic and Archean. These estimates are consistent with the surface geology of cratons which also have similar- old ages



Representative compilation of the compositional and density structure of cratons.

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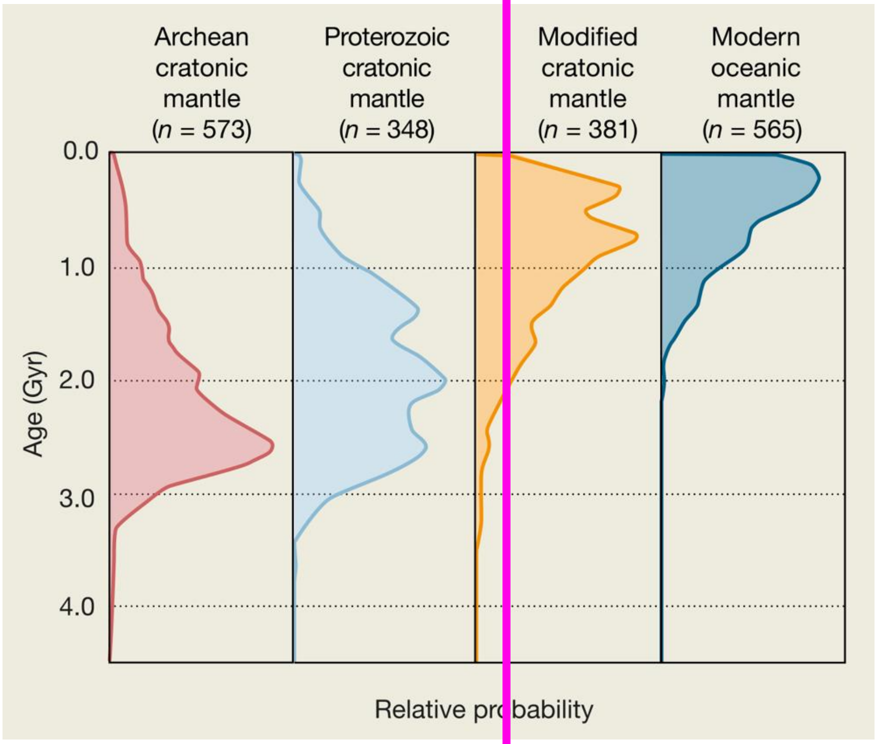


Questions…..

How do Cratons Form: Tying Everything Together

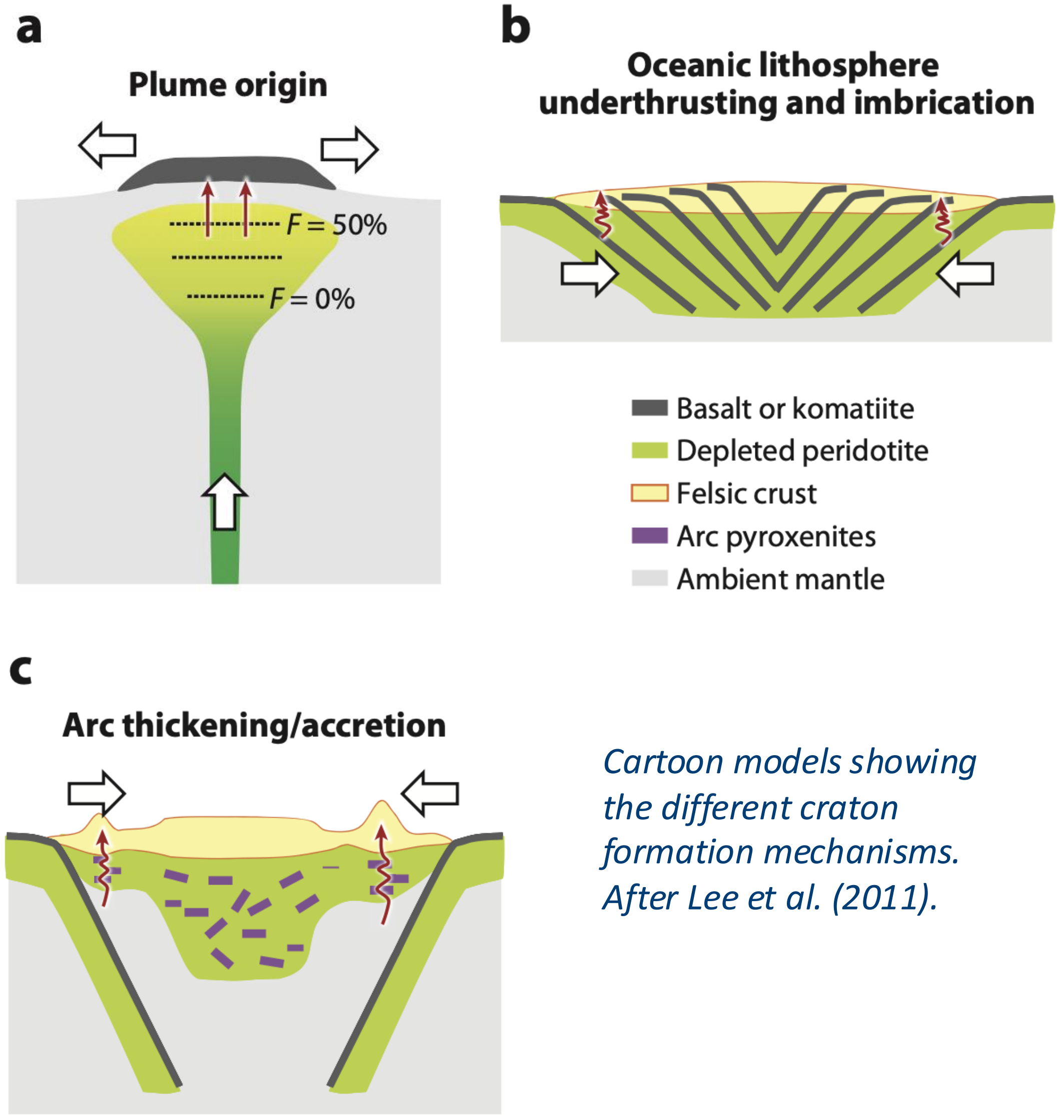
- **Tying together petrological, geochemical and geophysical observations of the cratonic lithospheric mantle are crucial for understanding how these unique geological terranes form**
- Constraining craton formation mechanisms has been a major research topic for over 50 years!
- However, there are still many unanswered questions (Lecture Part 4), and the mechanisms of craton formation remain widely debated
- We will now discuss some of the main mechanism that are though to be responsible for forming cratons and their underlying lithosphere:

How do Cratons Form

We know that cratons are comprised of melt-depleted peridotite 'residue' down to 200–250 km depth and that high-temperatures and high-degrees of melting are needed to generate these rocks

What were the conditions and tectonic settings for generating the melt-depleted peridotites and obtaining a thick cratonic keel?

- **Mantle Plumes**
- **Accretion of depleted mantle**
- **Melting in mid-ocean ridge**
- **Hydrous melting in subduction zone**

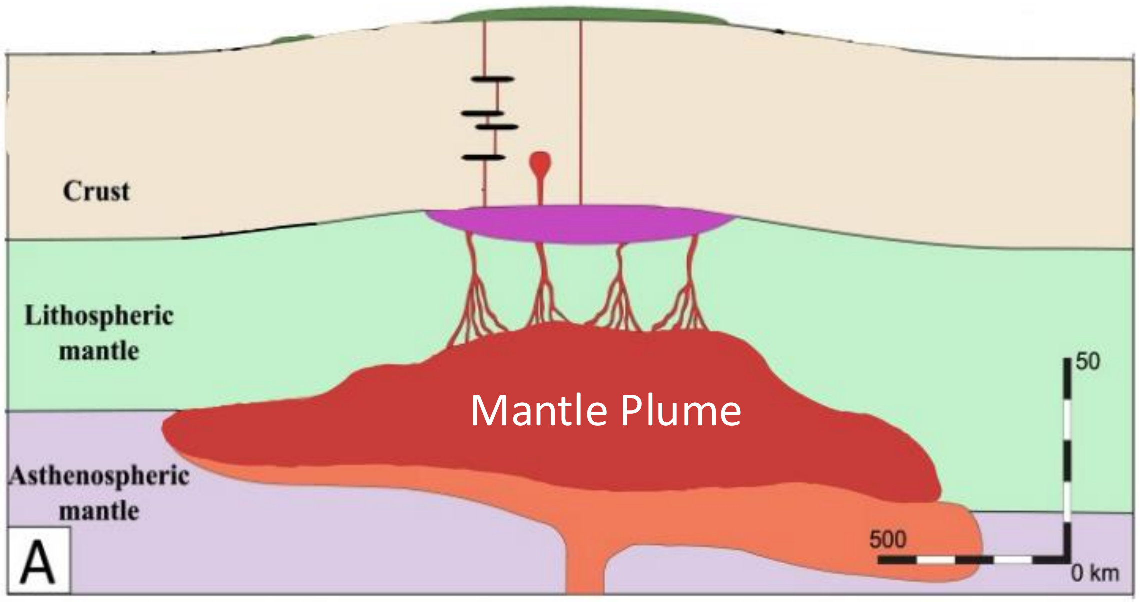


Cartoon models showing the different craton formation mechanisms. After Lee et al. (2011).

How do Cratons Form: Mantle Plumes

Low-density (buoyant) melt-depleted peridotite residue generated from high-temperature high-degree partial melting from mantle plume

This mechanism generates large amounts of melt by high-temperature high-degree melting (up to 50%) of the pre-existing lithosphere. The 'left-over' rocks after melt extraction will form the cratonic lithospheric mantle. The extracted melts may go to the surface to form distinct volcanic rocks such as komatiites and high-MgO basalts



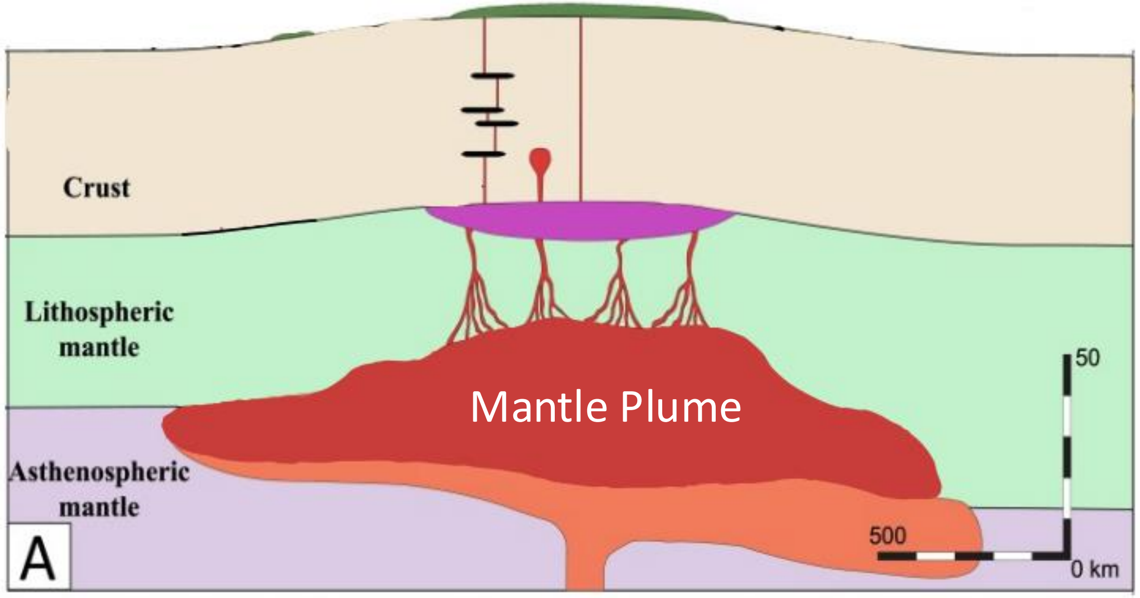
Simplified illustration of a mantle plume and its interaction with the lithospheric mantle to generate melt-depleted low-density (buoyant) peridotite. This material is generated by very high-temperature and high-degree of partial melting and may help to form the mantle beneath cratons. The melt generated may travel to the surface to form distinct volcanic rocks. Modified after Ernst et al. (2019).

How do Cratons Form: Mantle Plumes

A mantle plume is generated at CMB (?). After its ascent, the plume head will intercept the shallow lithospheric mantle (perhaps <150 km)

The high-temperatures associated with the mantle plume causes the mantle rocks (predominately lherzolite) to melt

The high temperature may promote melting until cpx-out (>1550 C). The melts travel to the surface and leave behind a melt-depleted low-density residue that is devoid of clinopyroxene



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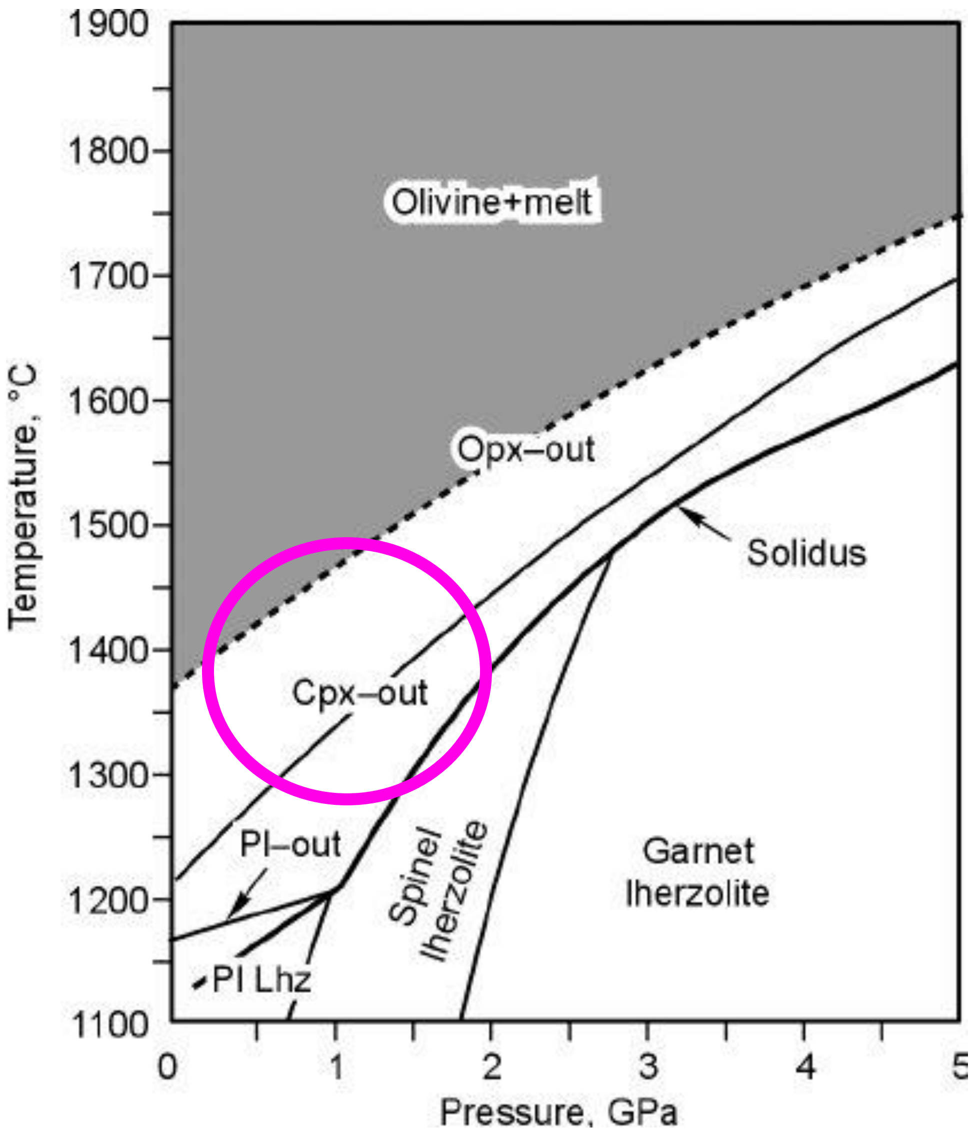
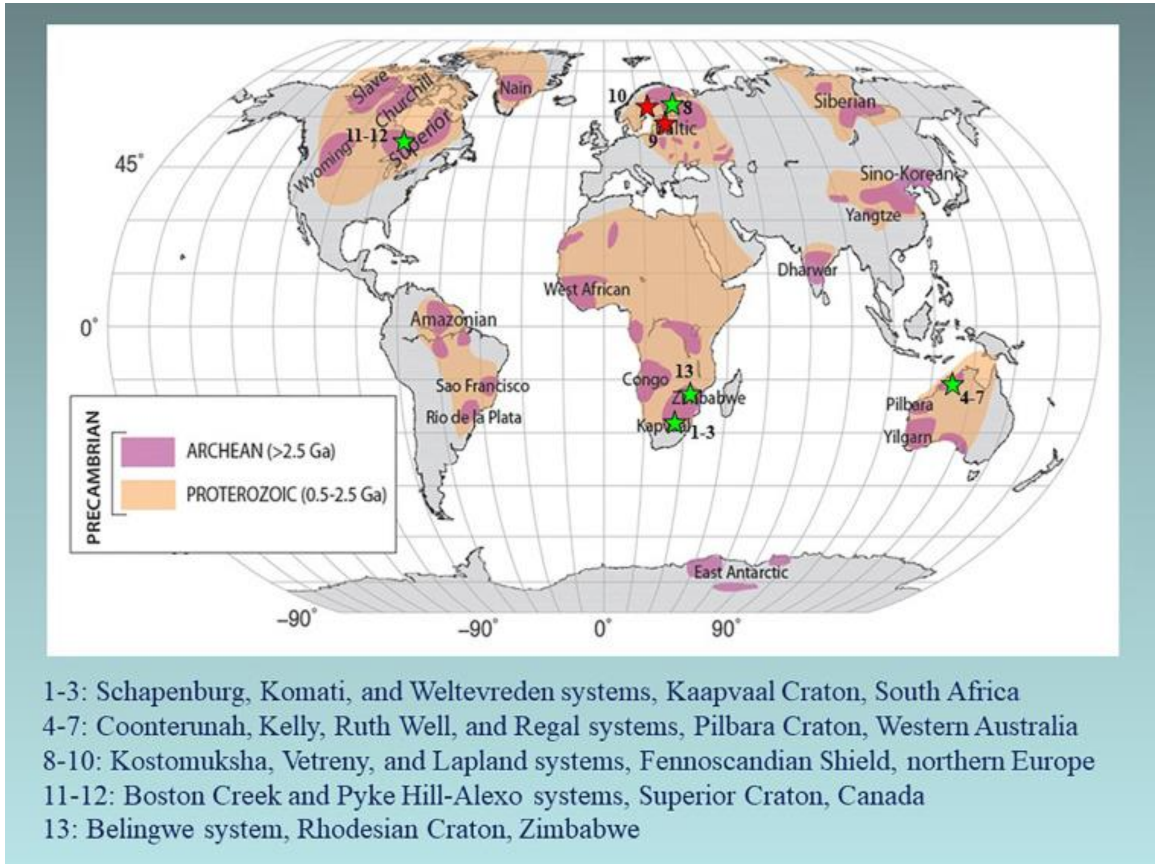


How do Cratons Form: Mantle Plumes

A mantle plume model for forming cratonic lithospheric mantle is favored because it can explain most features with a single-process. It also agrees with other observations:

The melts that are expected to be generated by high-temperature high-degree partial melting in a mantle plume (i.e., komatiites and high-MgO basalts) occur within many cratons and have eruption ages that agree well with the Re-Os depletion ages for many mantle rocks (the time of last major melting). They also occur beneath some modern hot-spots and mantle plumes



Global distribution of some komatiites and related rocks that are expected to form in a high-temperature mantle plume environment. The occurrence of komatiites within cratons attests to their probable links to craton formation.

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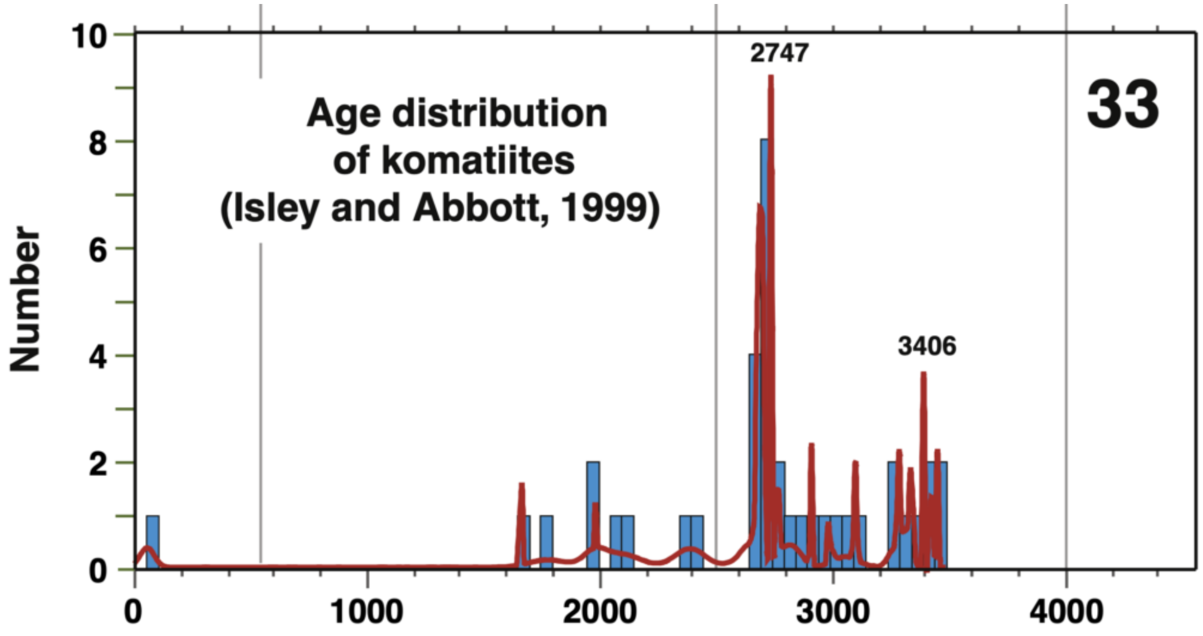


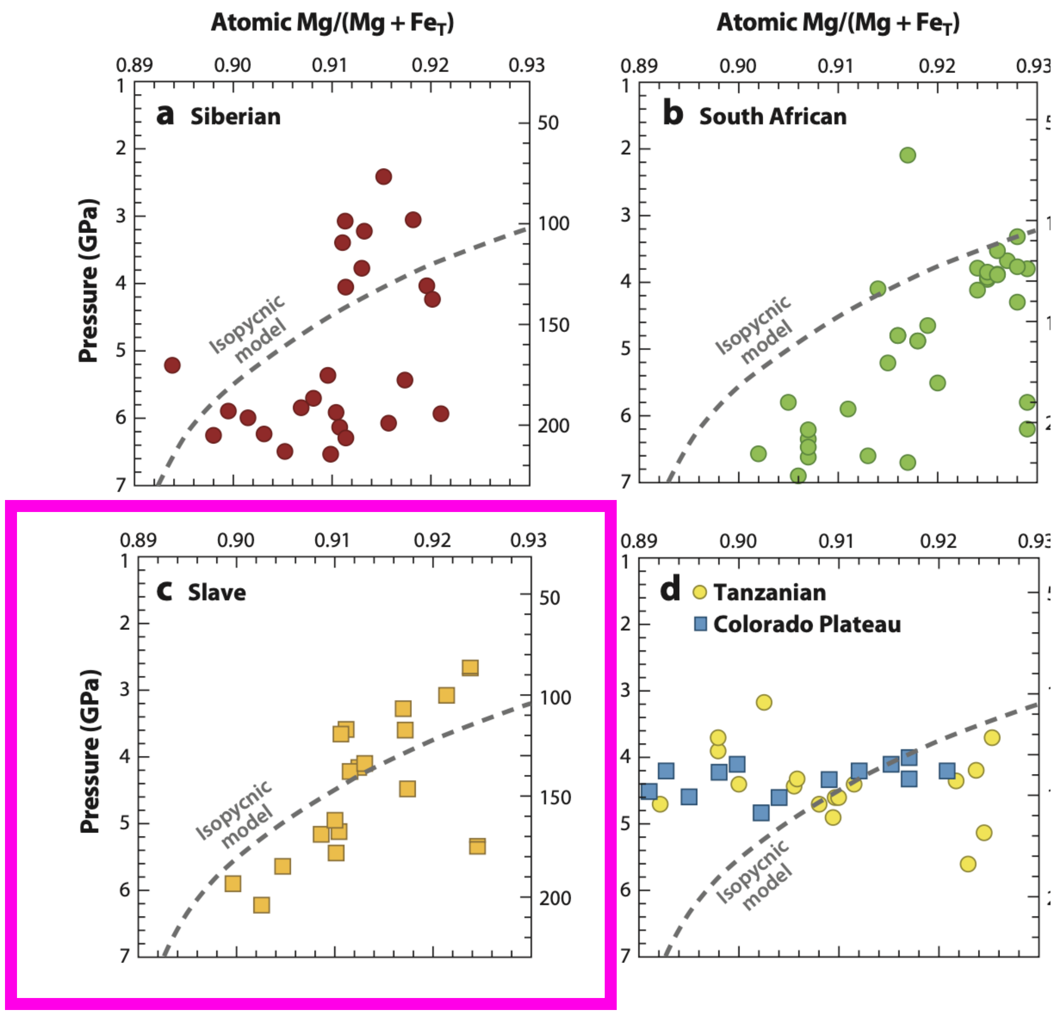
The age distribution of komatiites. Modified after Isley and Abbott (1999). Note that most global komatiites were emplaced between 2500 and 3000 Myr. This time interval ALSO overlaps with the Re-Os depletion ages of many cratonic peridotite mantle xenoliths. The Re-Os ages typically represent the age that the mantle last experienced a major melt extraction event.

How do Cratons Form: Mantle Plumes

Cratons that form by mantle plumes are expected to have some characteristic features:

- Melt extraction is expected to be greatest at shallow depth. This region is first to interact with the hot plume head and is first to melt. The Mg# (proxy for melt extraction) of xenoliths should be highest at shallow depths

For several cratons such as the Gawler (South Australia) and Slave Cratons (Canada) the mantle has greater melt depletion at shallow depths – consistent with a mantle plume model



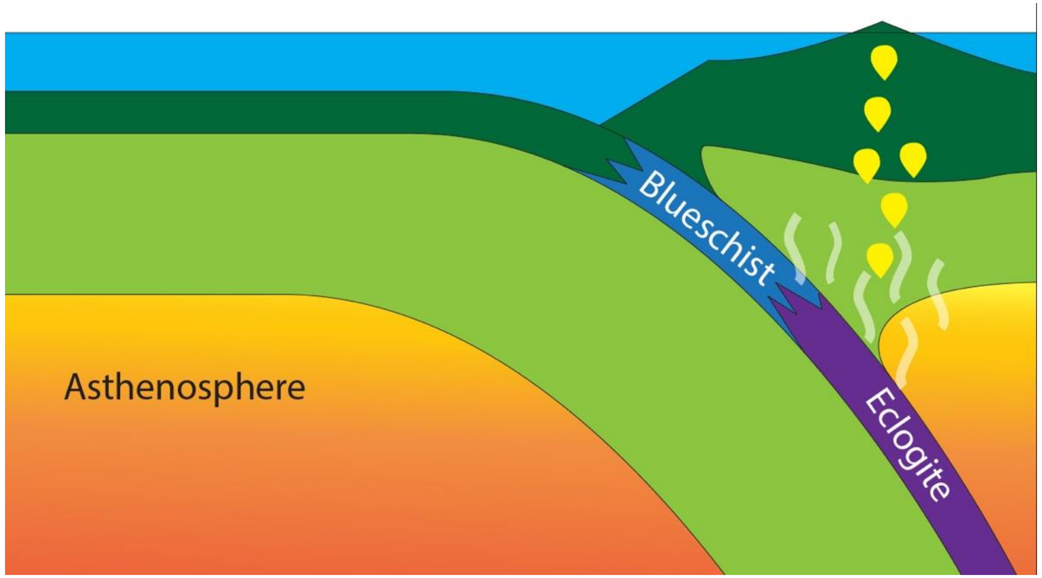
Whole-rock Mg# of cratonic peridotites versus equilibration depth (km and GPa). Note the relationship between P and Mg# for some locations. After Lee et al. (2011).

How do Cratons Form: Mantle Plumes

Cratons that form by mantle plumes are expected to have some characteristic features:

- The cratonic lithosphere should not contain any significant fragments of oceanic crust (eclogite or pyroxenite) (these would melt in a plume)

Cratons that do contain eclogite may have formed by subduction related processes – these processes are needed to get basalt into the mantle so that it can from eclogite. Cratons such as Gawler contain little to no eclogite over a large scale



Eclogite is the high-pressure poly-morph of basalt once it enters the mantle (purple). It enters the mantle by the subduction of oceanic crust. The absence of eclogite within cratons attests to formation mechanisms that do not necessarily involve subduction or accretion of oceanic crust and may be evidence that supports a mantle plume model.

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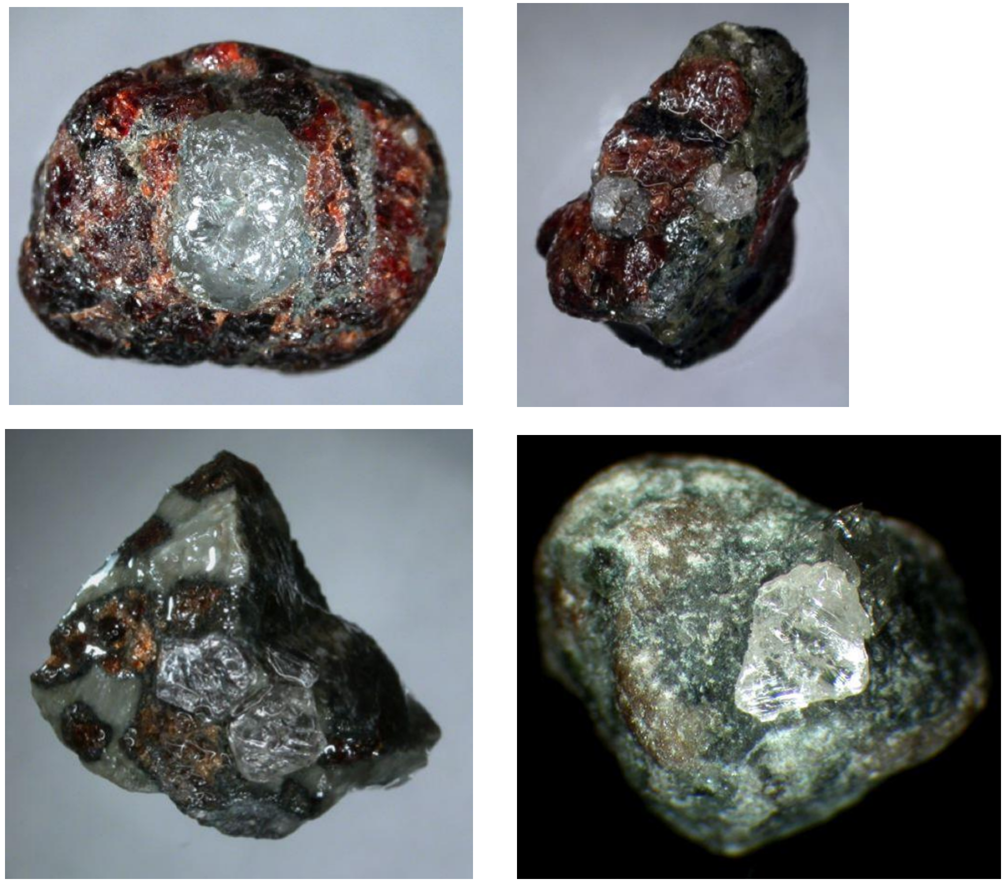
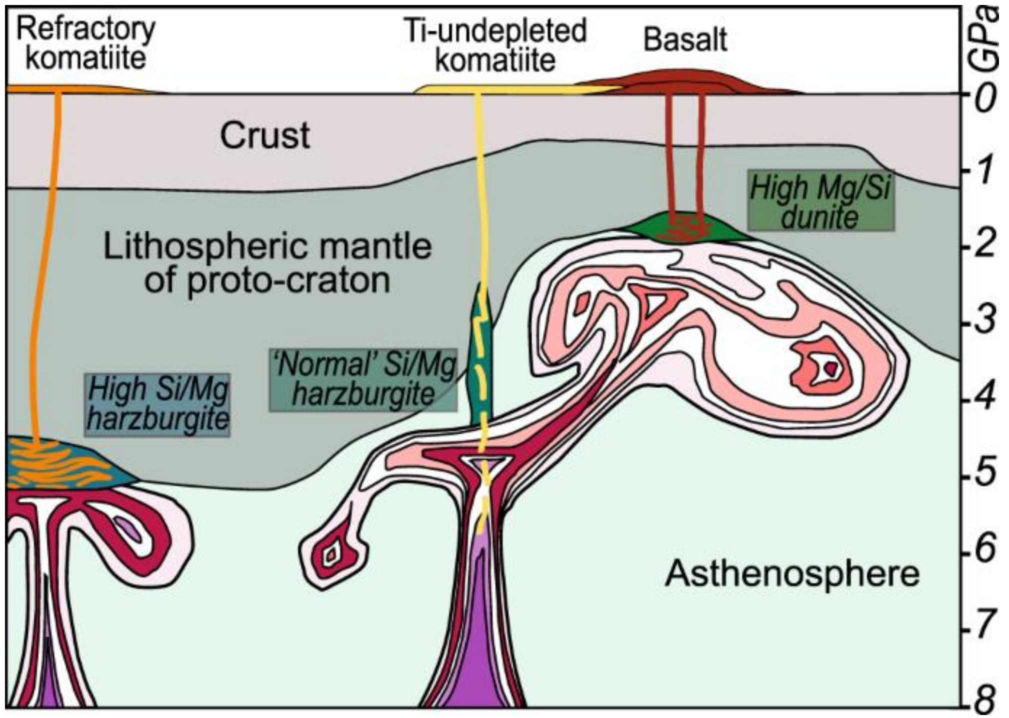


Some cratons contain eclogite. This evidence comes from mantle xenoliths of eclogite that have been transported to the surface by volcanic rocks. It is difficult to determine how eclogite may be distributed within the cratonic lithospheric mantle (i.e., does it occur as slabs or pods or has it been mixed up into very small fragments). Photos from University of Alberta (Team Diamond).

How do Cratons Form: Mantle Plumes

Cratons that form by mantle plumes are expected to have some characteristic features:

- Formation of the craton and timing of melt extraction (Re-Os age) should correspond with a large-scale tectonic-magmatic processes (supercontinent break-up)
- Surface geology of craton should not contain large lithospheric scale faults which may other wise be expected if the craton formed by subduction
- No metasomatic enrichment by subduction zone fluids which result in distinct geochemical compositions (high HFSE, LILE)



Simplified cartoon model that illustrates how mantle plume impingement may relate to the formation of basalts and komatiites at the surface. These melts form in mantle plumes by very high temperature high-degree partial melting. After Tomlinson and Kamber (2021).

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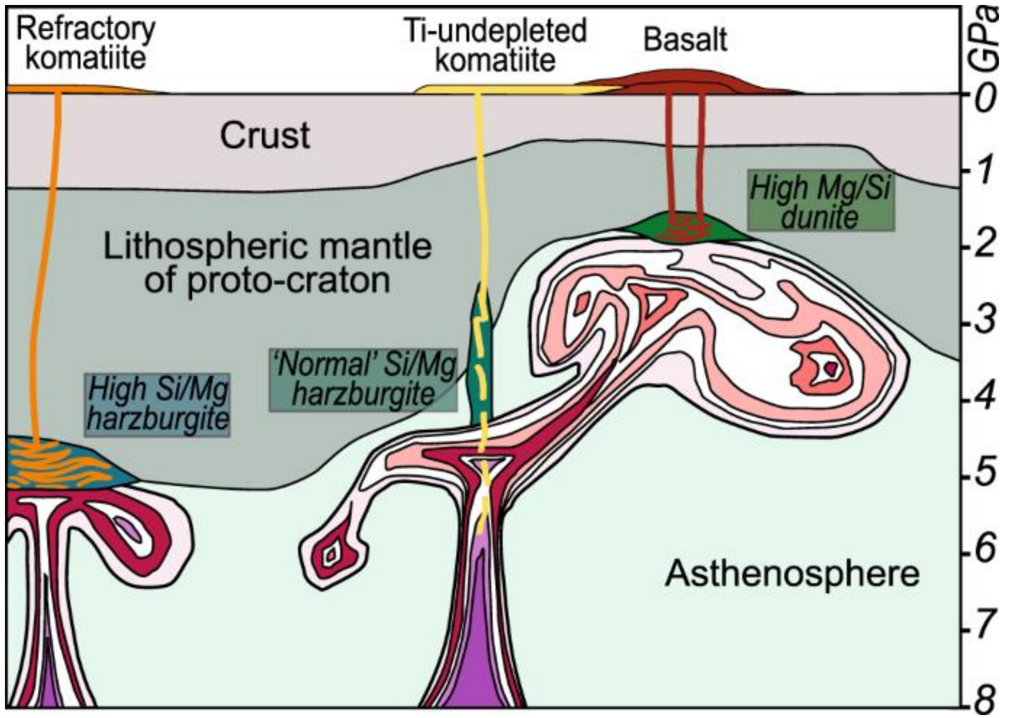

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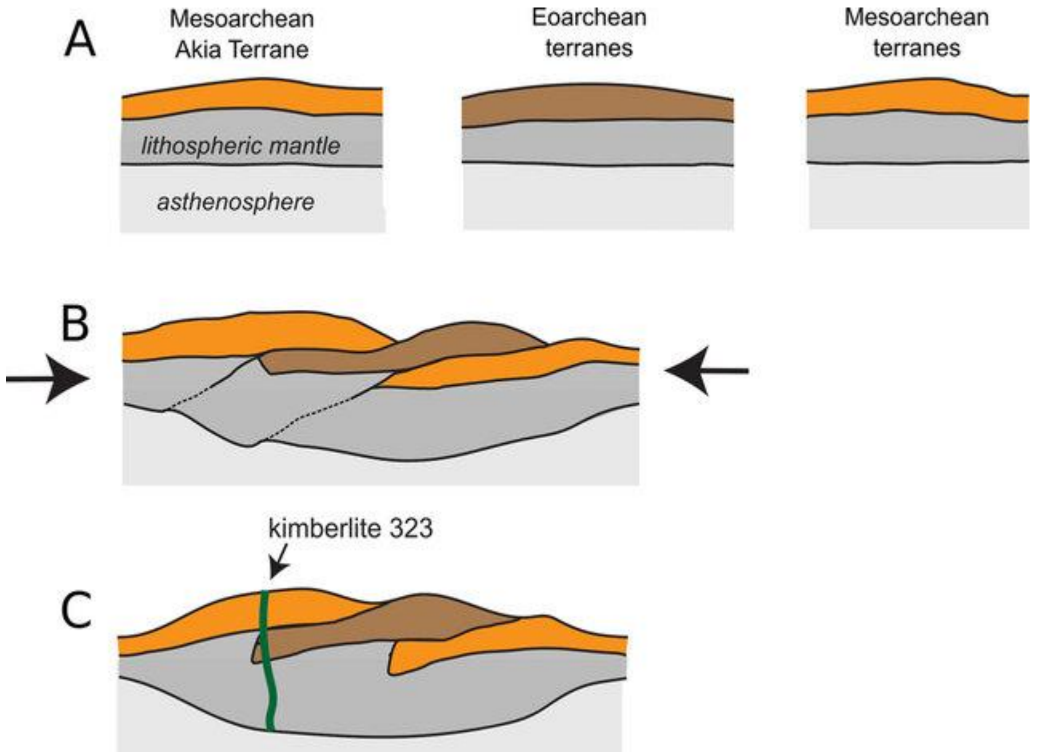
How do Cratons Form: Accretion of Oceanic Lithosphere

Accretion of Oceanic Lithosphere:

Oceanic crust is produced at mid-ocean ridge (MOR). The underlying mantle may be melt-depleted because of melt extraction to form MOR basalts

Oceanic crust and its underlying lithospheric mantle may be accreted onto existing continental crust or island arcs. The melt depleted compositions may prevent subduction of some oceanic lithosphere. Overtime several segments of oceanic crust/lithosphere may accumulate to form a craton

The process may be like the exhumation of ophiolites along continental margins (PART 1.)



Example of craton formation by the stacking/accretion of segments of oceanic lithosphere. This process may result in the formation of thick cratonic lithosphere with several distinct features. After Gardiner et al. (2020)

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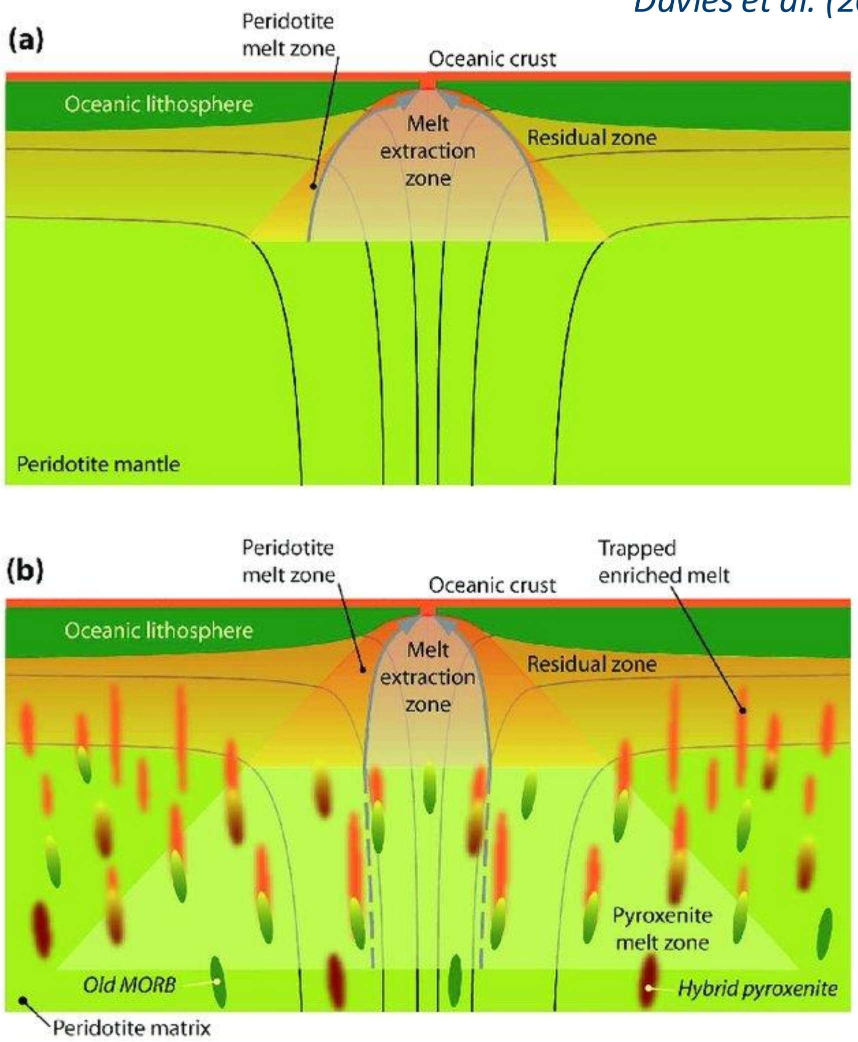
Davies et al. (2011)



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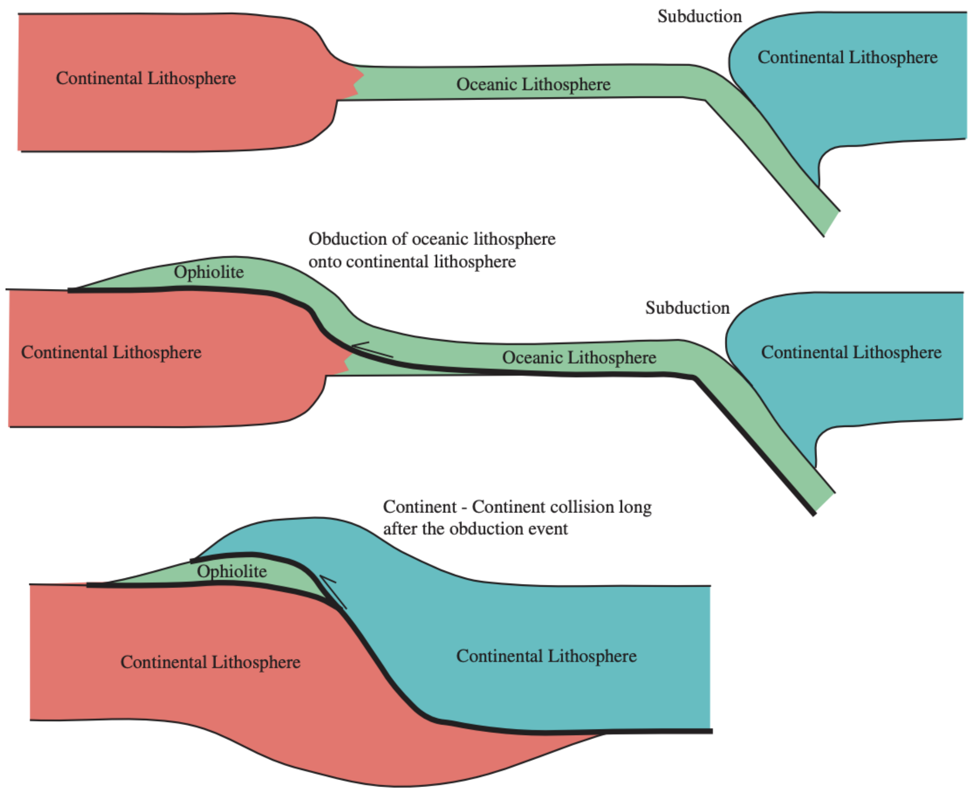
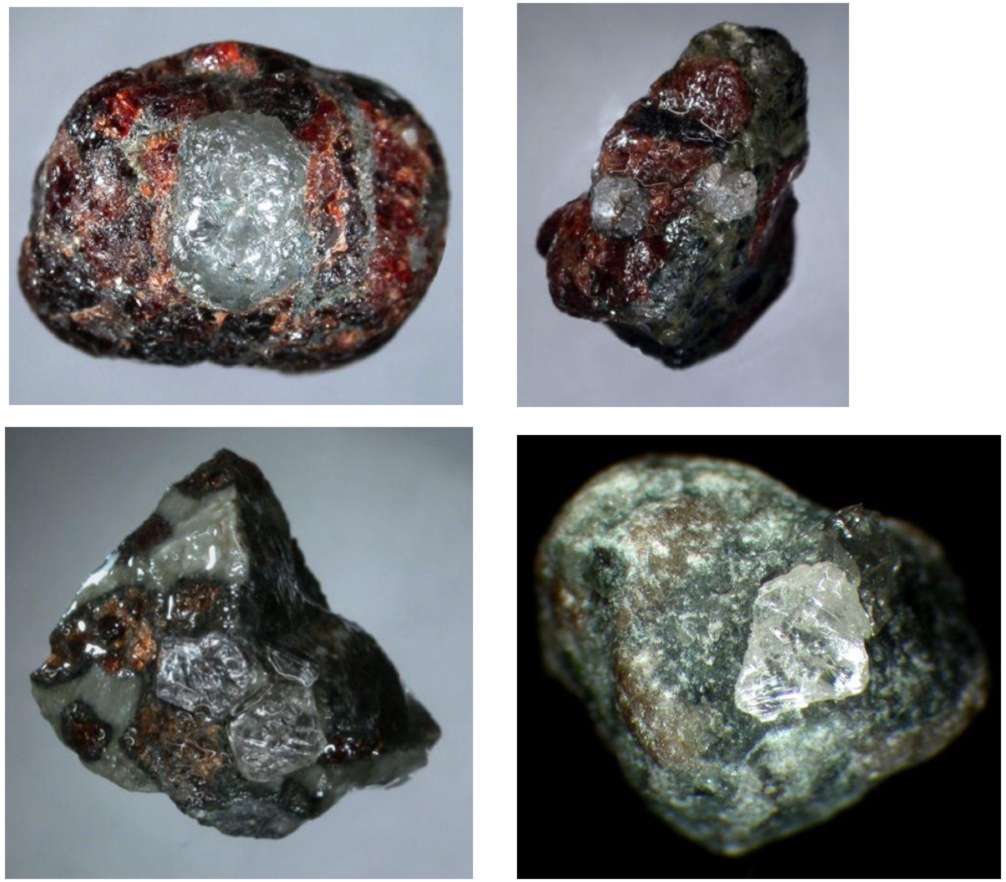


Simplified cartoon of how ophiolites may form. This process may be an analogue to how cratons formed many billions of years ago!

How do Cratons Form: Accretion of Oceanic Lithosphere

Cratons that form by accretion of oceanic lithosphere are expected to have some characteristic features:

- **Contain abundant eclogite (high-pressure fragments of oceanic crust)**
- A range of rock types should occur (representing different fragments of oceanic crust) and the vertical change in chemical composition should be highly varied (including Mg#)
- Surface geology should contain linear lithospheric-scale faults which represent stacked fragments of oceanic lithosphere



Eclogite xenoliths (w/ diamonds)

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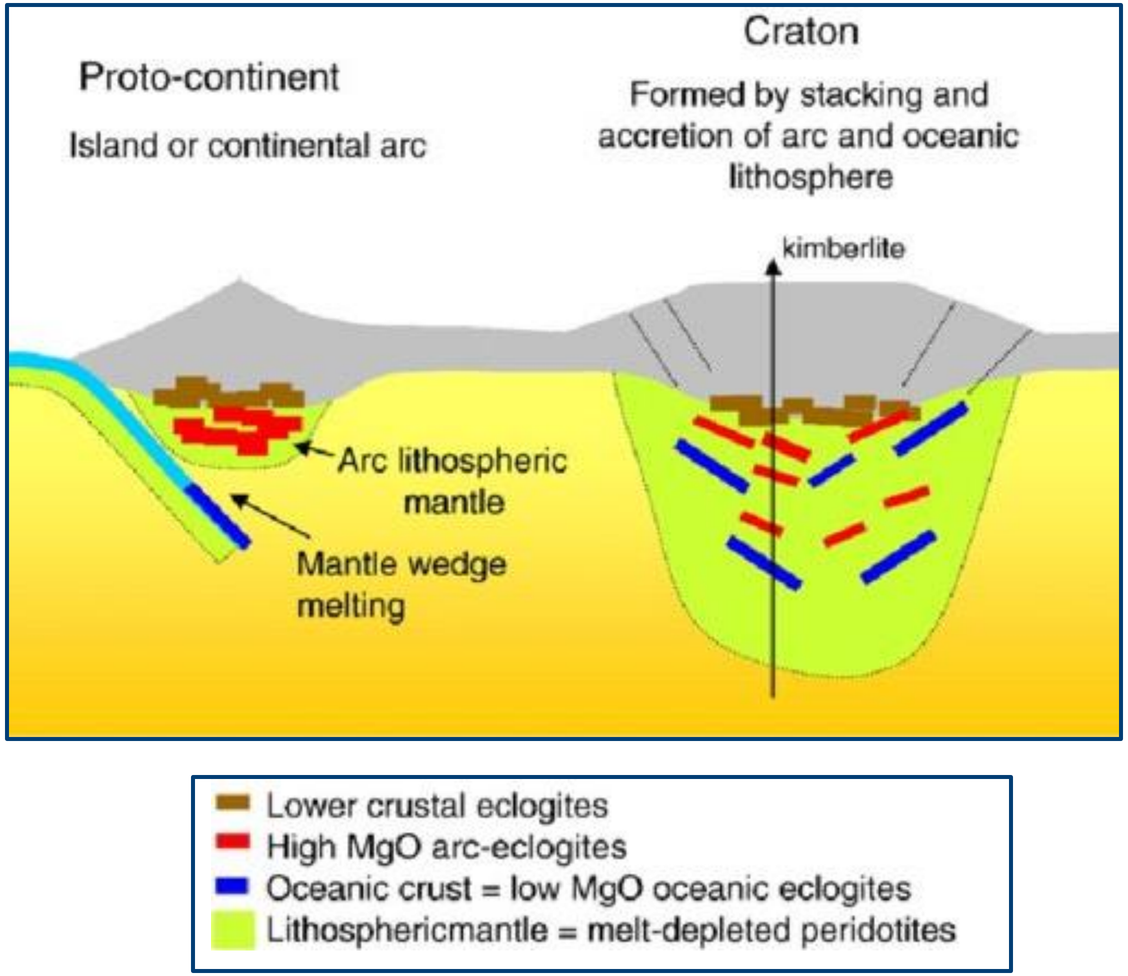

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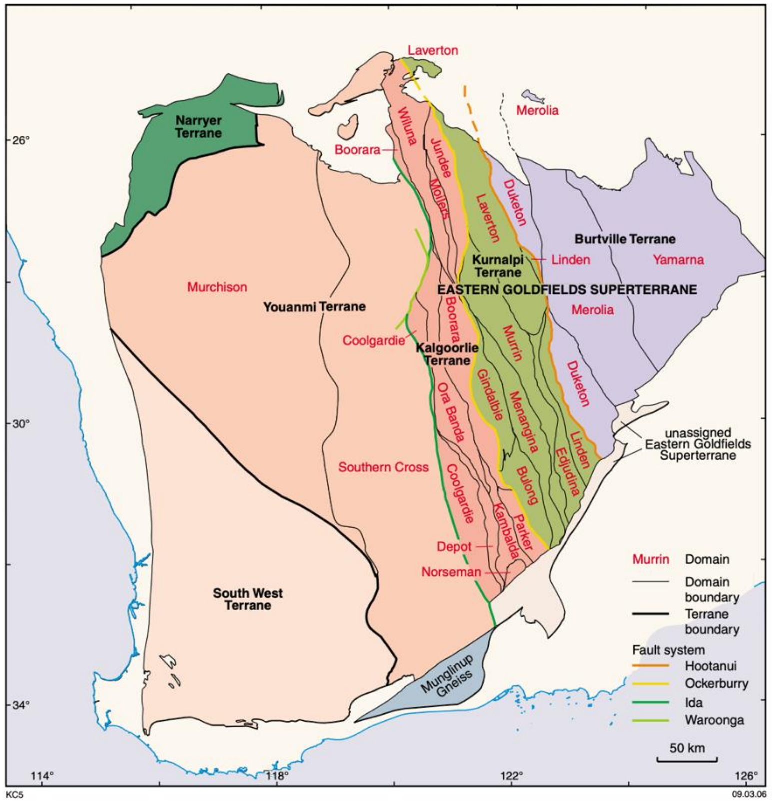

Many cratons are not just simple blocks of lithosphere, but rather several micro-continents or island arcs that were accreted together billions of years ago. The Yilgarn Craton is a classic example of several terranes forming a larger cratonic block.

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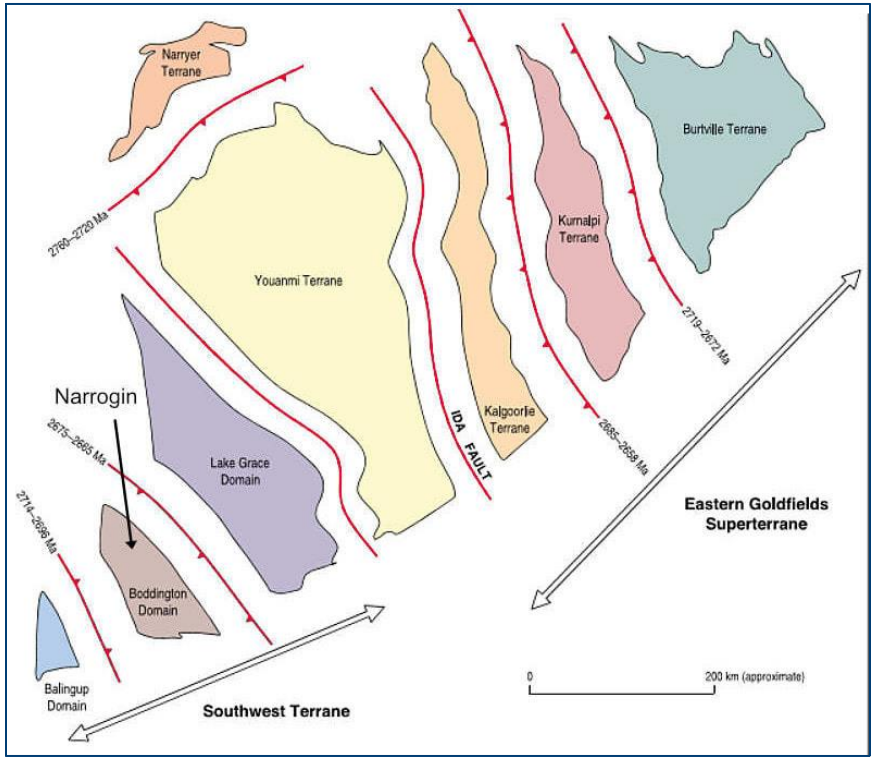

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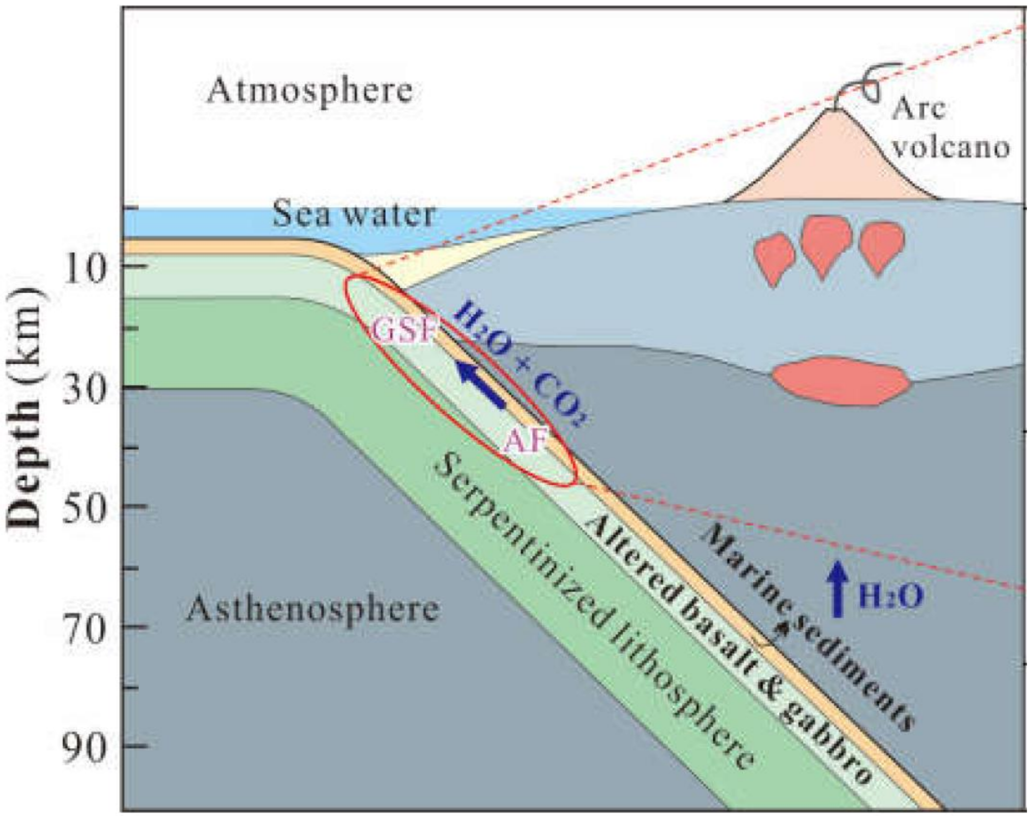
- **Metasomatic enrichment by subduction zone fluids (fluids exsolved off a subducted slab of oceanic lithosphere)**
- Craton formation should correspond with a specific composition of surface volcanism such as andesites and sanukitoids
- Absence of high-temperature and high-volume melts (such as those formed in plumes)



During subduction and/or the stacking of oceanic segments of lithosphere, there may be fluids that are exsolved off the slab into the underlying mantle. These fluids cause geochemical enrichment of the surrounding rocks.

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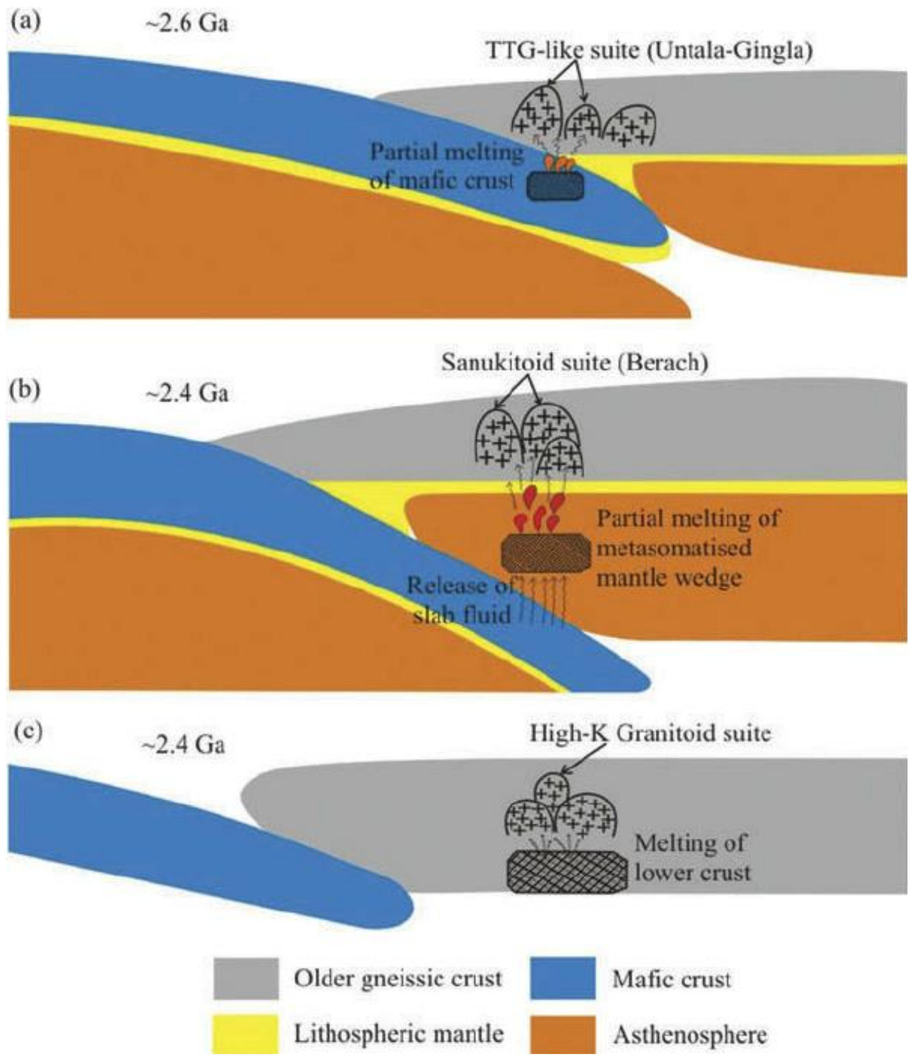
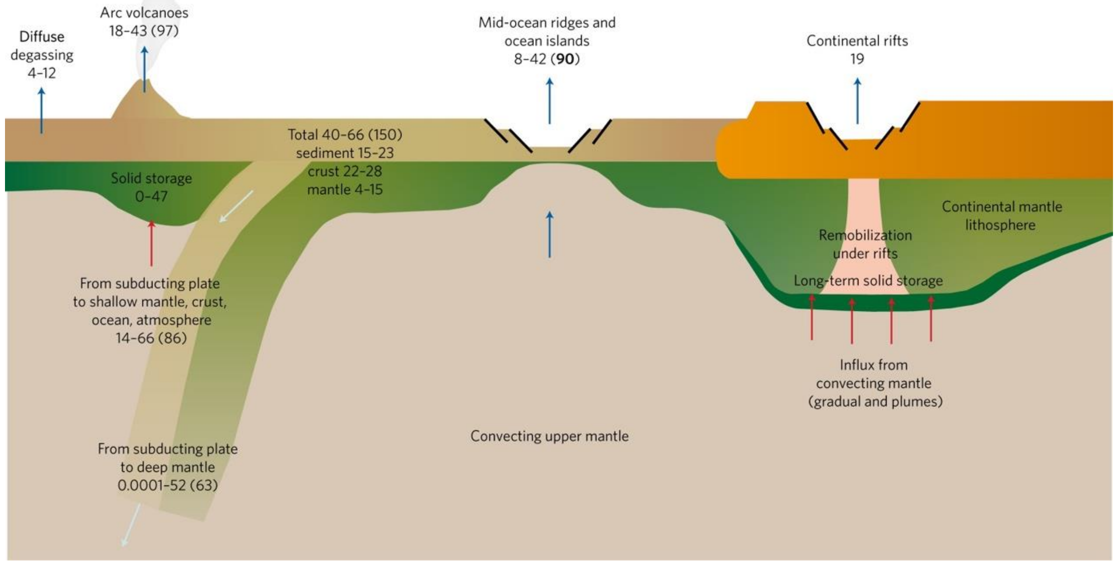


Can Cratons be Destroyed?

The chemical properties of cratonic lithospheric mantle (melt-depleted and buoyant) helps preserve cratons for billions of years:

- The buoyant lithosphere is cold, but it is geochemically depleted and is therefore difficult into subduct beneath continents
- Cratons are melt-depleted and therefore it is extremely difficult to re-melt cratons further above new mantle plumes
- **These properties prevent deformation and magmatism within the interiors of cratons and contribute to their longevity**



The geochemical properties of cratons (owing to their formation mechanisms) allow for very thick and buoyant lithosphere that is very difficult to subduct and re-melt. These properties help for cratons to survive on Earth for Billions of years.

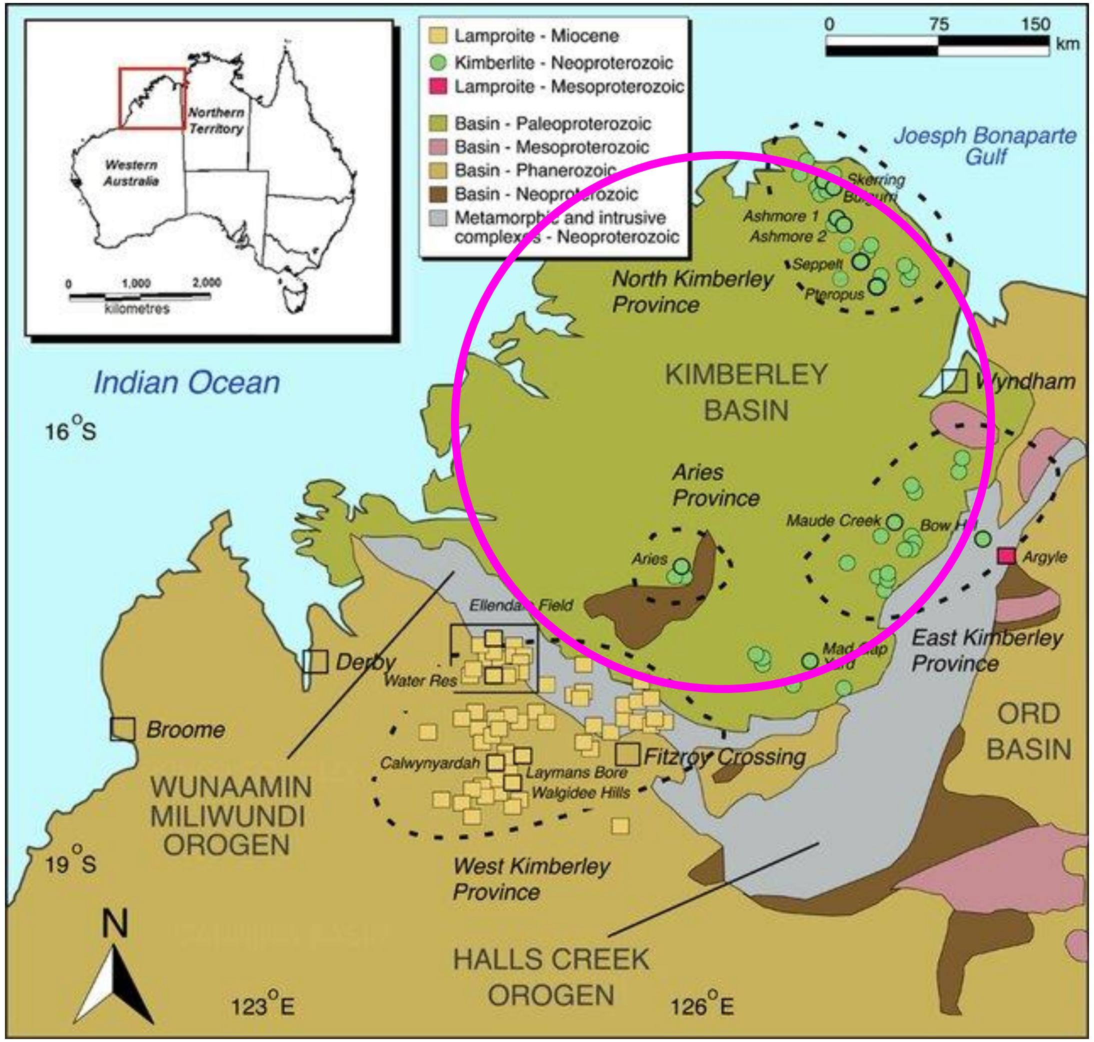
Destroying and Modifying Cratons

Indeed, the surface geology of many cratons show considerable deformation and magmatism along their margins but almost nothing within the interior:

The interiors of cratons are usually the thickest and most melt-depleted meaning they cannot subduct and rarely re-melt

Examples of magmatism and deformation around the margins of cratons can be observed at the Kimberley Craton (Australia) and most of Kaapvaal and surrounds (Southern Africa)

Craton interior

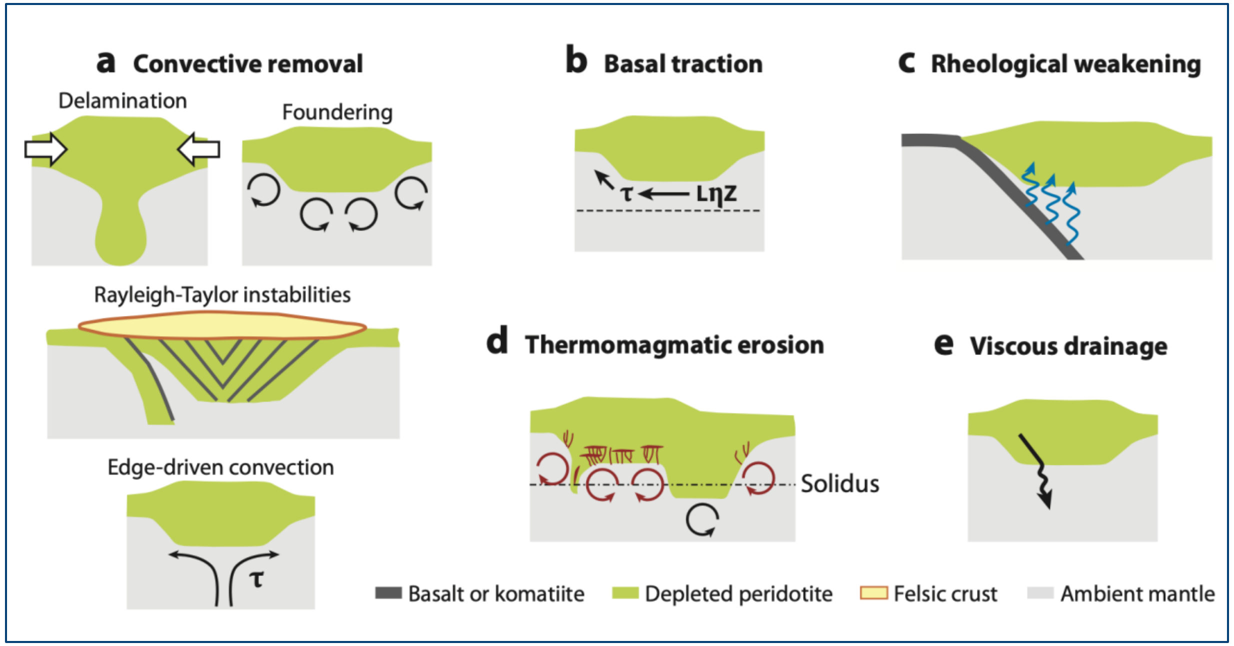


Destroying and Modifying Cratons

There are several mechanisms that may result in the modification and/or removal of cratonic lithospheric mantle:

- Convective removal
- Basal traction
- Rheological weakening
- Thermal-magmatic erosion
- Viscous drainage

These mechanisms have, to some capacity, likely operated throughout geological time, although it is not always easy to observe them and quantify their effects on the structure of the cratonic lithospheric mantle



Summary of different mechanisms that may result in the modification and/or removal of cratonic lithospheric mantle through time. a) Convective removal. b) Basal traction. c) Rheological weakening. d) Thermal-magmatic erosion. e) Viscous drainage. After Lee et al. (2011).

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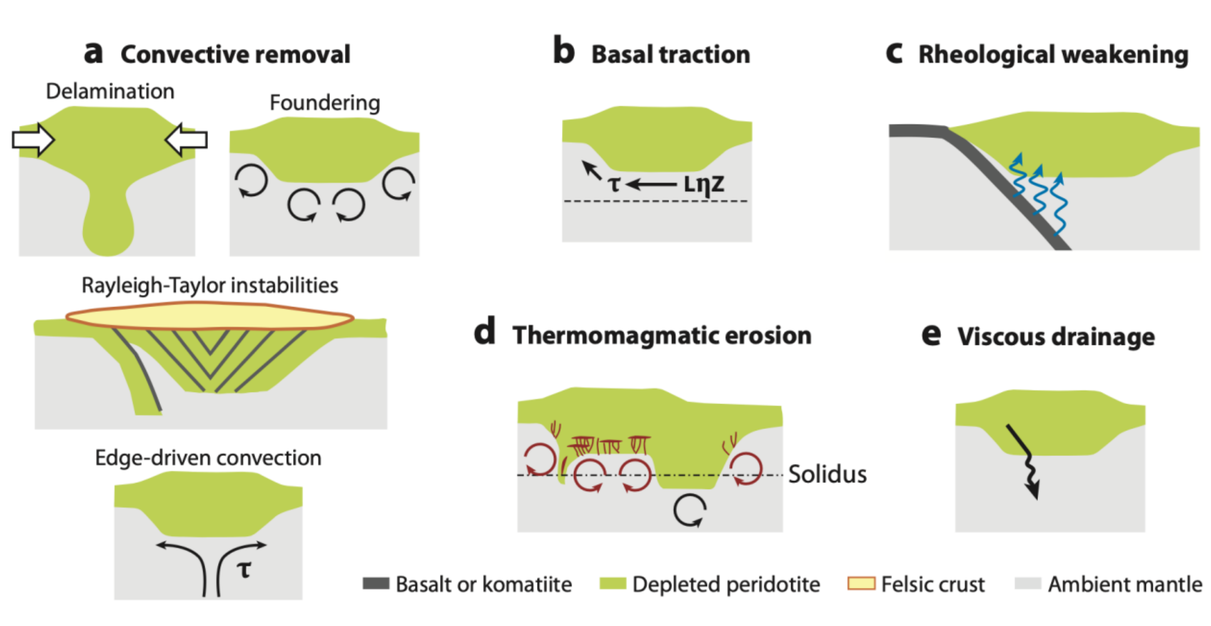
The deformation and modification of cratons is an important area of research that requires additional observations and constraints (outside of just NC Craton)



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Destroying and Modifying Cratons

Convective removal: Any lithospheric removal driven by thermal or chemical buoyancy forces (e.g., density-driven forces) is referred to as convective removal

Degree to which buoyancy forces exceed resisting forces (e.g., friction) defines the rate and nature of convective removal

Both vertical and lateral temperature contrasts can drive small-scale convective instabilities, promoting lithospheric erosion from below

Examples: Wyoming and Tanzania

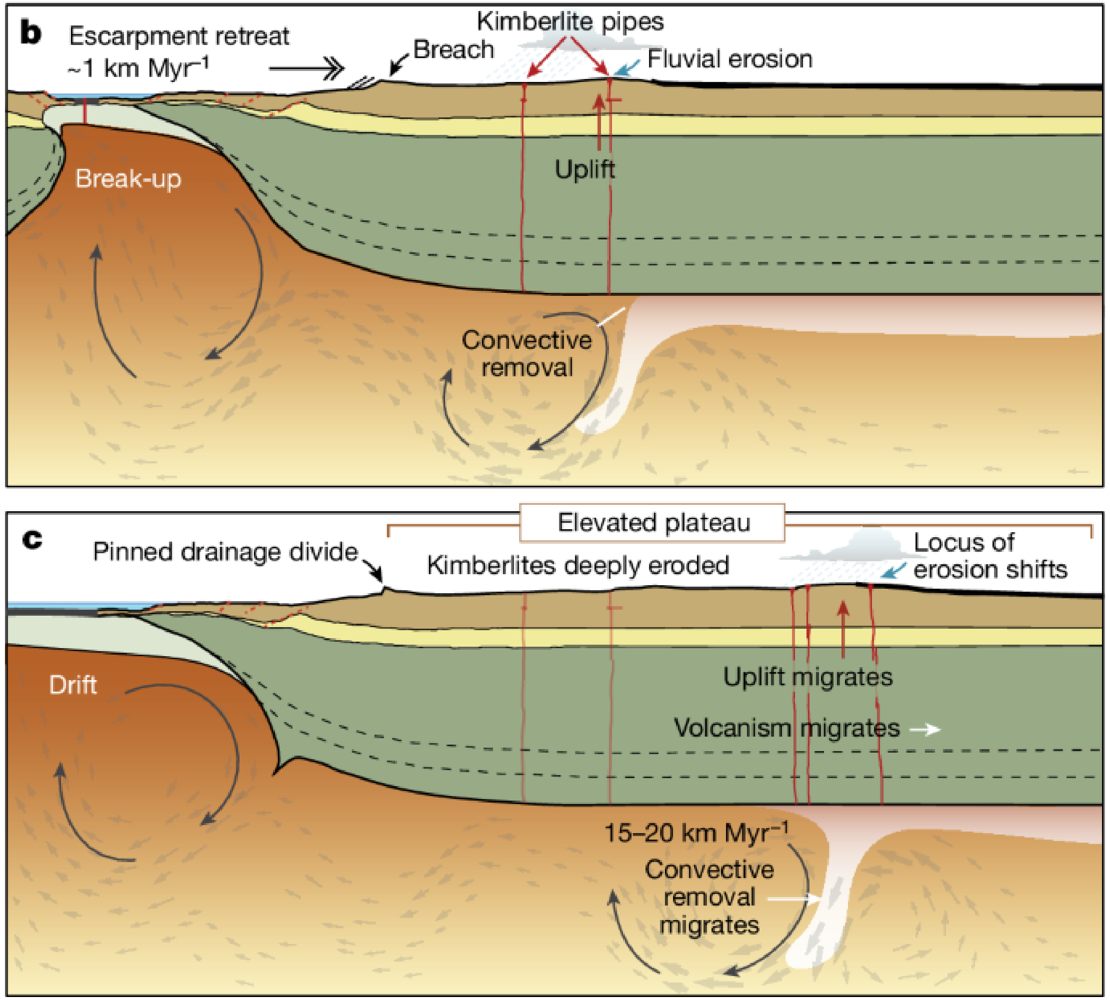

Image: *Cartoon of convective removal (after Gernon et al. 2024)*

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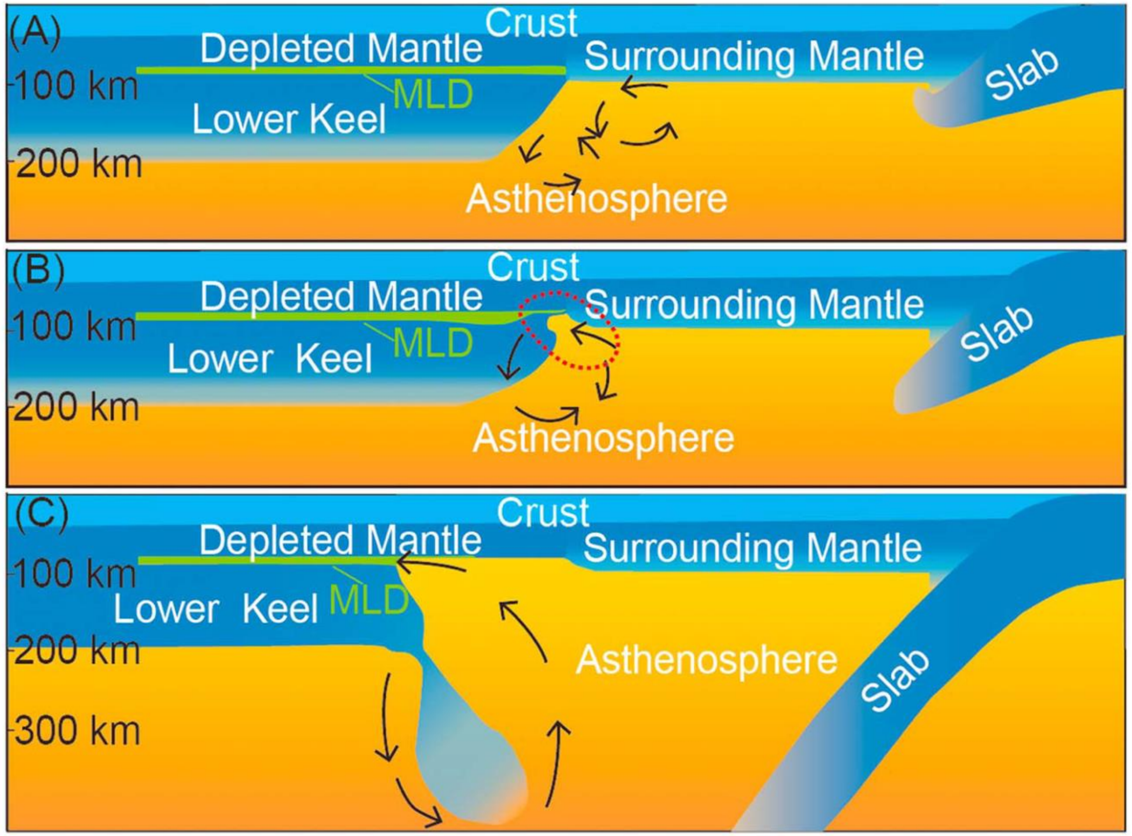

***Image:** Cartoon of convective removal (delamination) (after Liu et al. 2018)*

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Destroying and Modifying Cratons

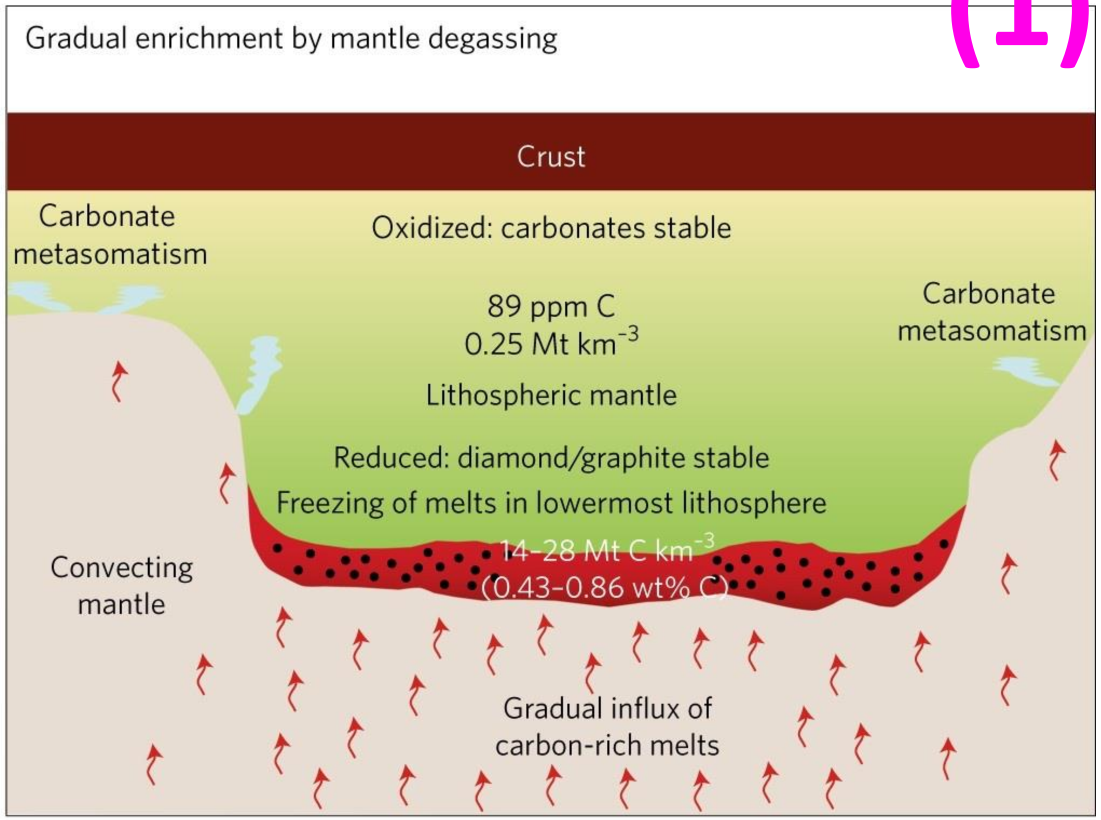
(1)

Rheological weakening: The base of the lithospheric mantle is nominally anhydrous, but it may become rehydrated (addition of volatiles) by metasomatic processes

The addition of volatiles (to form new minerals like phlogopite or amphibole) helps to lower the melting temperature of the base of the lithosphere and changes its strengths

These properties make it easier for convective removal of sections of rehydrated and metamorphosed lithosphere. Likely small-scale removal/erosion

a



b

***Image:** Cartoon of rheological weaking which may facilitate convective removal. After Foley and Fischer (2017)*

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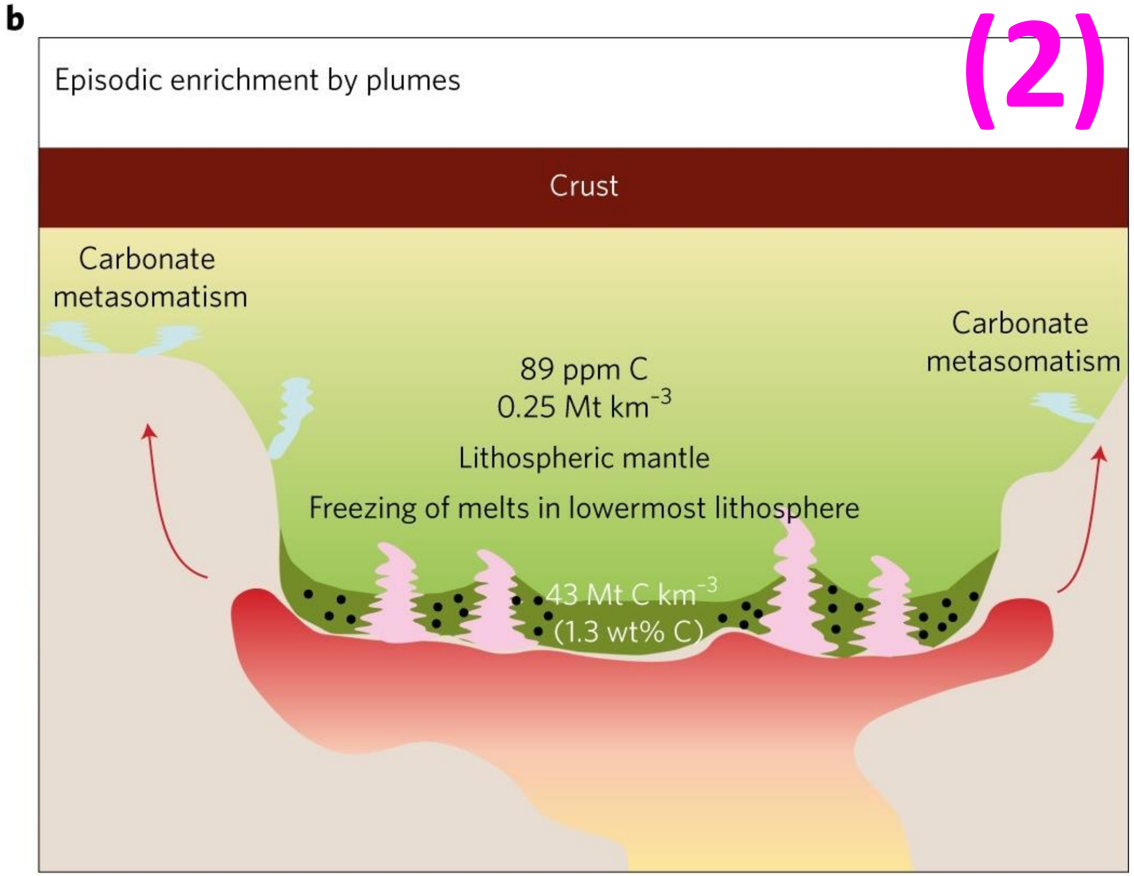

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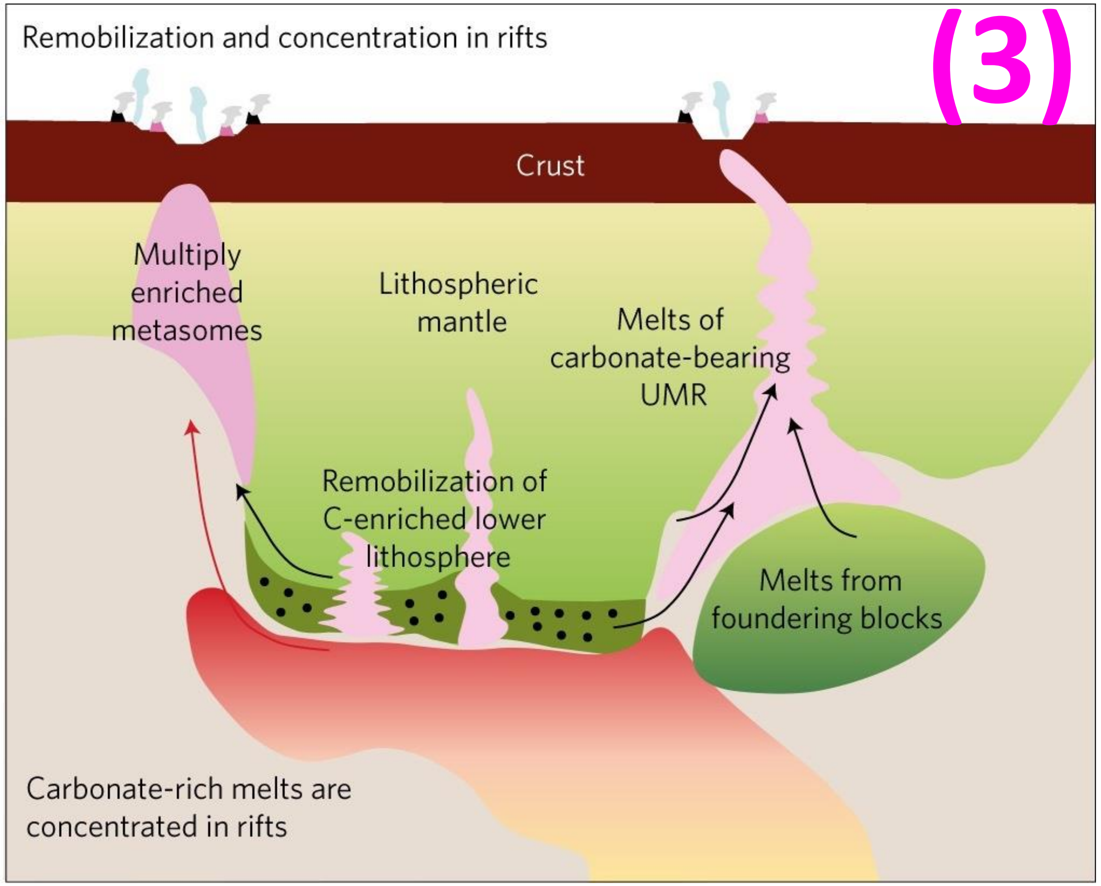

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Quick break for Questions…..