Understanding Earth's Lithospheric Mantle as a Geochemical and Petrological System: Part 1.

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About Me –

Dr. Zachary John Sudholz

BSc. (Geoscience) – Monash University
BSc. (Hons) (Met. Petrology) – University of Western Aust.
PhD. (Exp. Petrology) – Australian National University
Postdoctoral Fellow – Australian National University
Research Associate – University of Cambridge

Primary Research Interests:
High temperature petrology/geochemistry
Experimental and mantle petrology
Lithosphere structure and composition
Formation and evolution of cratons
Magma emplacement mechanisms

Me at the Olivine Capital of Australia (Extinct Volcano at Mortlake Western Victoria)!

Aims and Motivation for Part 1.

Lithospheric Mantle as a Geochemical and Petrological System

- Understand how mantle petrology can be studied (i.e., experiments, xenoliths…)
- Understand the main rock types and minerals within the lithospheric mantle
- Understand how pressure-temperature can influence mantle mineralogy and lithology (rock type)
- Understand how volatiles (CO2 and H2O) can affect mantle mineralogy and lithology
- Sufficient context for following lectures on Structure of Lithosphere (petrology and geochemistry)

Recommended Reading:

- Pearson, D. G., D. Canil, and S. B. Shirey. "Mantle samples included in volcanic rocks: xenoliths and diamonds." *Treatise on geochemistry* 2 (2003): 568.
- Anderson, Don L., and Jay D. Bass. "Mineralogy and composition of the upper mantle." *Geophysical Research Letters* 11.7 (1984): 637-640.
- Hacker, Bradley R., Geoffrey A. Abers, and Simon M. Peacock. "Subduction factory 1. Theoretical mineralogy, densities, seismic wave speeds, and H2O contents." *Journal of Geophysical Research: Solid Earth* 108.B1 (2003).

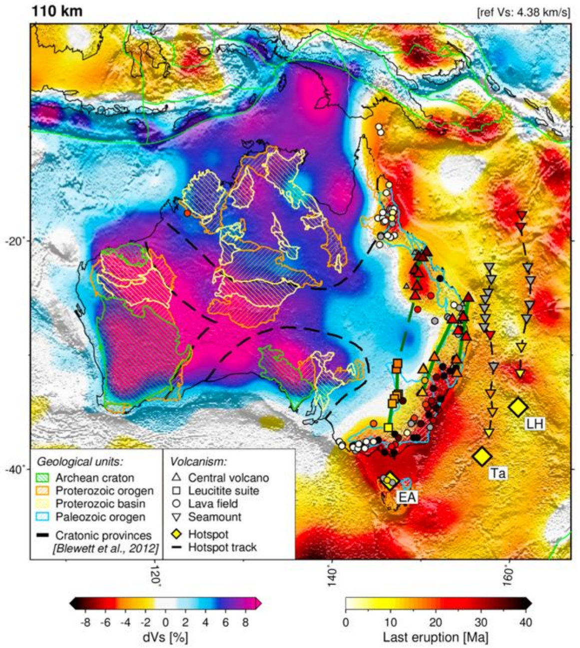
Petrology and Geochemistry of the Mantle

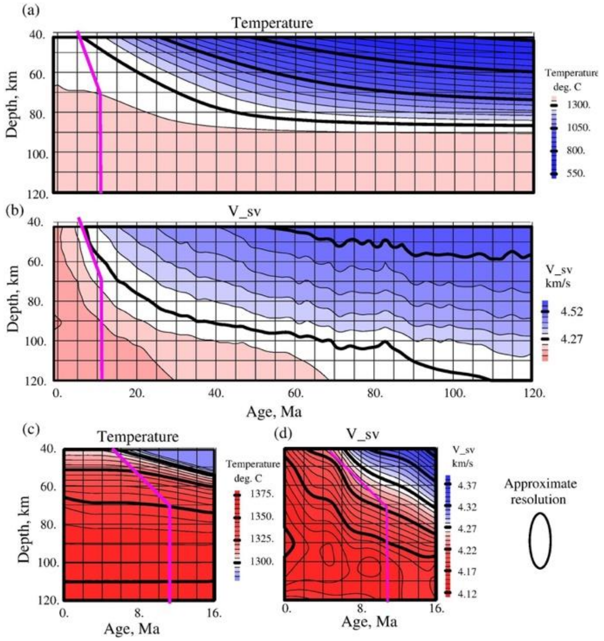
Geophysics

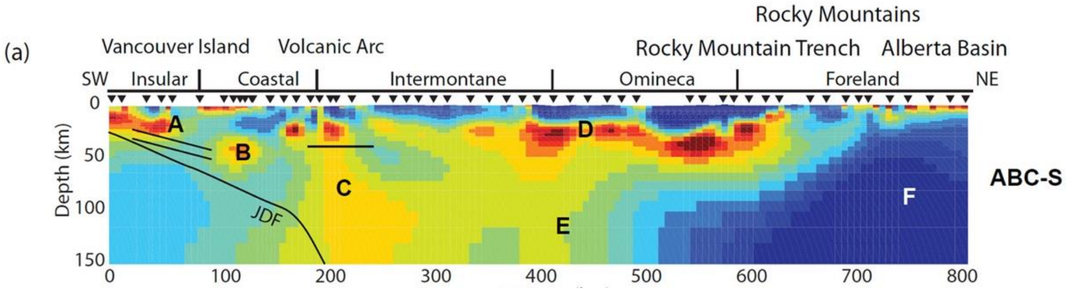
- Surface and Body Waves
- Magnetotellurics
- Geodynamics and Theory

Petrology and Geochemistry

- Experimental Petrology
    - Piston Cylinder and Multi Anvil
    - Furnace Experiments
- Natural Samples
    - Ocean Dredging and Ophiolites
    - Extra Terrestrial
    - Volcanic Erruptions







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Experimental Petrology:
Make synthetic rocks and minerals in the lab using specialized experimental equipment – study mantle experimentally

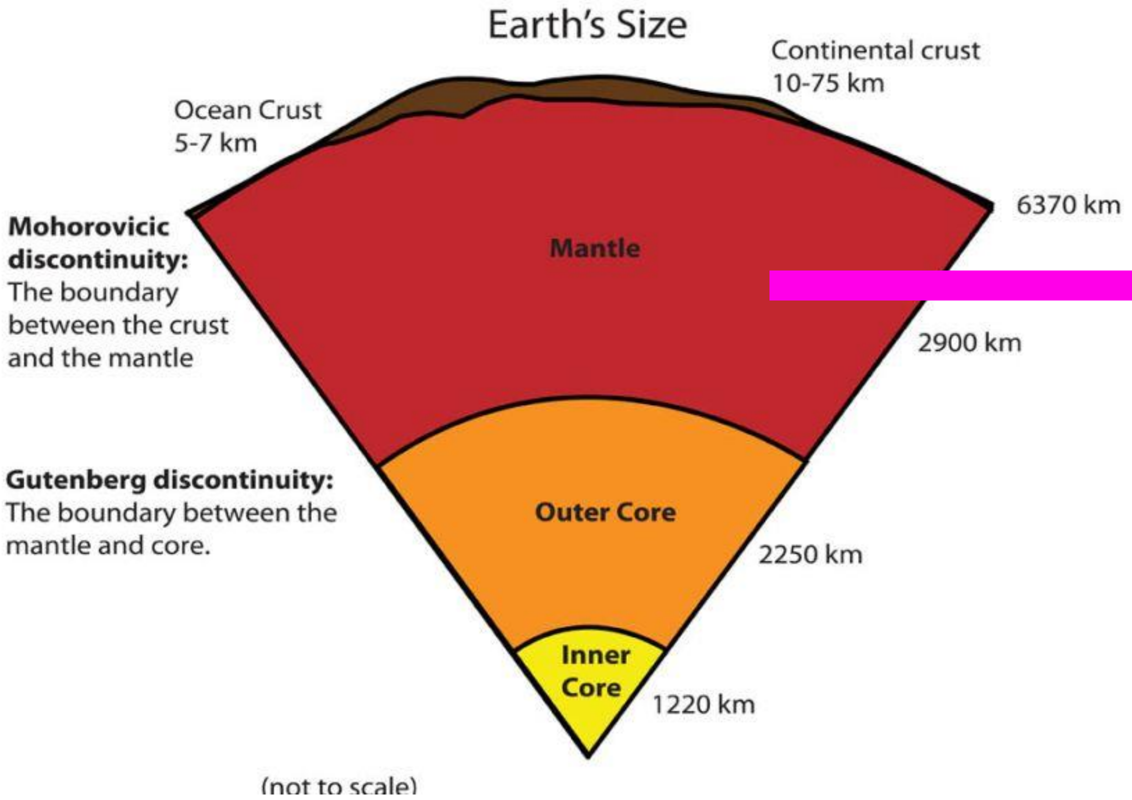
Natural samples:
Collect pieces of the mantle from volcanoes or exposed segments of the upper mantle – study mantle naturally

The next 20 minutes will will briefly discuss the use of these approaches for studying the petrology and geochemistry of the lithospheric mantle

Petrology: (from Ancient Greek πέτρος (pétros) 'rock' and -λογία (-logía) 'study of') is the branch of geology that studies rocks, their mineralogy, composition, texture, structure and the conditions under which they form. Petrology has three subdivisions: igneous, metamorphic, and sedimentary petrology.

Geochemistry: is the science that uses the tools and principles of chemistry to explain the mechanisms behind major geological systems such as the Earth’s crust and its mantle.

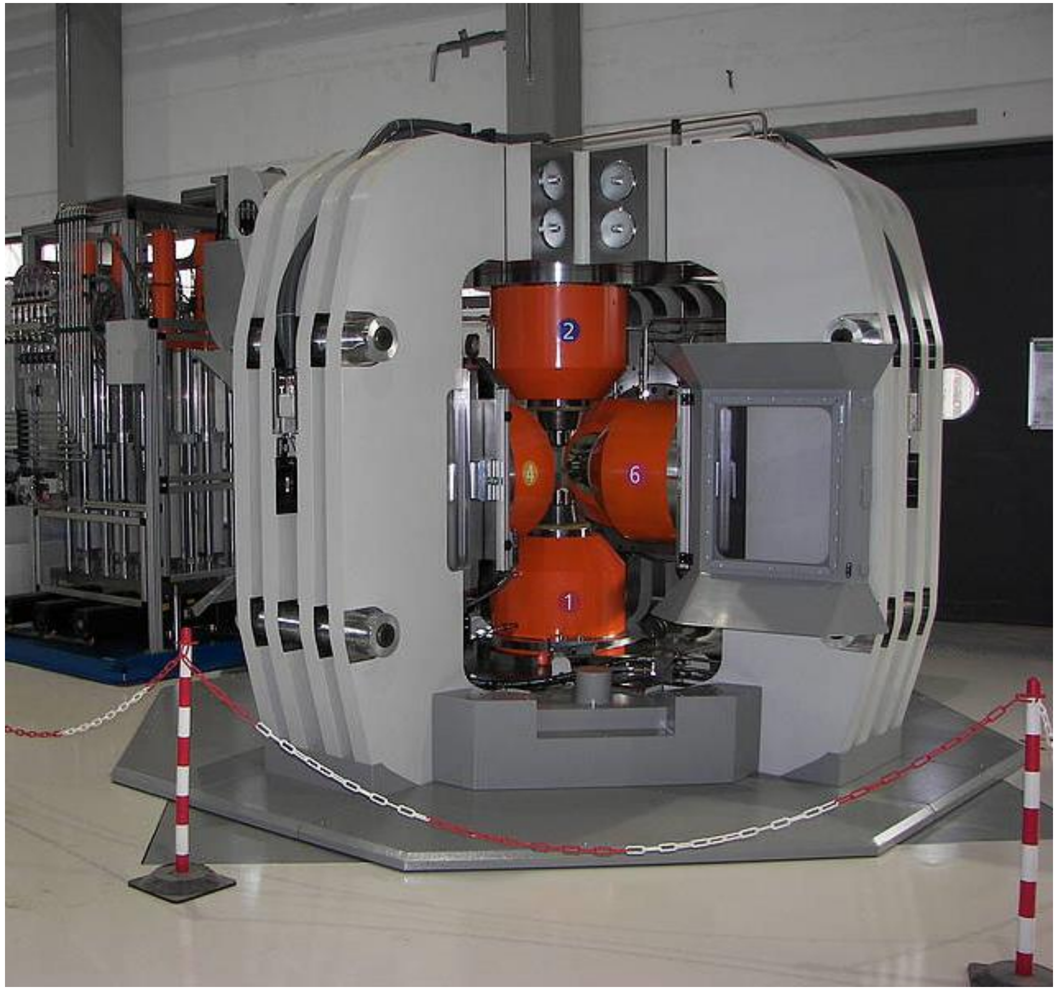
Petrology and Geochemistry of the Mantle – Experiments

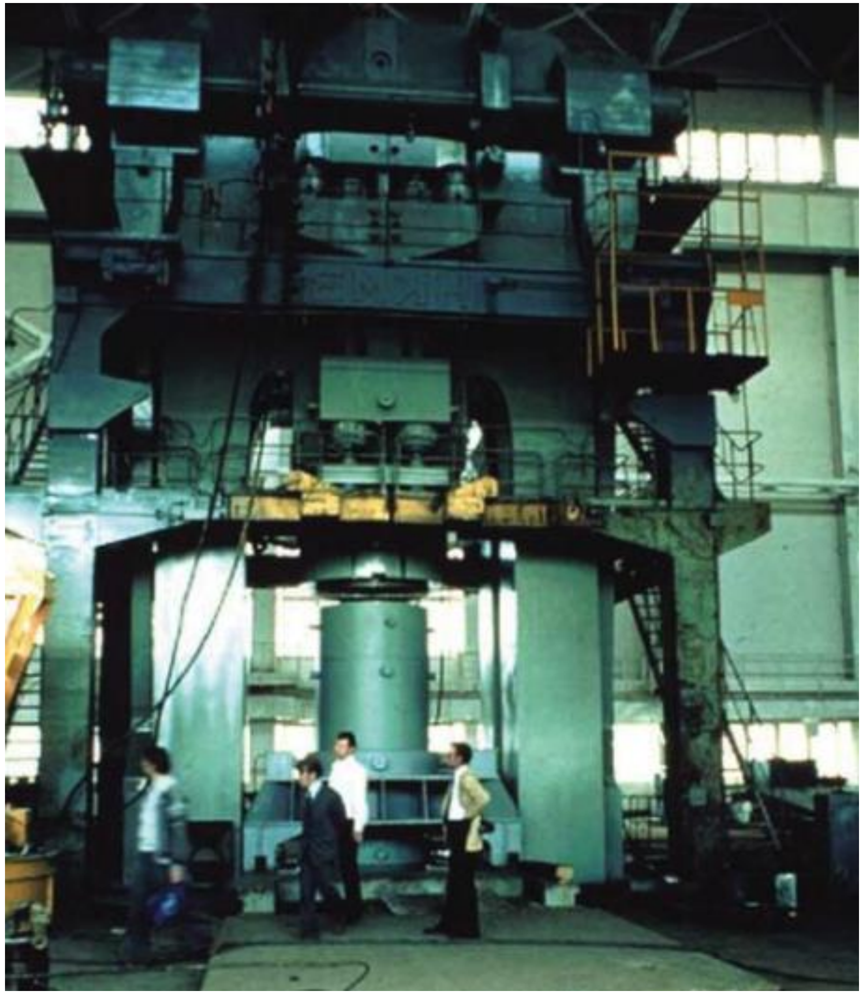


Simulate PT conditions of mantle in the lab

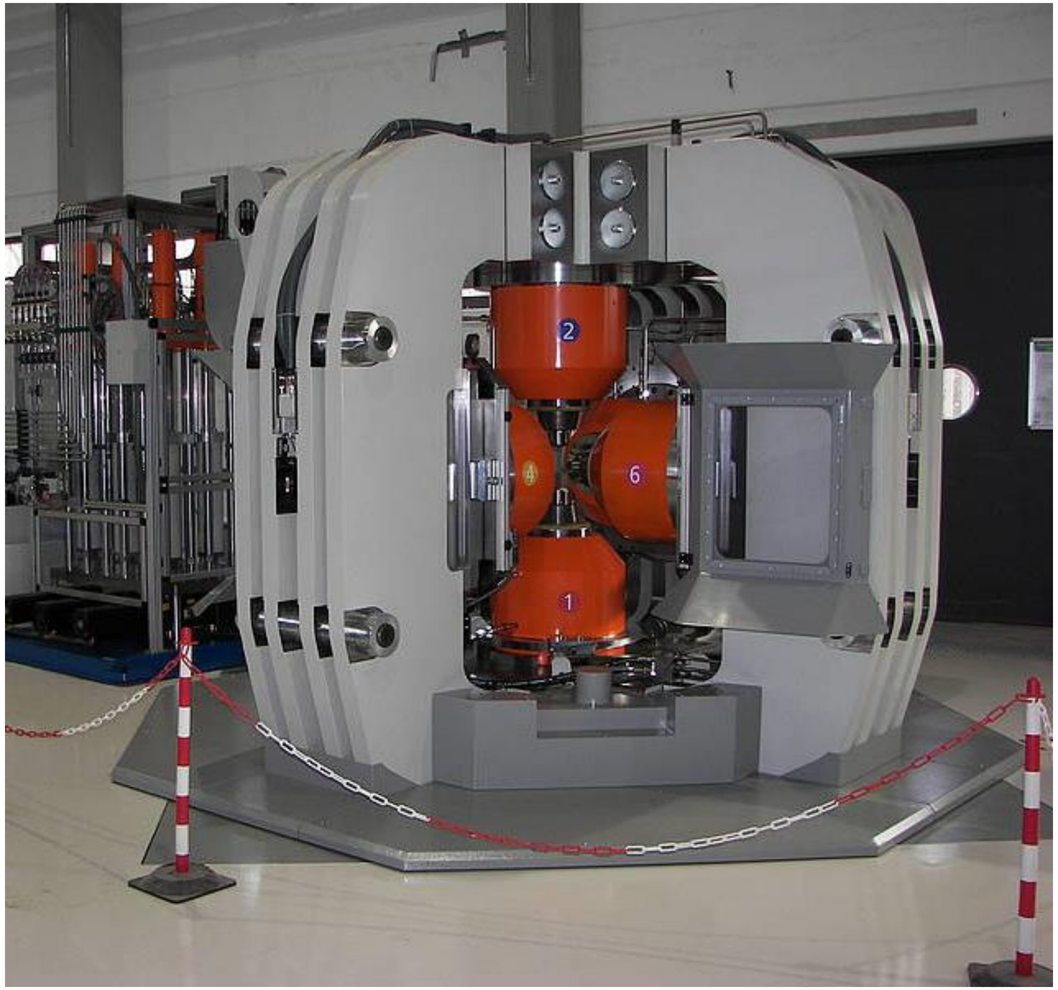
Piston-cylinder press used for high-temperature high-pressure experiments of Earth's lithosphere. After USGS

Petrology and Geochemistry of the Mantle – Experiments

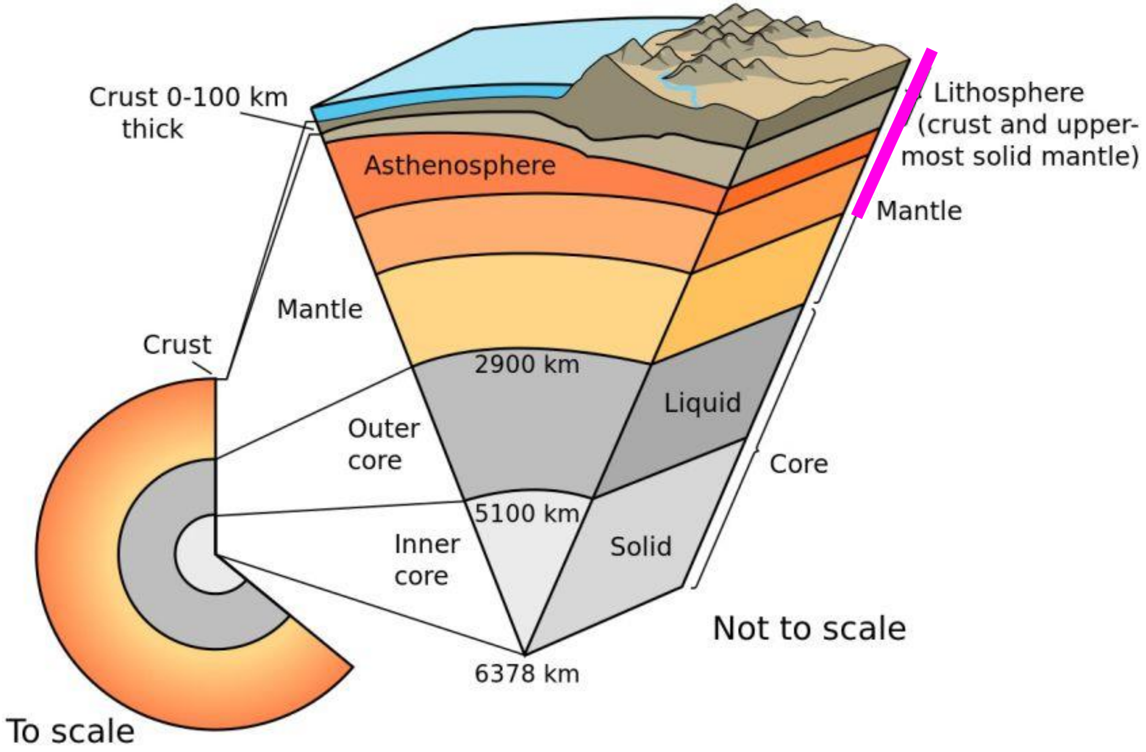




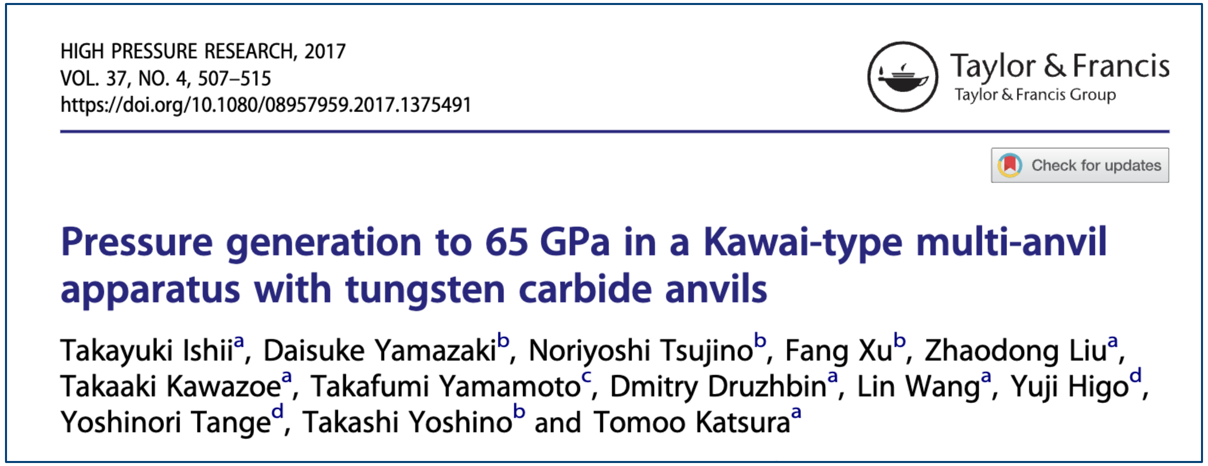
Petrology and Geochemistry of the Mantle – Experiments



Most experimental apparatuses can simulate pressures and temperatures from the lithospheric mantle to transition zone



Petrology and Geochemistry of the Mantle – Experiments



HIGH PRESSURE RESEARCH, 2017
VOL. 37, NO. 4, 507–515
https://doi.org/10.1080/08957959.2017.1375491

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Pressure generation to 65 GPa in a Kawai-type multi-anvil apparatus with tungsten carbide anvils

Takayuki Ishii[a], Daisuke Yamazaki[b], Noriyoshi Tsujino[b], Fang Xu[b], Zhaodong Liu[a], Takaaki Kawazoe[a], Takafumi Yamamoto[c], Dmitry Druzhbin[a], Lin Wang[a], Yuji Higo[d], Yoshinori Tange[d], Takashi Yoshino[b] and Tomoo Katsura[a]

Check for updates

Diamond anvil cell behavior up to 4 Mbar

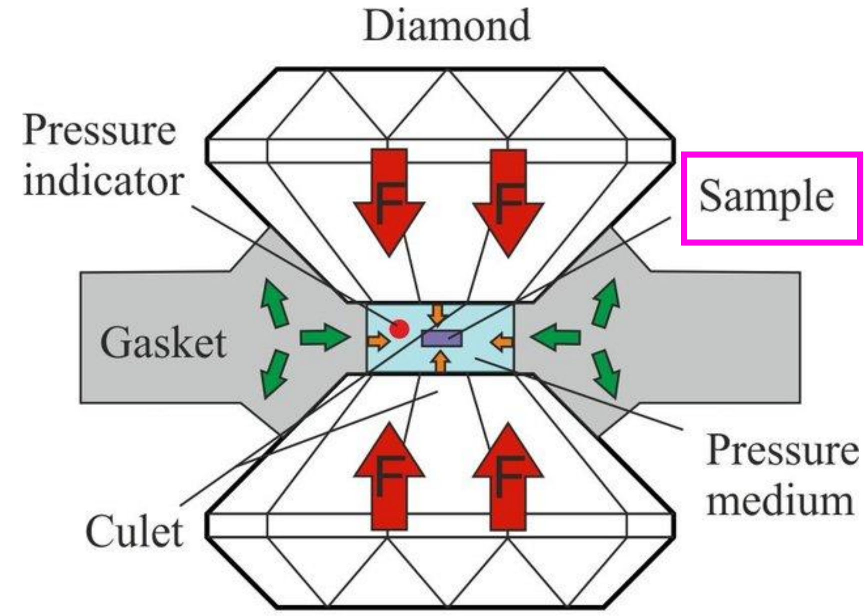
Bing Li[a,b,c,d,1], Cheng Ji[d,e], Wenge Yang[a,d], Junyue Wang[a,d], Ke Yang[f], Ruqing Xu[g], Wenjun Liu[g], Zhonghou Cai[g], Jiuhua Chen[a,b,c], and Ho-kwang Mao[a,d,h,1]

[a]Center for High Pressure Science and Technology Advanced Research, 201203 Shanghai, China; [b]Center for the Study of Matter at Extreme Conditions, Florida International University, Miami, FL 33199; [c]Department of Mechanical and Materials Engineering, Florida International University, Miami, FL 33199; [d]High Pressure Synergetic Consortium, Carnegie Institution of Washington, Argonne, IL 60439; [e]High Pressure Collaborative Access Team, Geophysical Laboratory, Carnegie Institution of Washington, Argonne, IL 60439; [f]Shanghai Synchrotron Radiation Facility, Shanghai Institute of Applied Physics, Chinese Academy of Sciences, 201800 Shanghai, People's Republic of China; [g]Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439; and [h]Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC 20015

Contributed by Ho-kwang Mao, January 12, 2018 (sent for review December 13, 2017; reviewed by Takehiko Yagi and Choong-Shik Yoo)

PNAS

More pressure = apply more force to a smaller sample size



$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

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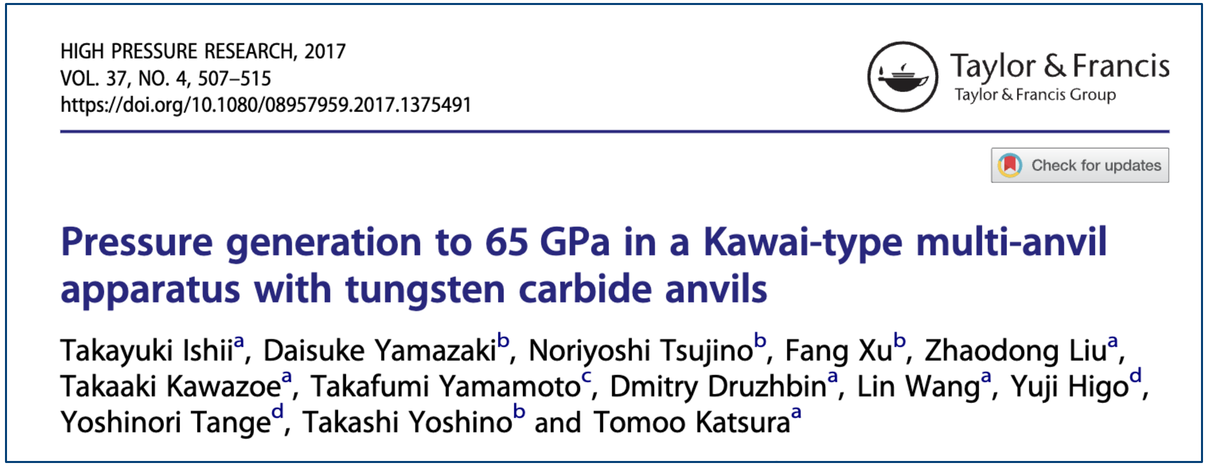

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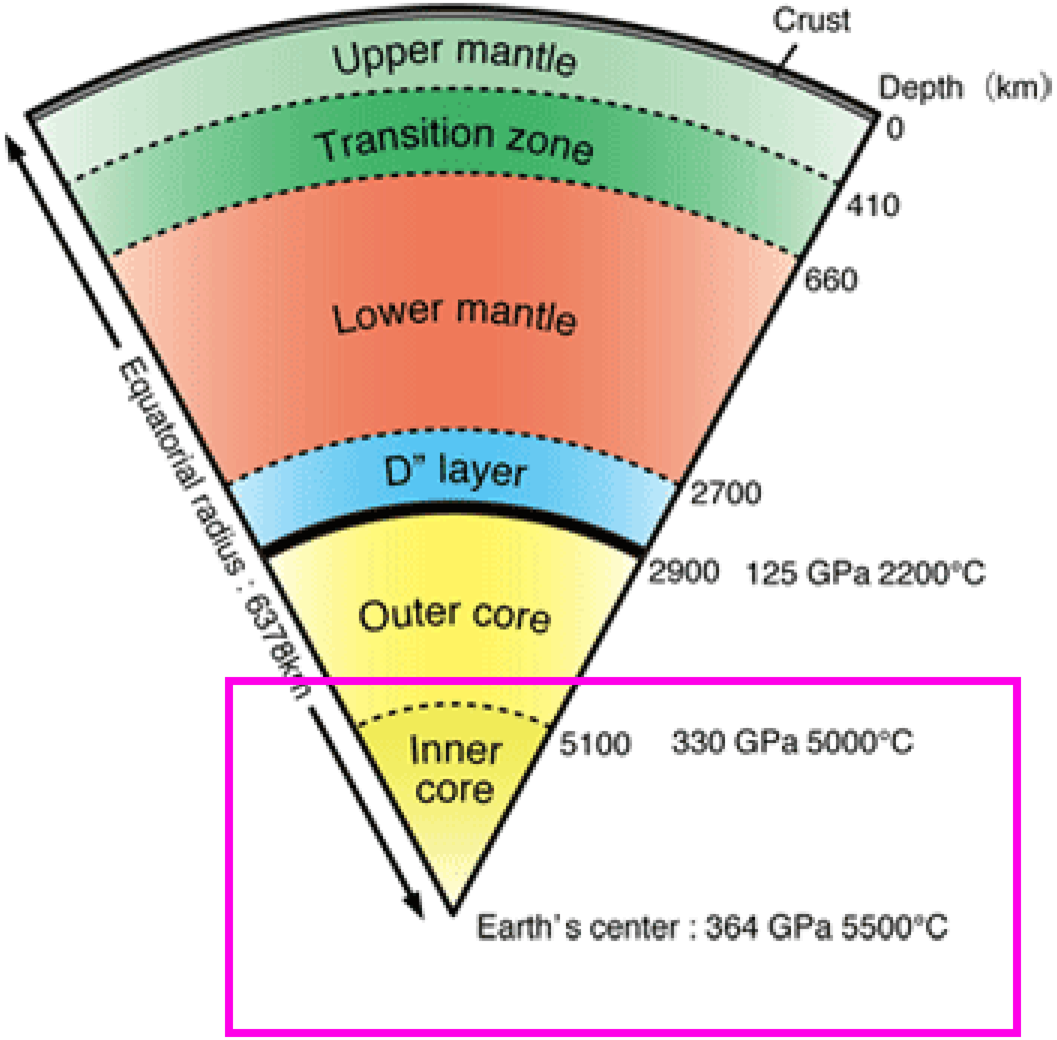

Petrology and Geochemistry of the Mantle – Experiments

Experimental Petrology of Mantle:

Study the chemical and physical behavior of synthetic rock and mineral mixtures at elevated pressures and temperatures using a piston cylinder and/or multi-anvil apparatus

Purpose: Simulate the pressure and temperature conditions of the mantle in the laboratory

Common approach is to use a starting mixture that is representative of the composition of the mantle and study the PT conditions that different rocks and minerals occur (MORB and Pyrolite)

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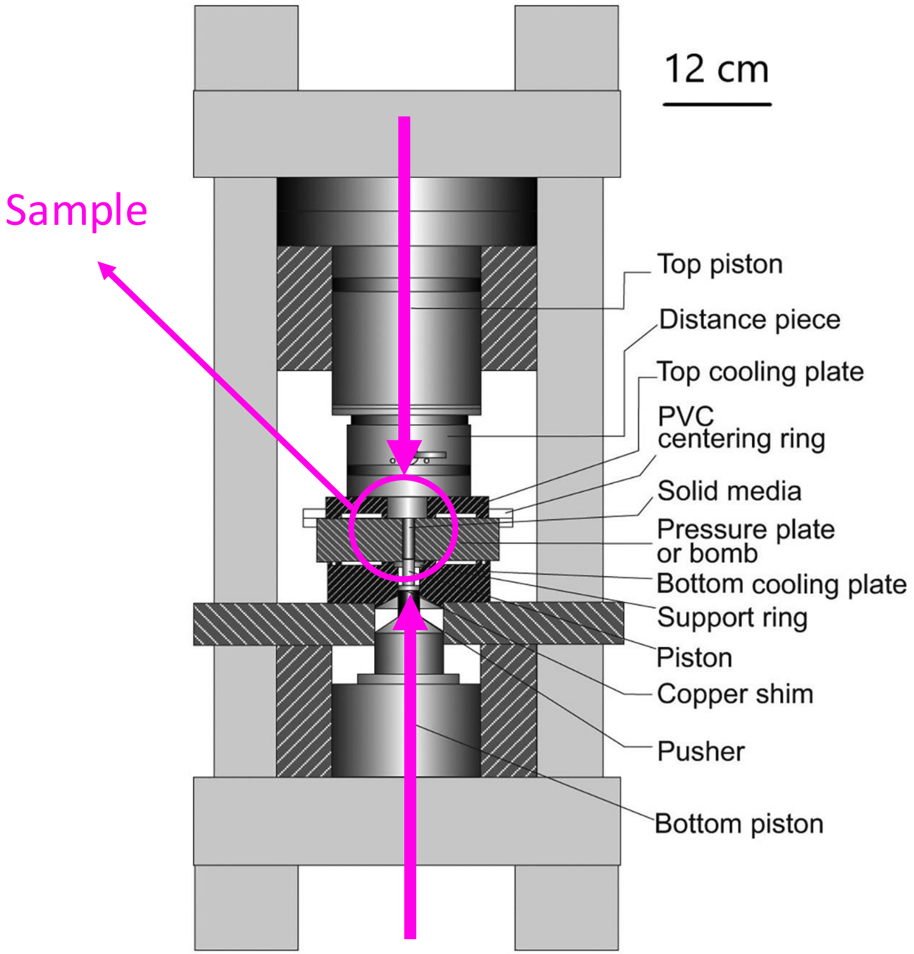

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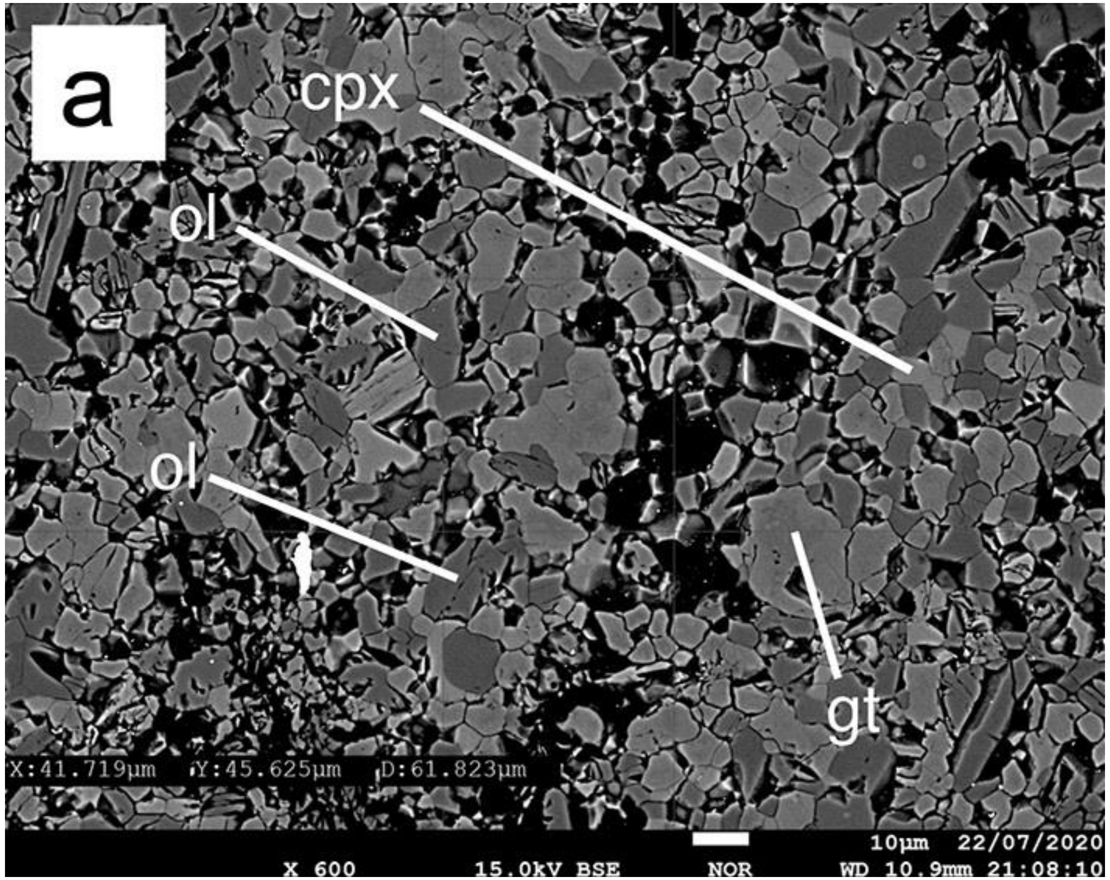


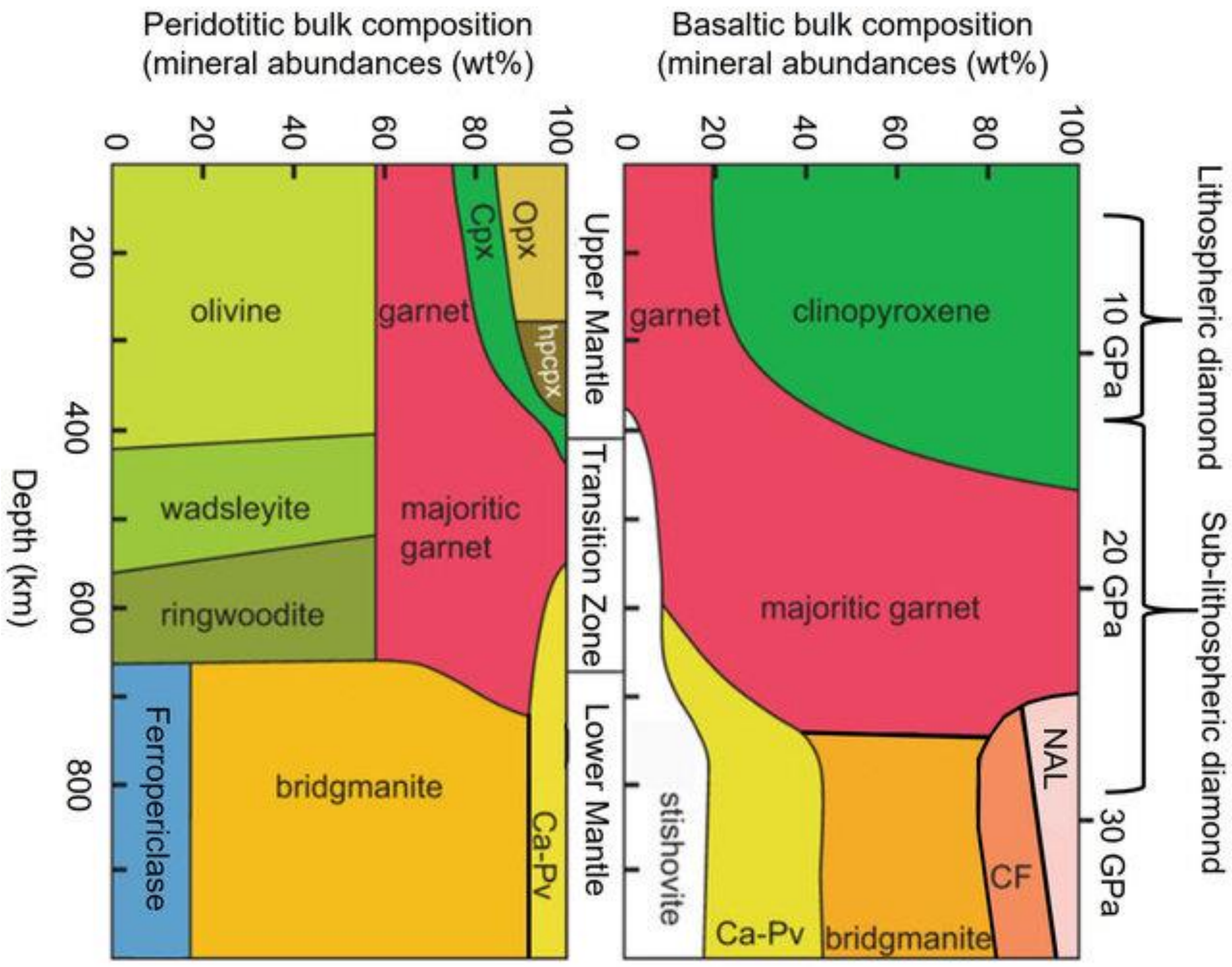
Scanning electron microscope image of synthetic mineral grains produced from a high-pressure and high-temperature experiment on a mantle-like composition. After Sudholz et al. (2021)

Petrology and Geochemistry of the Mantle – Experiments

Experimental Petrology of Mantle:
Important technique in the 1960's to identify phase transitions in the upper mantle

Conduct experiments on a fixed composition at different pressures and temperatures. Observe changes in the mineralogy that occur because of changes in PT

- Plagioclase to Spinel (<30 km)
- Spinel to Garnet (~60 km)
- Olivine to Wadsleyite (410 km discontinuity)
- Ringwoodite to Bridgmanite (660 km discontinuity)
- Ringwoodite to Ferro periclase (660 km)



Day et al. (2023)

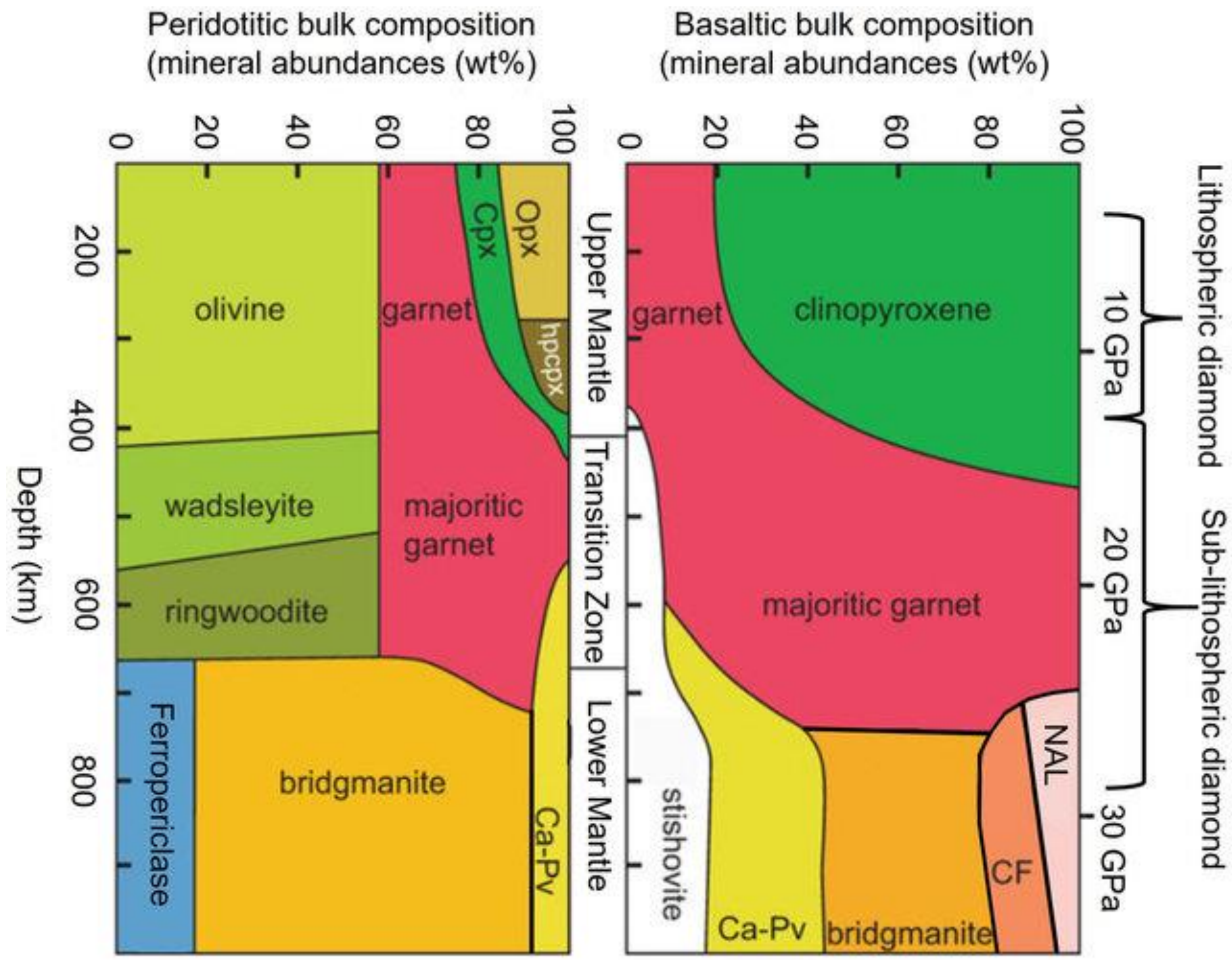
Petrology and Geochemistry of the Mantle – Experiments

Experimental Petrology of Mantle - Benefits:

- Ability to study inaccessible parts of the lithospheric mantle
- Test different geodynamic scenarios within the mantle (i.e., melting, decompression etc.)
- Study cont. and oceanic mantle

Experimental Petrology of Mantle - Challenges:

- Small sample sizes and unrepresentative grain size
- Experiments often assume a pyrolite mantle composition – is this truly representative?
- Errors and uncertainty on the pressure and temperature of experiments



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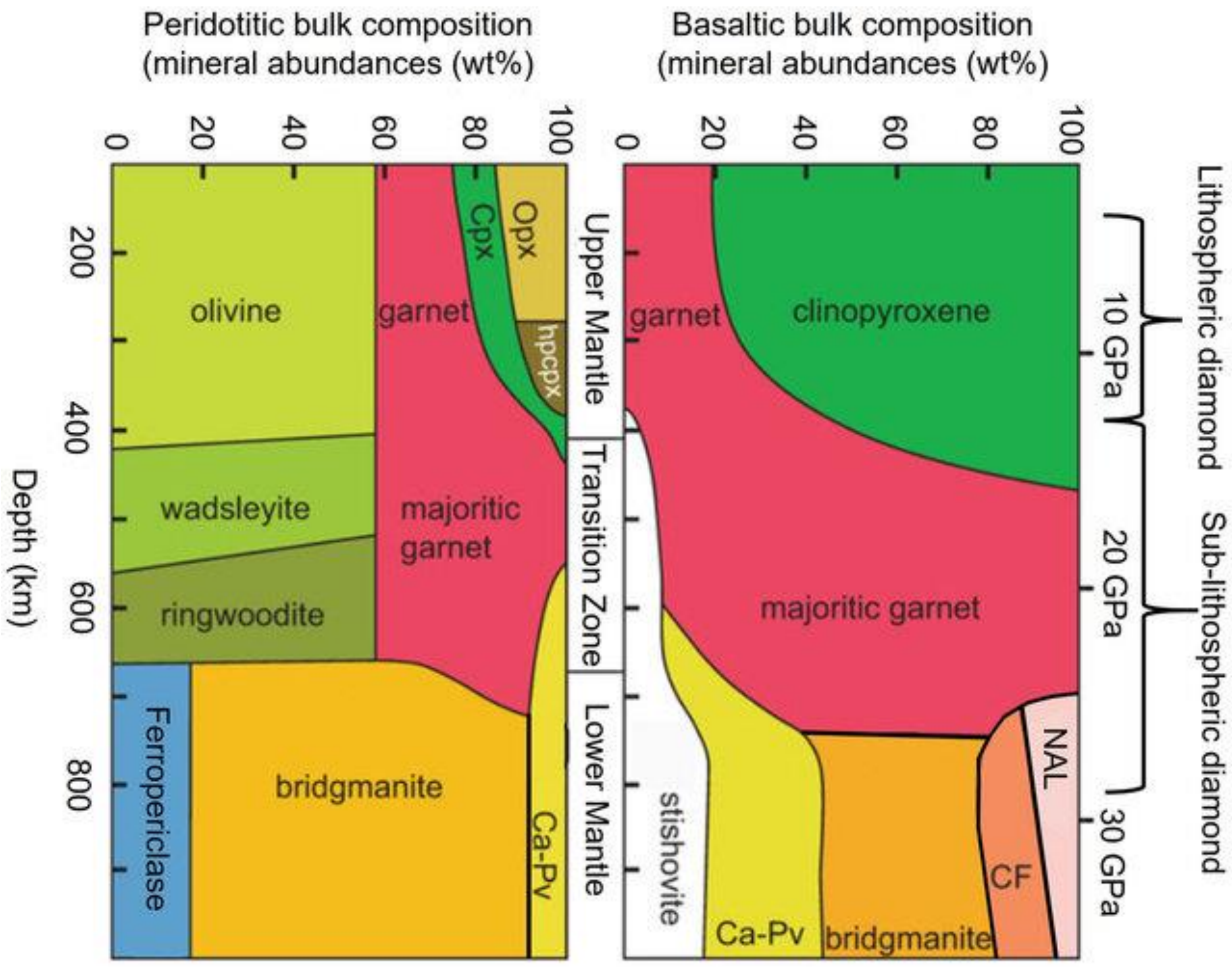
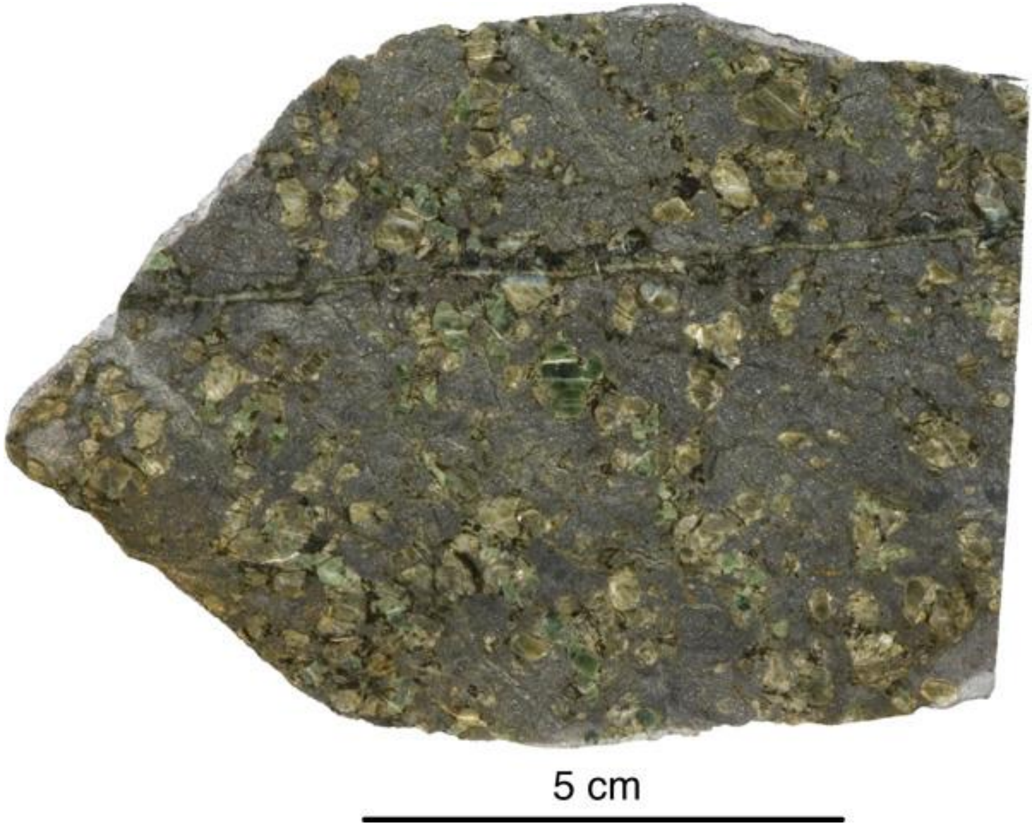
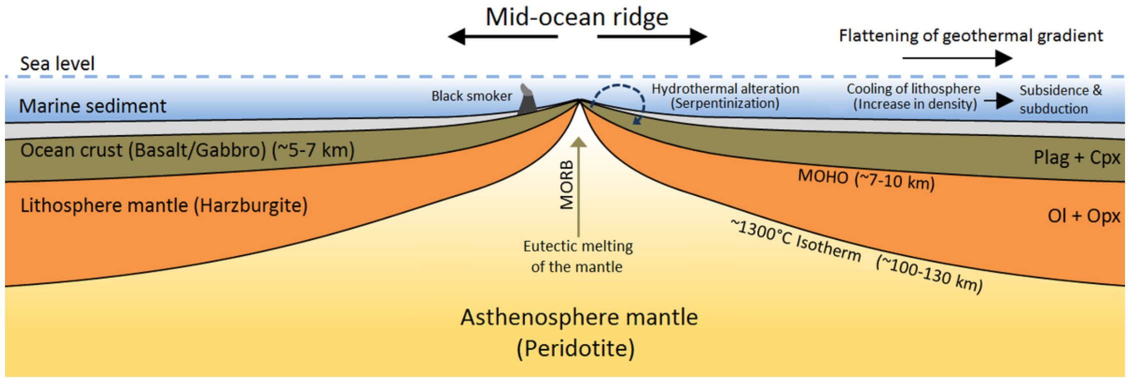


Day et al. (2023)

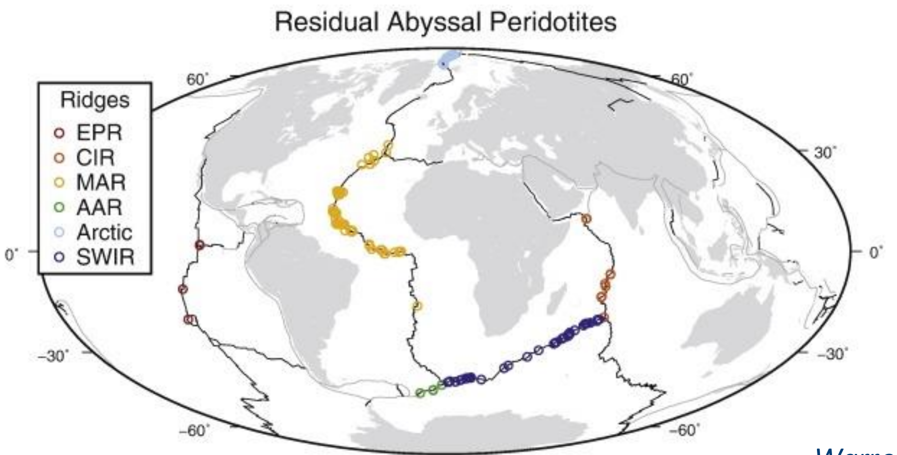
Petrology and Geochemistry of the Mantle – Natural Samples

Exposed pieces of oceanic lithospheric mantle – either at/near mid-ocean ridges or exhumed on convergent margins





Simplified illustration of a Mid-ocean ridge



Warren (2016) LITHOS

Petrology and Geochemistry of the Mantle – Natural Samples

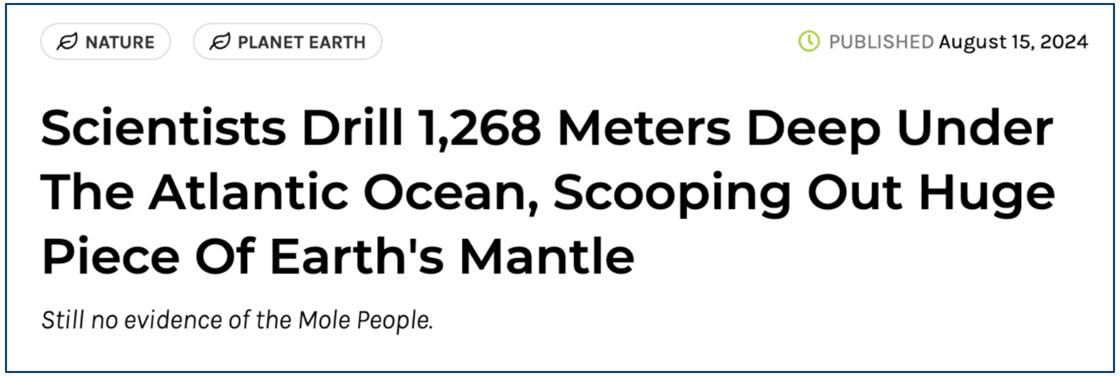
Deepest-ever samples of rock from Earth's mantle unveiled

Kilometre-long rock cores leave scientists wanting to know more – just when an international exploration effort is coming to an end.

At long last, ocean drillers exhume a bounty of rocks from Earth's mantle

Rocks fulfill 60-year-old quest and could yield science bonanza

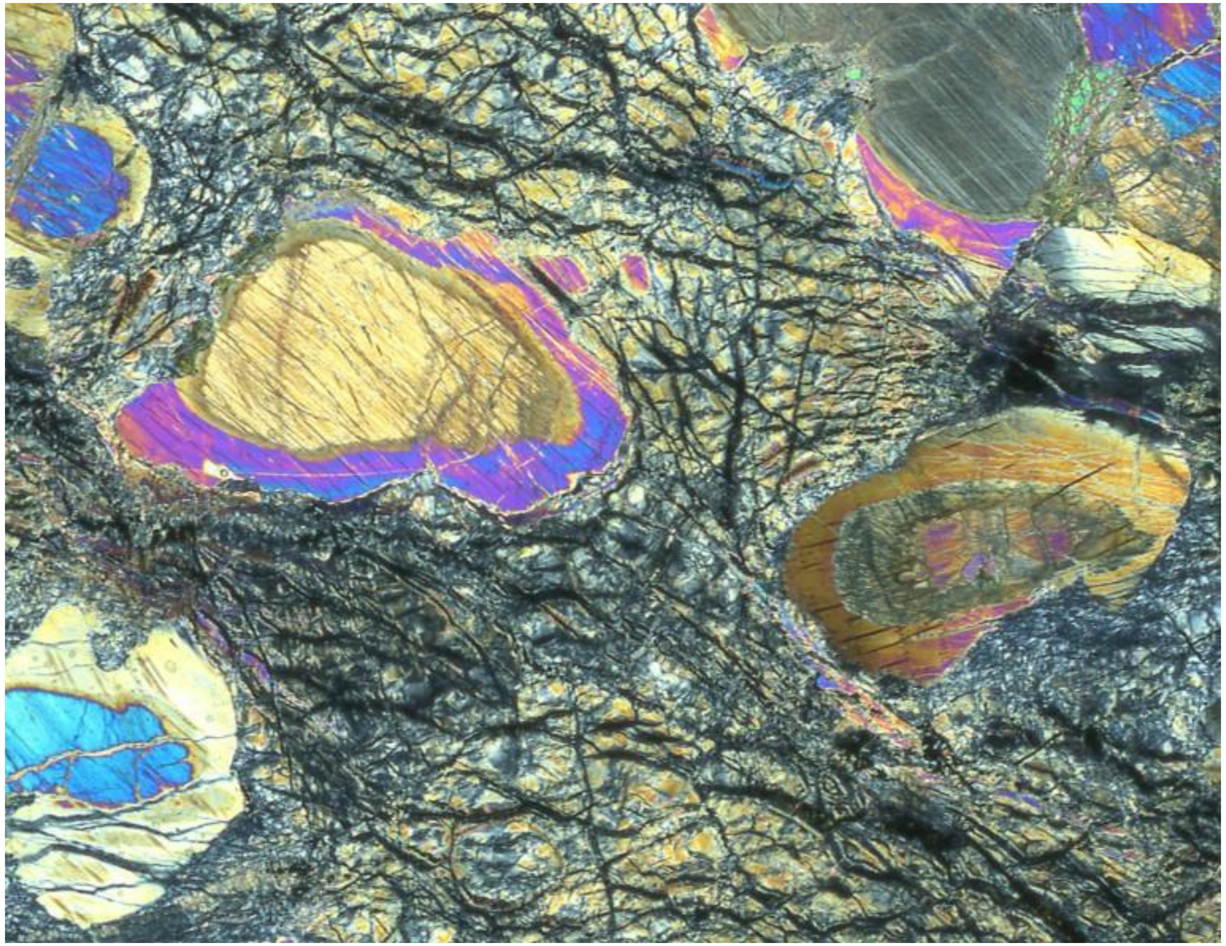
25 MAY 2023 • 12:20 PM ET • BY PAUL VOOSEN



NATURE PLANET EARTH PUBLISHED August 15, 2024

Scientists Drill 1,268 Meters Deep Under The Atlantic Ocean, Scooping Out Huge Piece Of Earth's Mantle

Still no evidence of the Mole People.



Fragment of upper mantle: credit Johan Lissenberg

Petrology and Geochemistry of the Mantle – Natural Samples

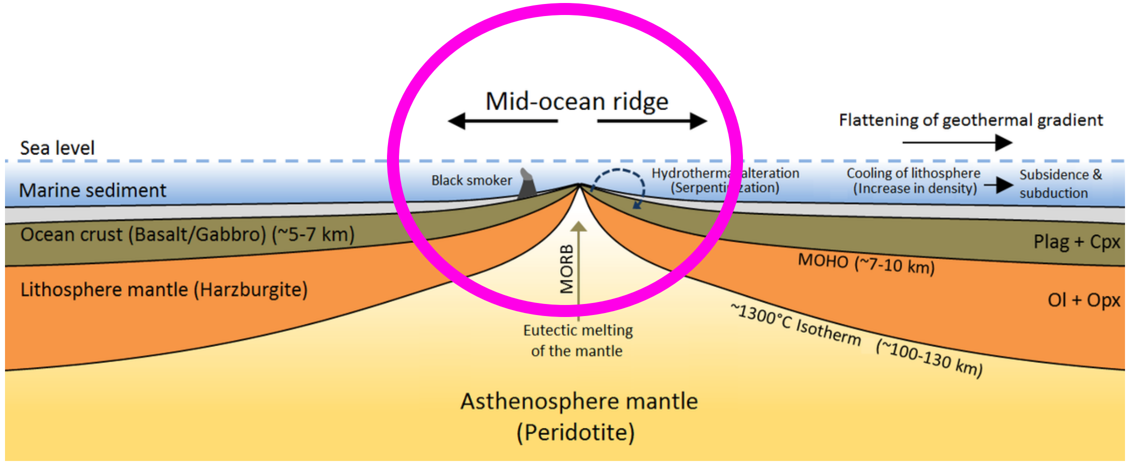
Dredging/Drilling of ocean seafloor:

Segments of the lithospheric mantle are commonly exposed along transform faults at mid-ocean ridges. These samples can be collected by seafloor dredging and/or drilling.

Ophiolites on continents:

If these segments of exposed lithospheric mantle are accreted onto a continent during plate collisions, they may form an ophiolite complex.

Often provides insights into relatively shallow lithospheric mantle



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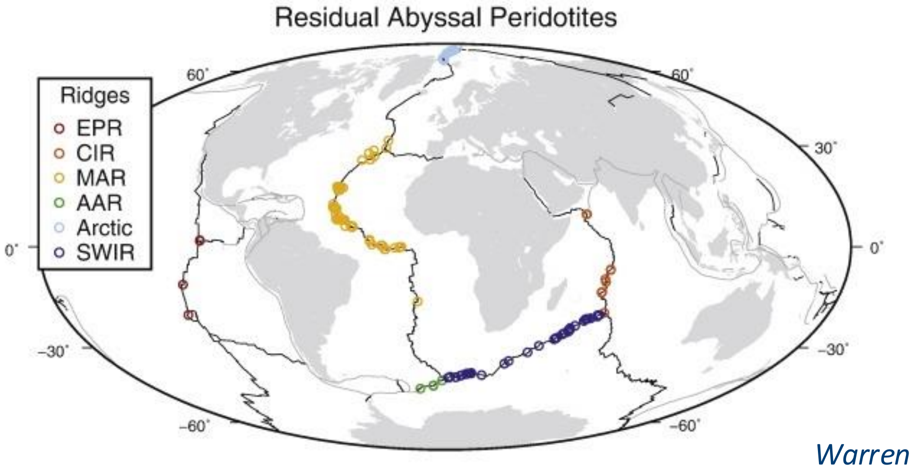

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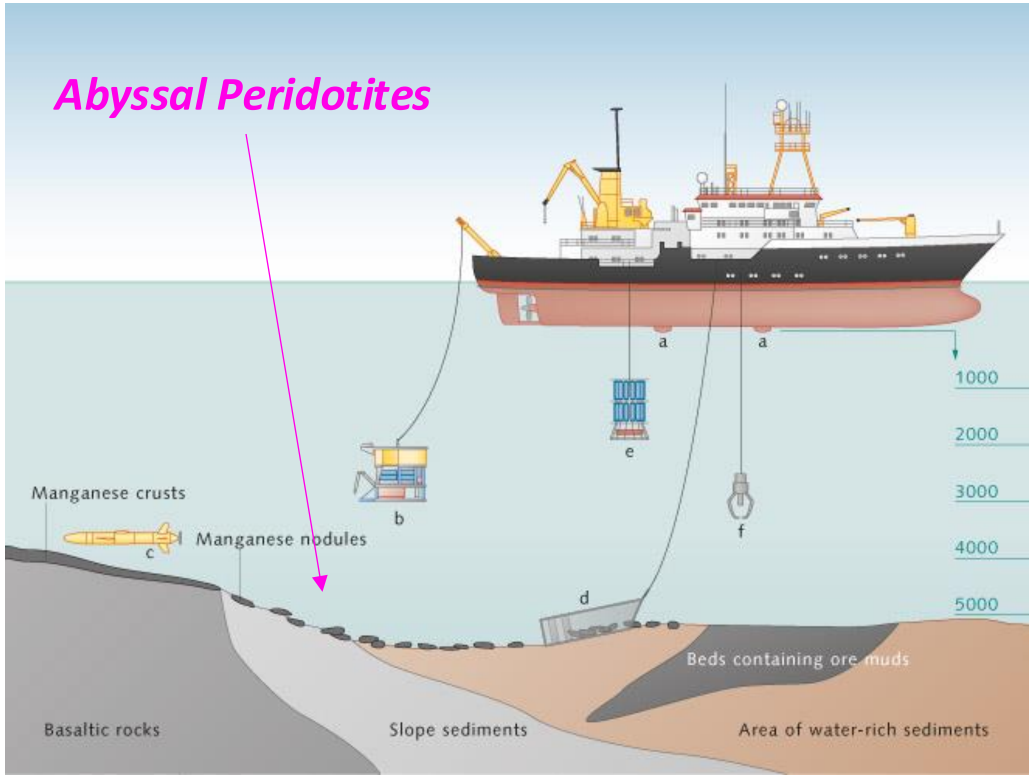
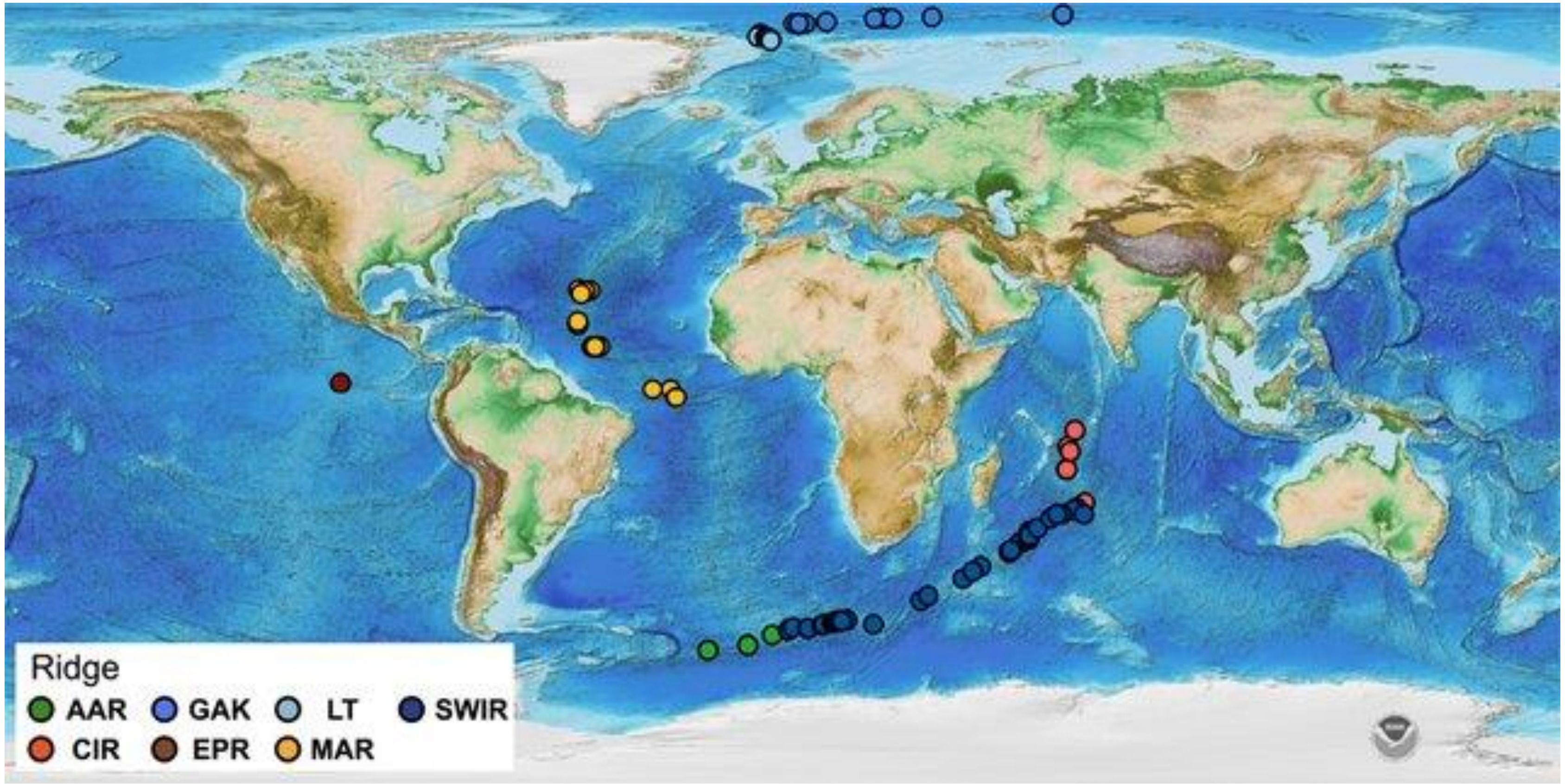


Simplified illustration of dredging sea floor to collect exposed segments of the lithospheric mantle.

Petrology and Geochemistry of the Mantle – Natural Samples



Global distribution of screened residual abyssal peridotites (n = 267). Ridge abbreviations are American-Antarctic Ridge (AAR), Central Indian Ridge/Carlsberg Ridge (CIR), East Pacific Rise (EPR), Mid-Atlantic Ridge (MAR), Gakkel Ridge (GAK), Lena Trough (LT), and Southwest Indian Ridge (SWIR). After Nishio et al. (2022)

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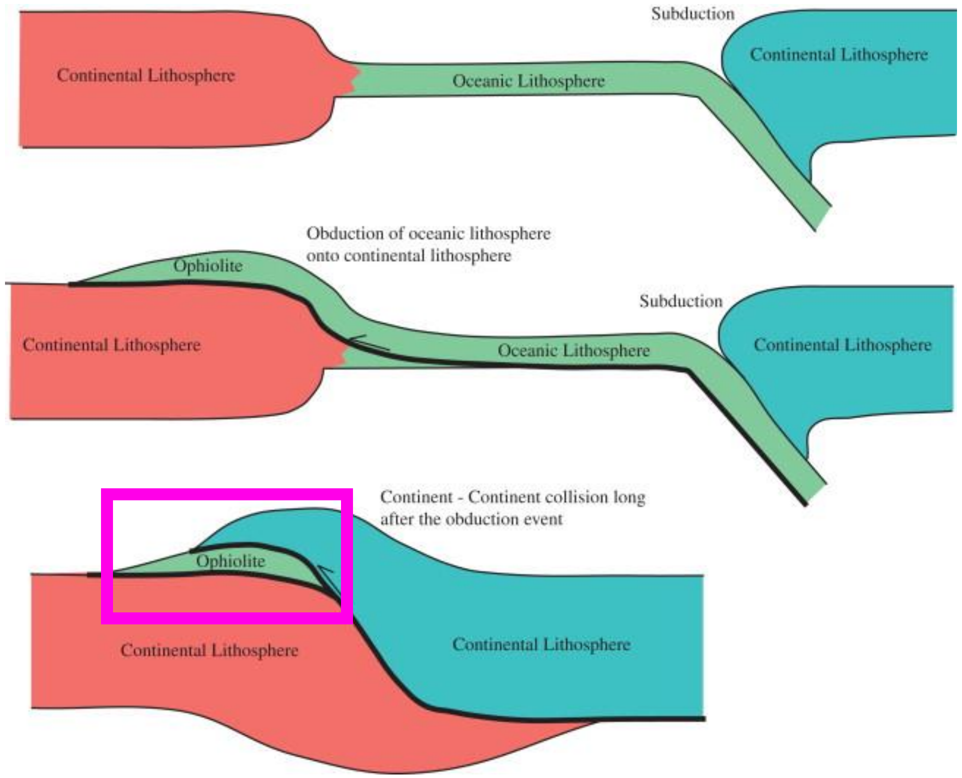

Simplified illustration of an ophiolite complex that is exposed in a convergent margin after plate collision.

Petrology and Geochemistry of the Mantle – Natural Samples

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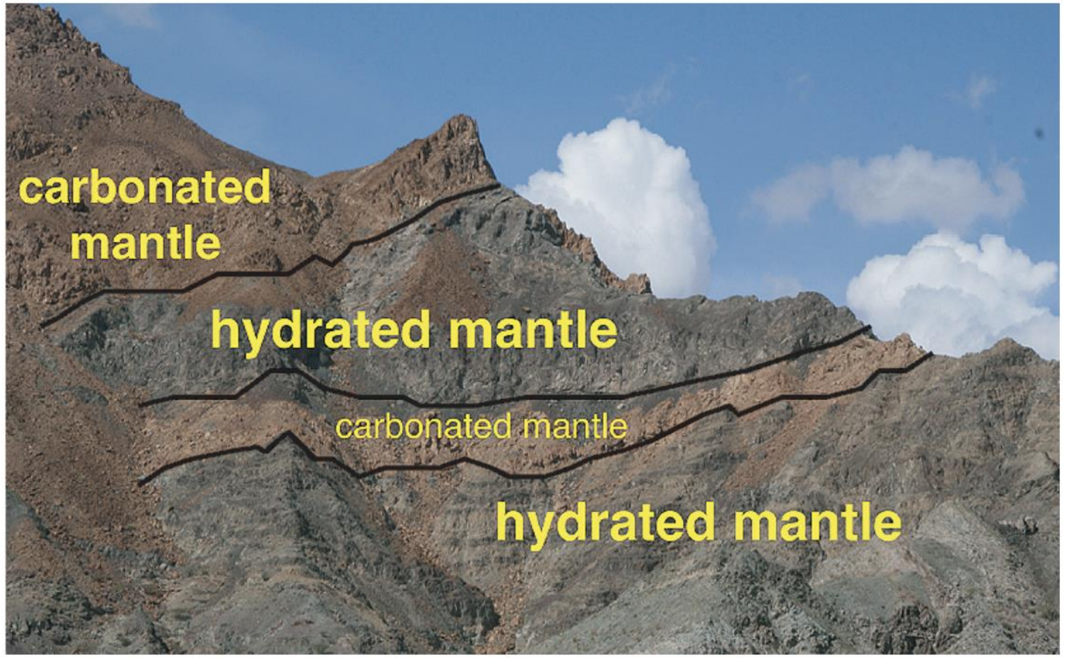
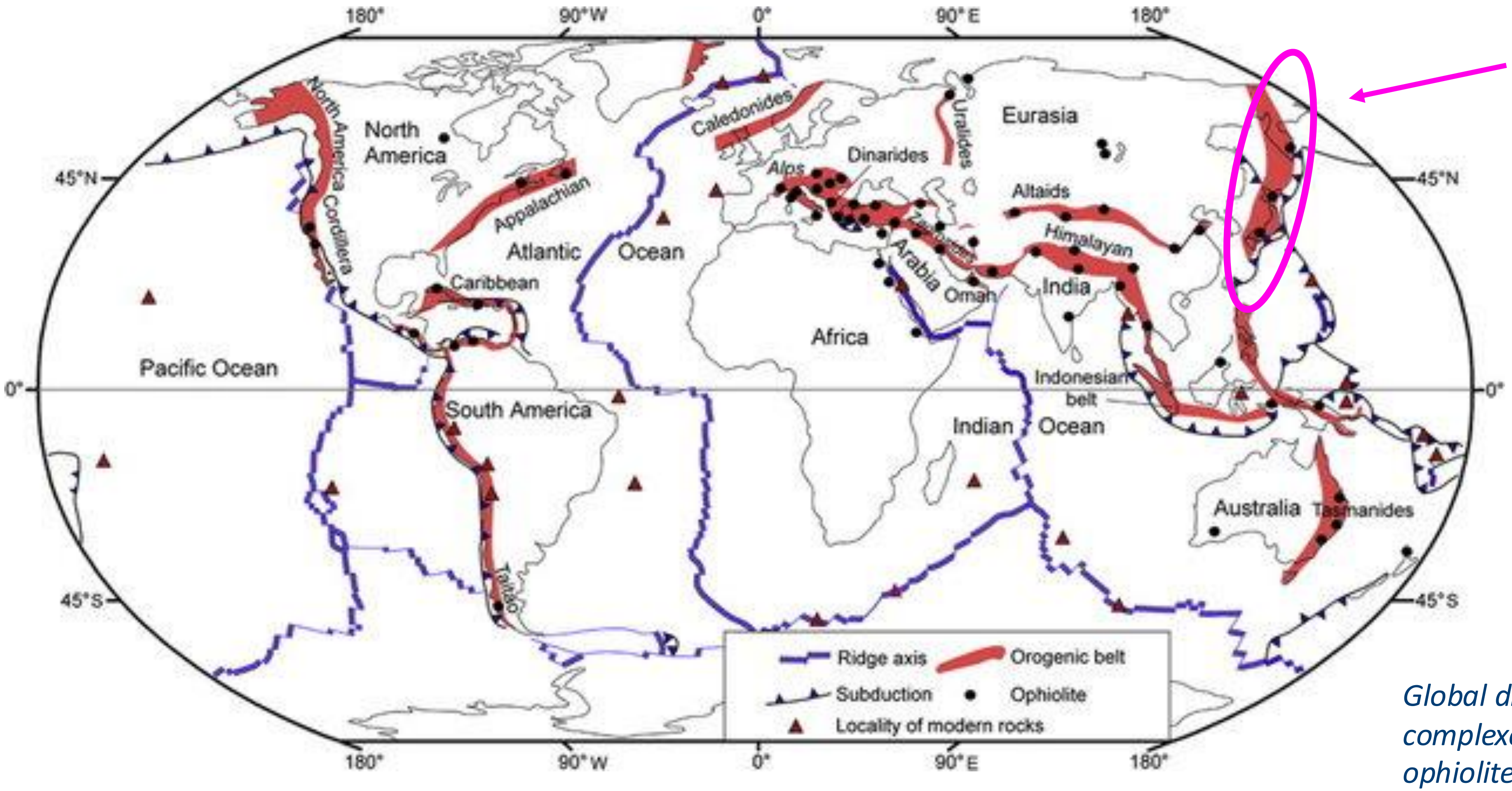


An example of exposed oceanic lithospheric mantle at the Oman Ophiolite. After Kelemen et al. (2013)

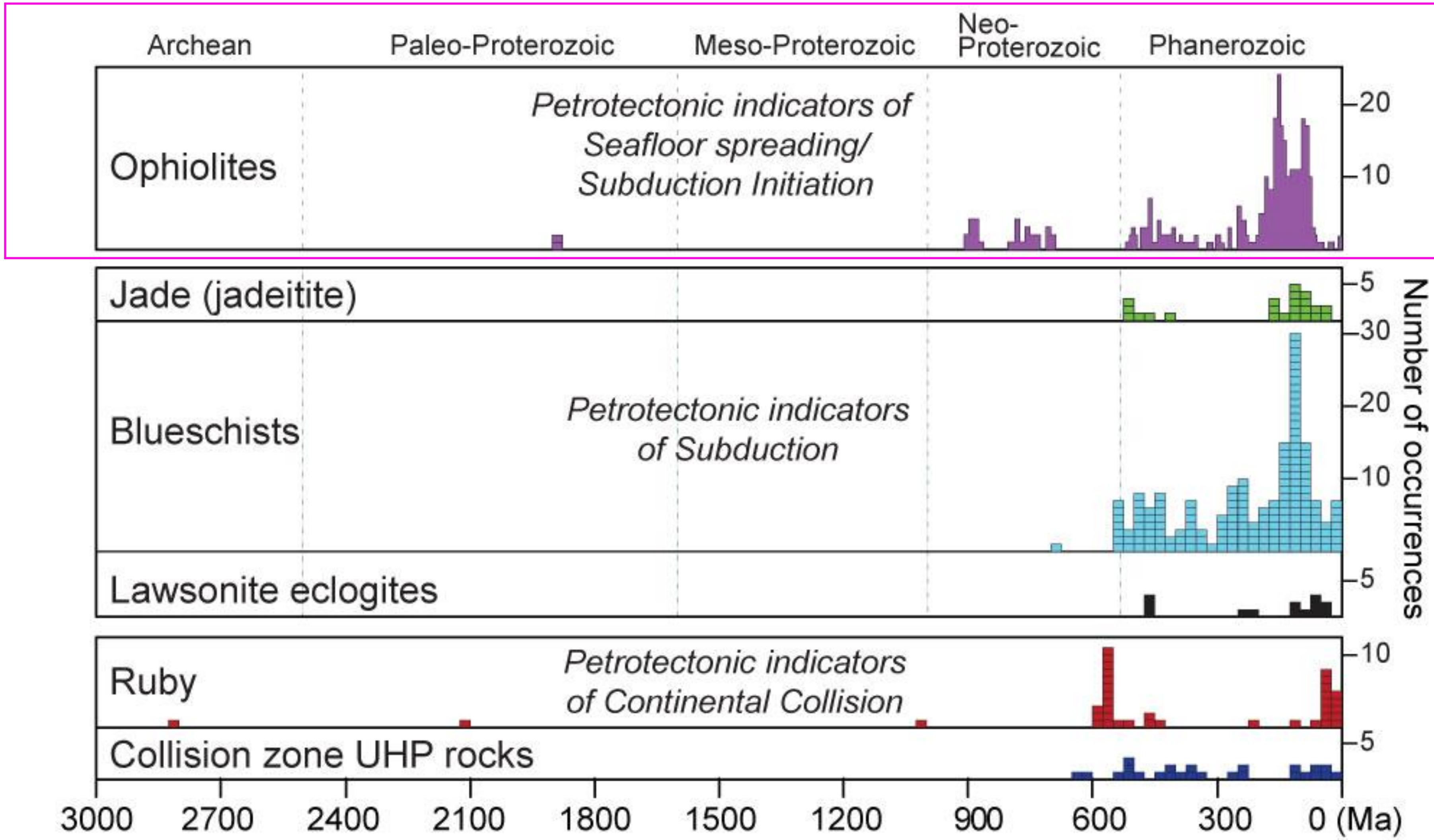
Petrology and Geochemistry of the Mantle – Natural Samples



Convergent margin where ophiolite is exposed

Global distribution of ophiolite complexes. Note that most ophiolites occur in orogenic belts. Image after Saccani (2014) Geosc. Front.

Petrology and Geochemistry of the Mantle – Natural Samples



Timeline of ages of ophiolites from a global compilation and compared with other indicators of continental collision and subduction. After Stern (2013).

Petrology and Geochemistry of the Mantle – Natural Samples

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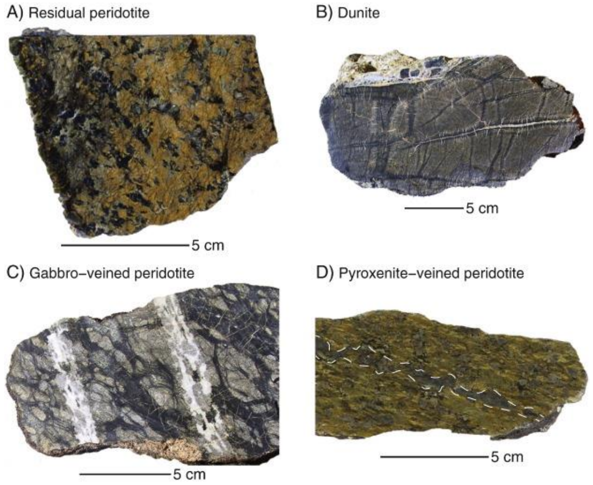
Photo: J. Warren



Arai et al. (2018) Minerals

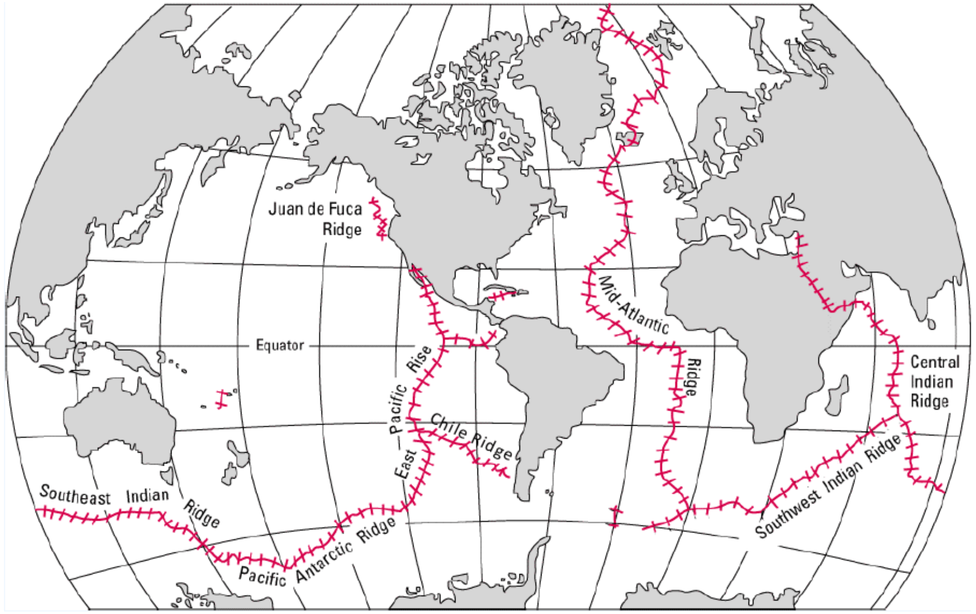
Petrology and Geochemistry of the Mantle – Natural Samples

Ophiolites and Abyssal Peridotites – Benefits

- Abyssal peridotites are abundant and usually fresh and recently exposed
- Insights into oceanic lithospheric mantle
- Study the shallow parts of lithospheric mantle

Ophiolites and Abyssal Peridotites – Challenges

- Ophiolites can be highly deformed and altered during exhumation
- Limited insights into continental and cratonic lithosphere
- Limited inter disciplinary constraints (i.e., OBS)
- Bias towards younger ages



Abyssal peridotites may be exposed or occur around mid ocean ridges where they are thought to occur

Petrology and Geochemistry of the Mantle – Natural Samples

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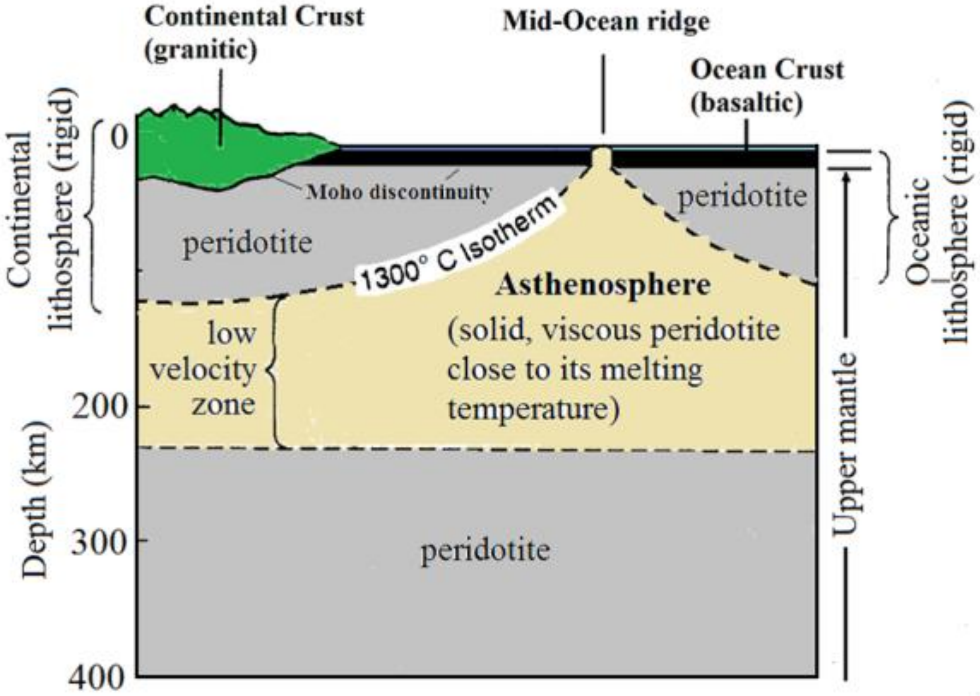

The lithospheric mantle beneath mid ocean ridges and most oceanic settings is very shallow (compared with continents and cratons)

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The exhumation of ophiolites to the surface is often accompanied by deformation and metamorphism which alters the original mantle textures and mineralogies. ***Guess what minerals make up this rock?***

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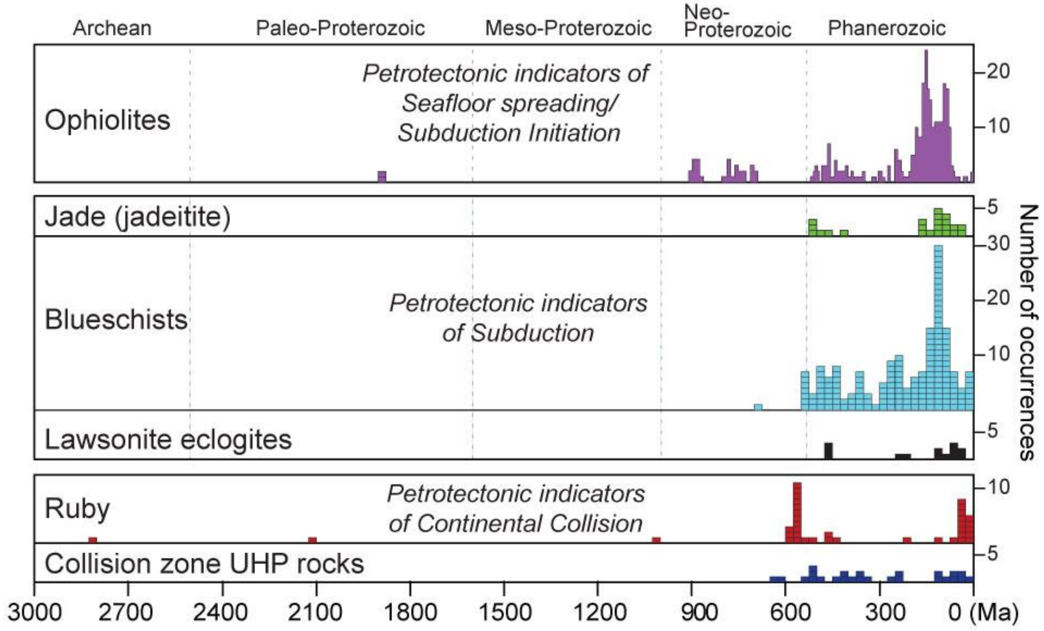
Ophiolites and Abyssal Peridotites – Challenges

- Ophiolites can be highly deformed and altered during exhumation
- Limited insights into continental and cratonic lithosphere
- Limited inter disciplinary constraints (i.e., OBS)
- Bias towards younger ages



Ophiolites are exposed in high topography and active areas and may be easily eroded. This may- in part, explain why ophiolites are bias to very young ages. It may also tell us about when exhumation events may have occurred.

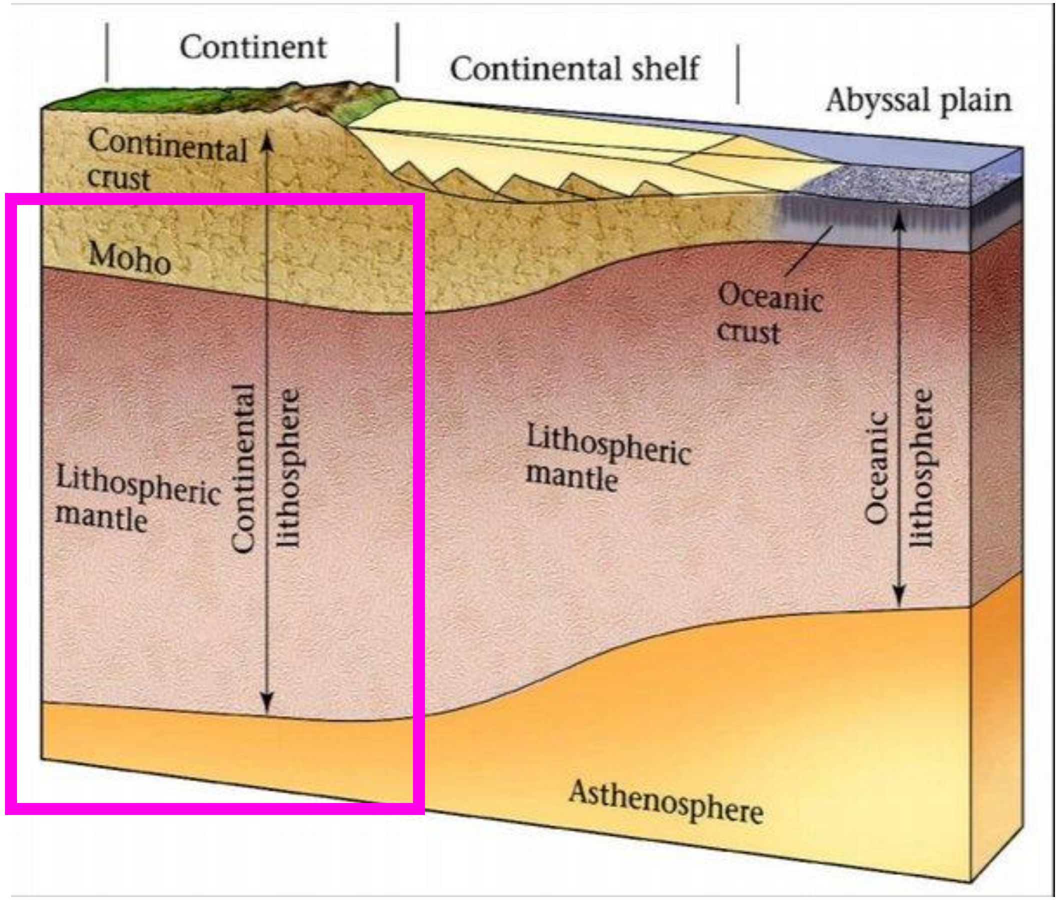
Petrology and Geochemistry of the Mantle – Natural Samples

Mantle Xenoliths in Volcanic Rocks:

Many magmas form deep within the lithospheric mantle. During their ascent to the surface, they often collect fragments of the surrounding mantle and transport them to the surface (mantle xenoliths).

- Range in size from <1 cm to >1 m
- Brought to surface in hours to days by magma
- Provide insight into nature of the mantle at time of eruption

Mantle xenoliths can range in depth from <20 km to >300 km. Provide insights into the entire lithosphere!



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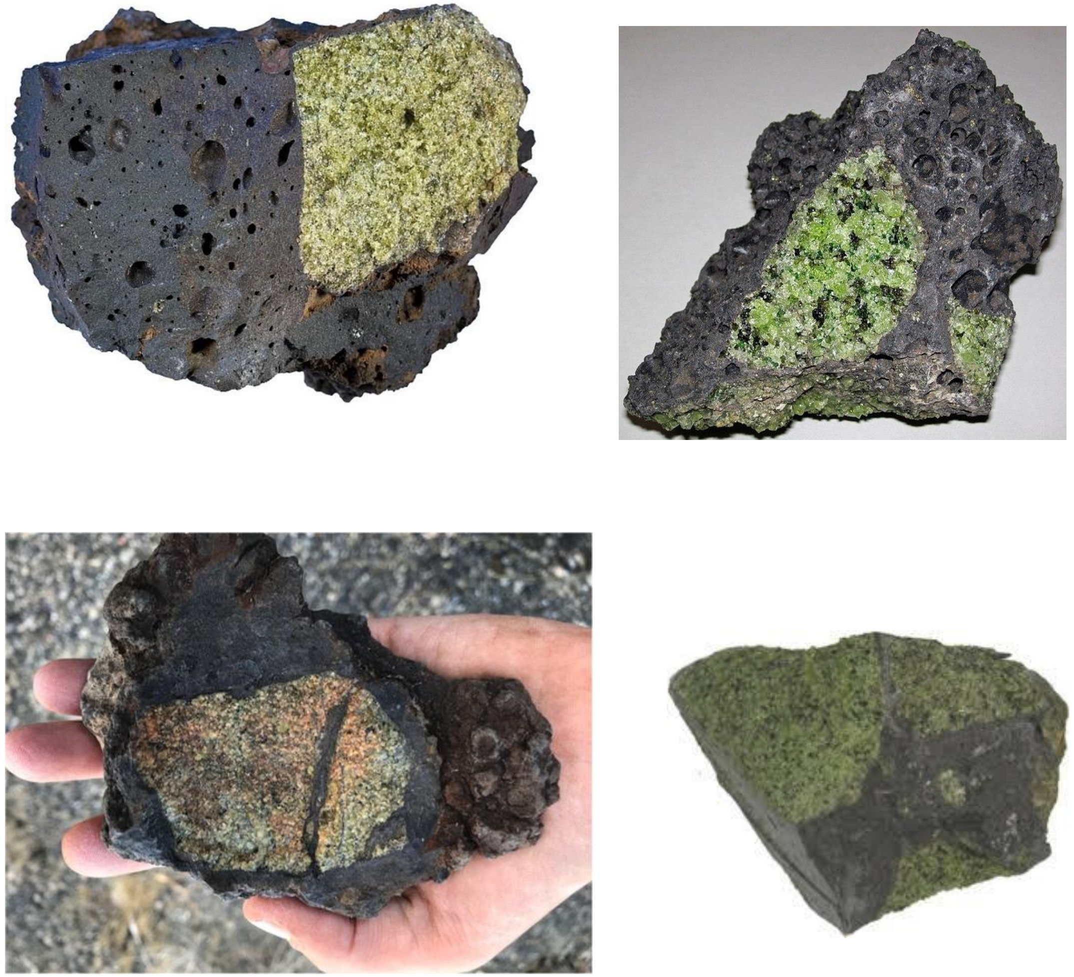

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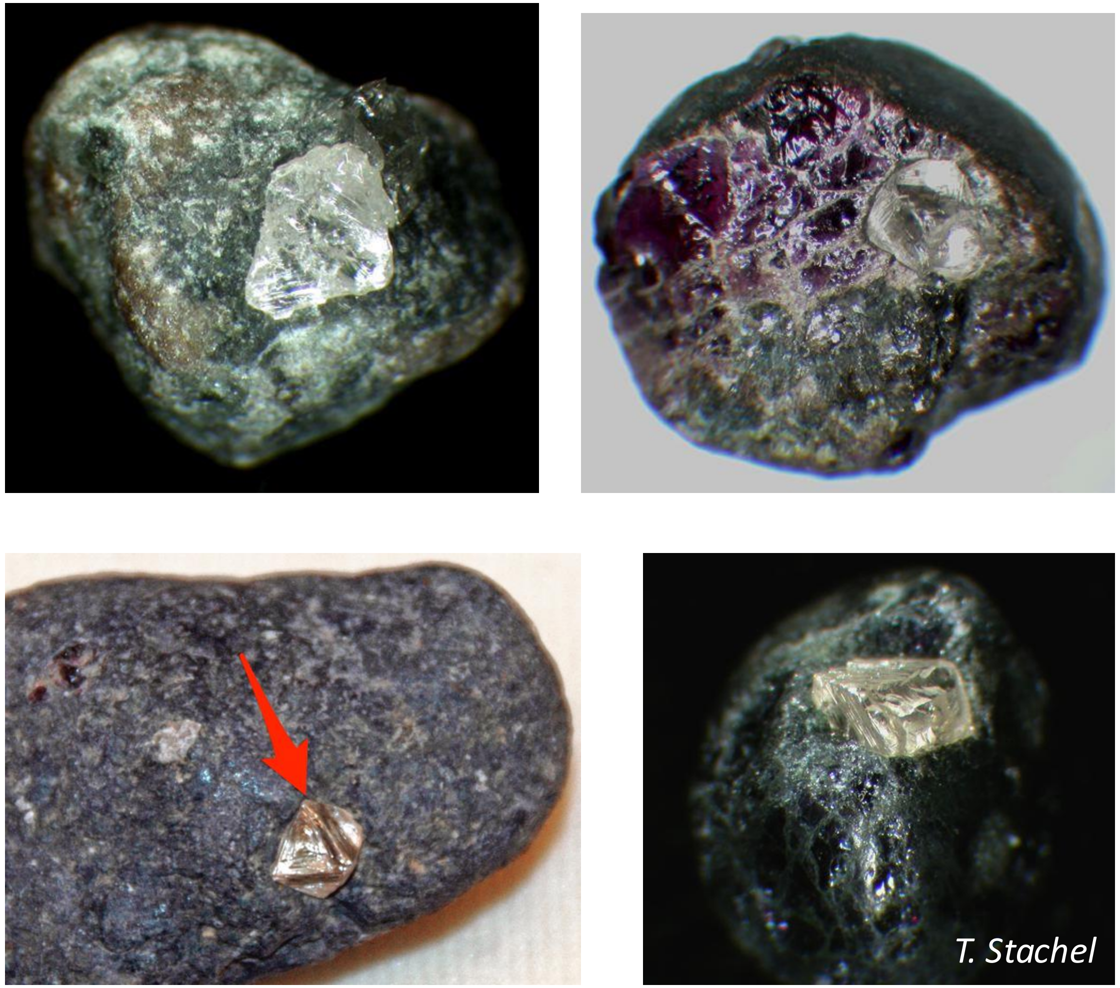
Diamonds



T. Stachel

Petrology and Geochemistry of the Mantle – Natural Samples

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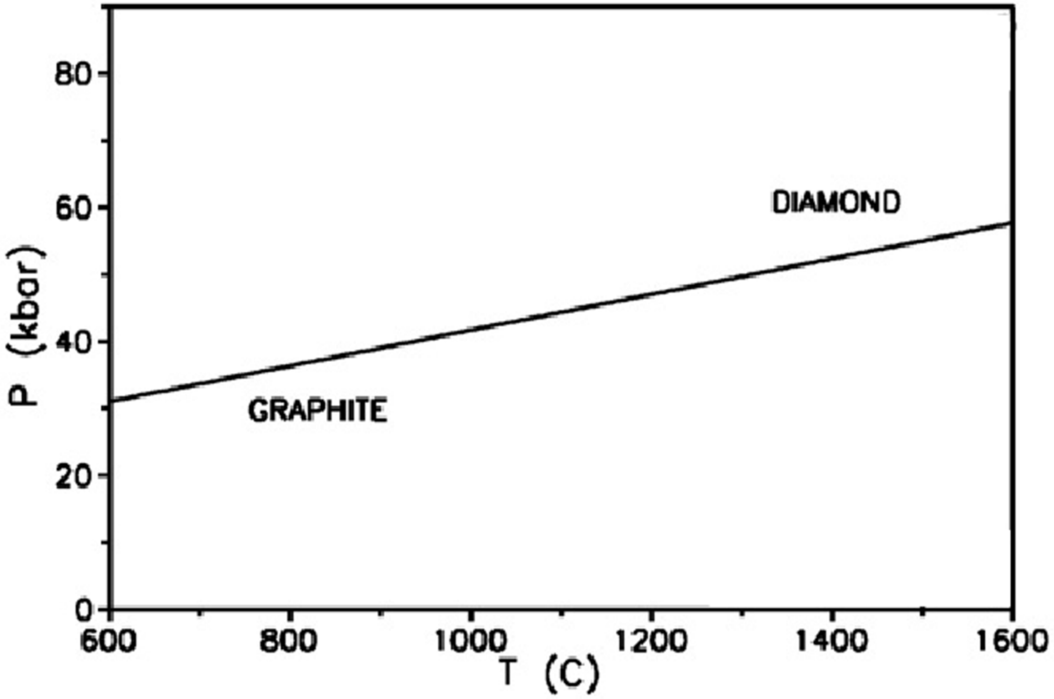

Graphite to diamond transition within the mantle. Diamond is only stable at very high pressures within the mantle.

Petrology and Geochemistry of the Mantle – Natural Samples

Mantle Xenoliths in Volcanic Rocks:

The volcanic rocks that transport mantle xenoliths to the surface have several compositions:

- **Kimberlites**
- Lamproites
- Lamprophyres
- Basalts

These host volcanic rocks form within the deep lithospheric mantle or in the convective mantle

The locations of these host volcanic rocks are in the continental lithospheric mantle and have a range eruption ages

Kimberlites are highly altered and brecciated rocks. They form by a very explosive eruption and contain lots of volatiles like H2O and CO2.

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Petrology and Geochemistry of the Mantle – Natural Samples

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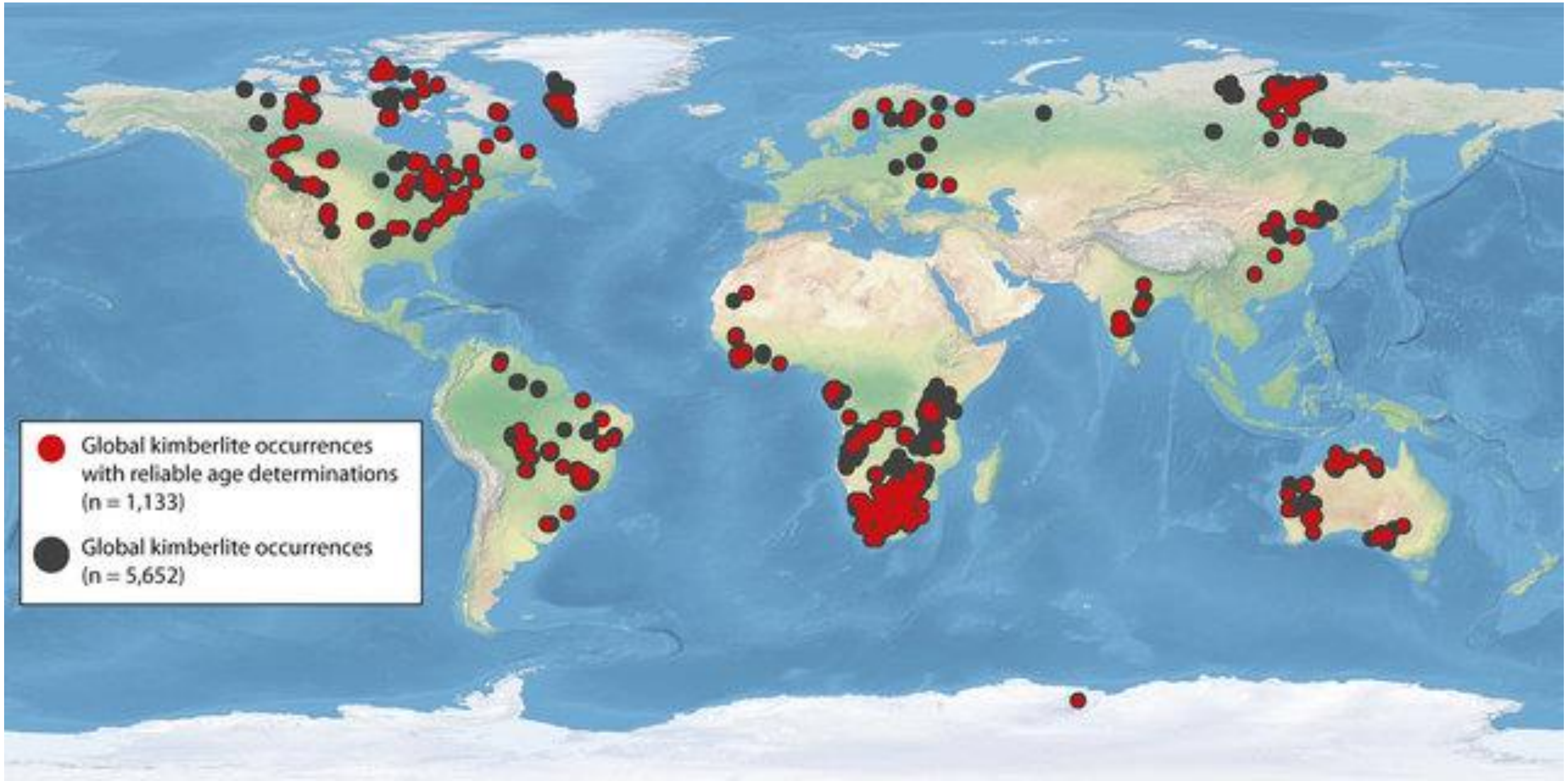
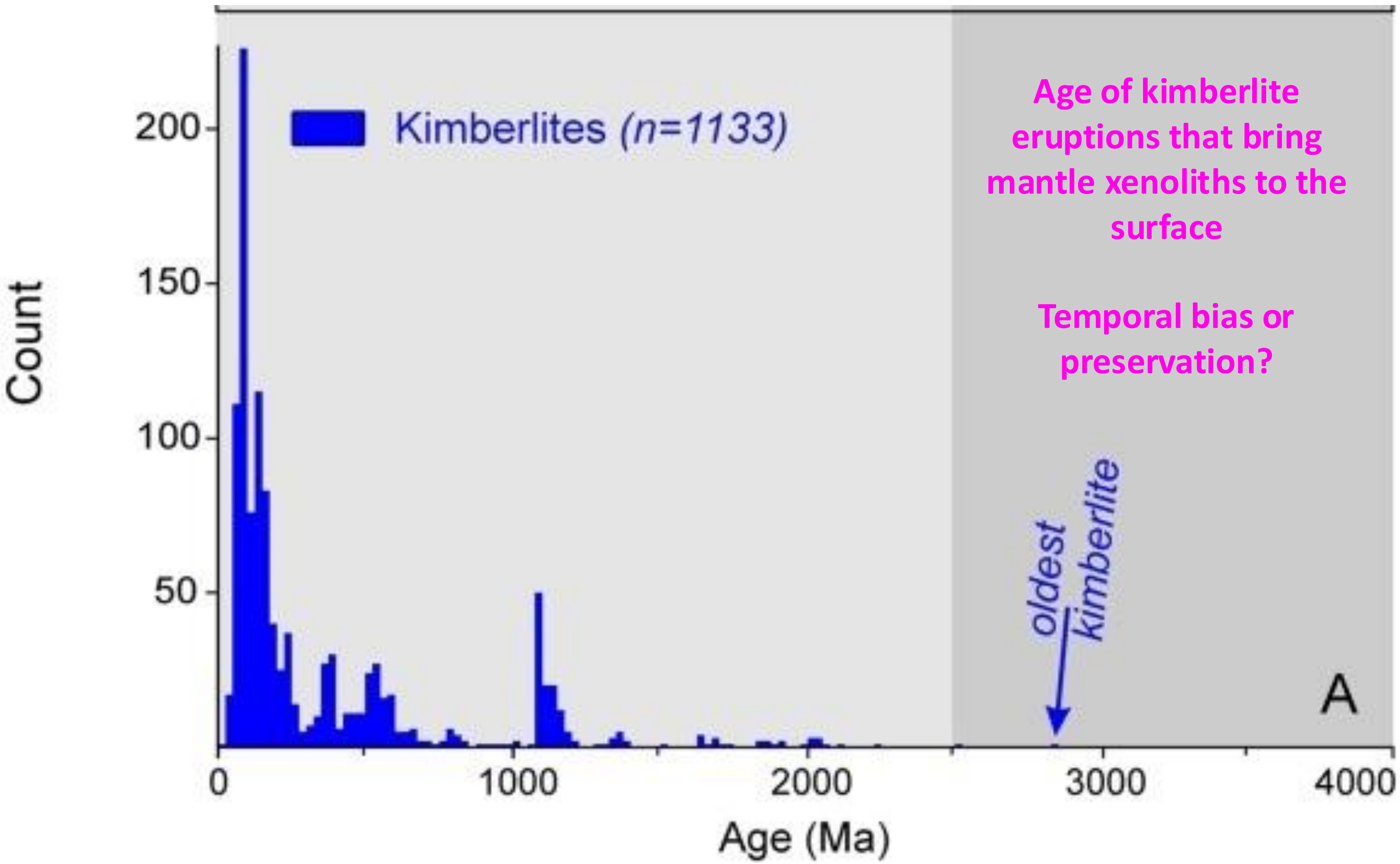


Showing Xenoliths from cratonic lithosphere only!

Locations of mantle xenoliths that occur in volcanic rocks that are emplaced into continental lithosphere. Majority of xenolith bearing rocks are kimberlites and occur within the interiors or margins of cratons. After Tappe et al. (2018)



Age of kimberlite eruptions that bring mantle xenoliths to the surface

Temporal bias or preservation?

Interestingly, kimberlites and many related rock types that host mantle xenoliths are skewed to very young eruption ages. This may reflect a poor preservation of these rocks in older settings, or a preference for younger tectonic and geodynamic regimes. Image after Tappe et al. (2018) (EPSL)

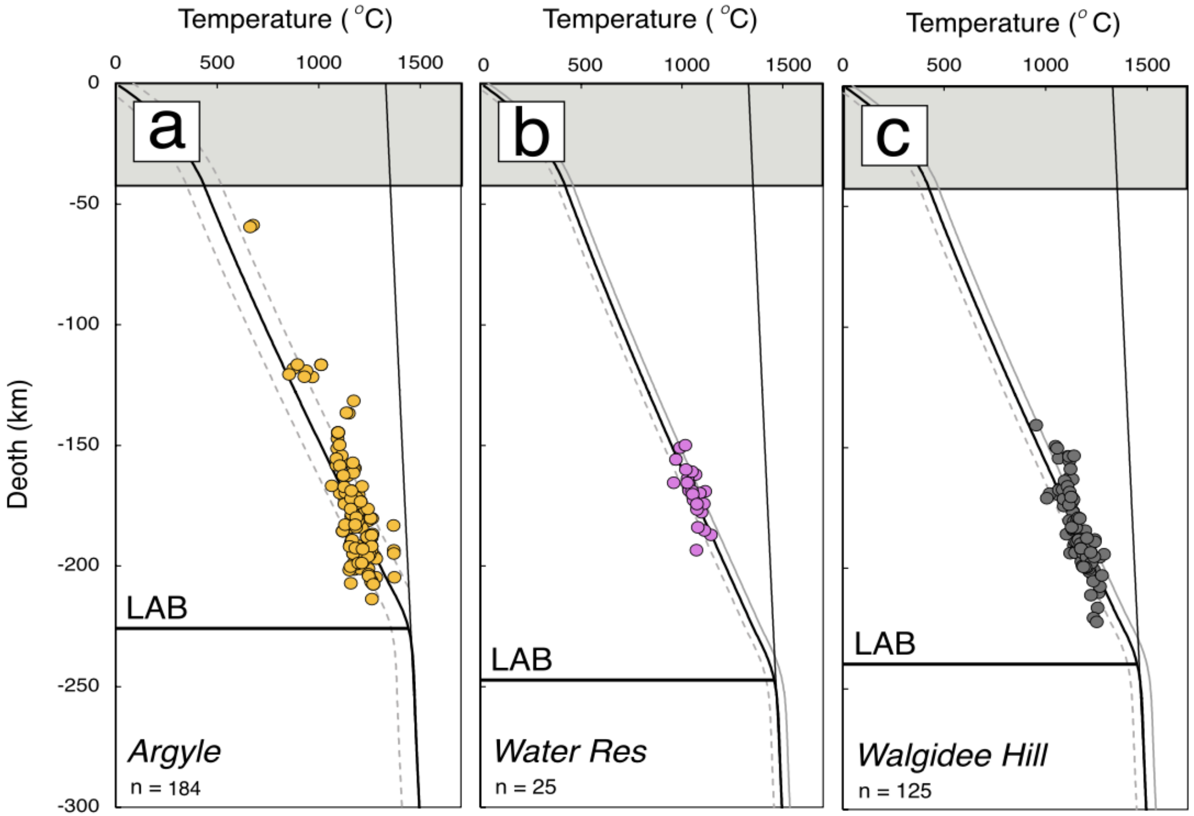
Petrology and Geochemistry of the Mantle – Natural Samples

Mantle Xenoliths in Volcanic Rocks:

Mantle xenoliths can be used to study many aspects of the lithospheric mantle:

- **Calculate the PT of xenoliths for paleogeotherm modelling**
- Vertical changes in mantle composition
- Changes in composition and thickness of lithospheric mantle overtime
- Calibrate seismic tomography models of lithosphere thickness
- Study mantle discontinuities (LAB and MLD)

More info in coming lectures…



Sudholz and Jaques et al. (2023)

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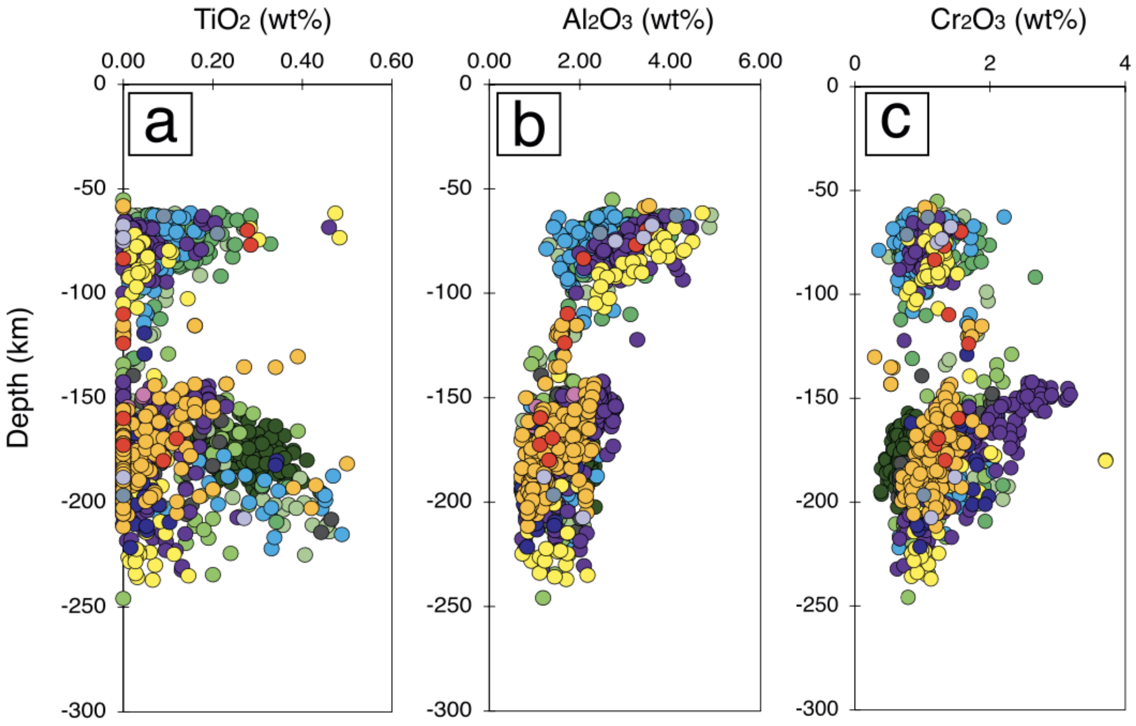

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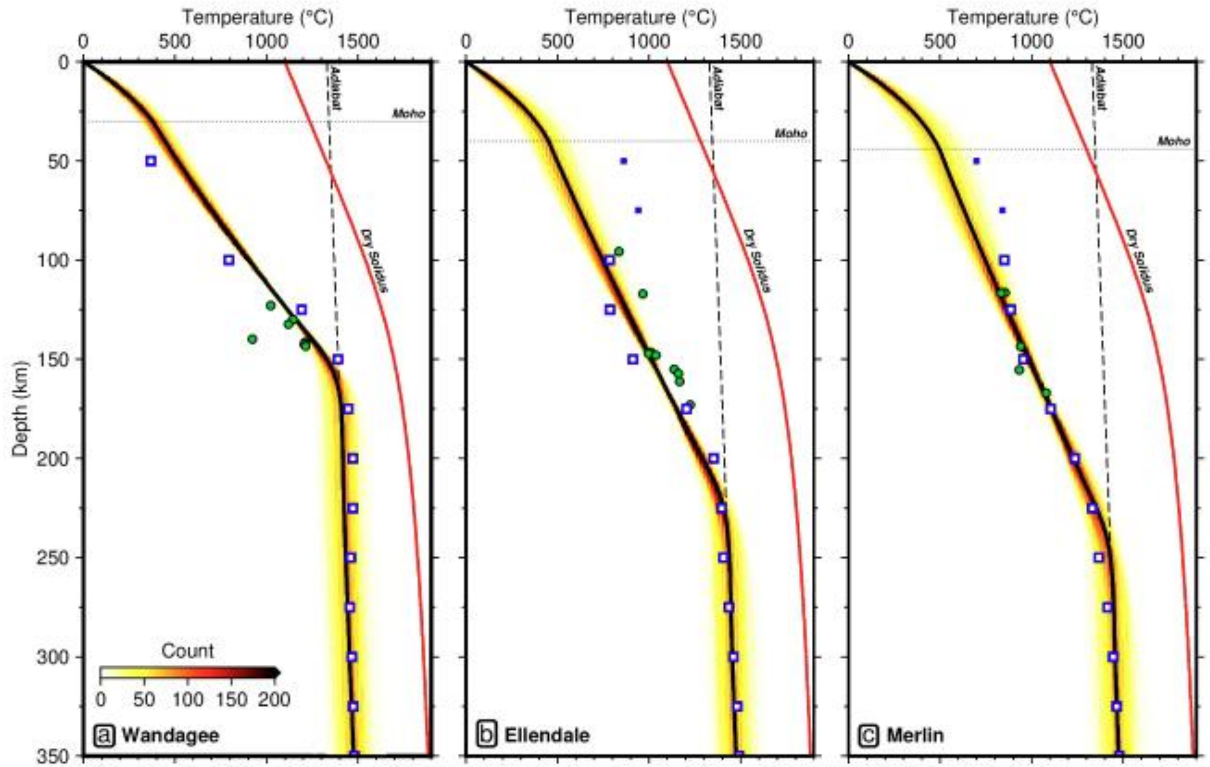


Mark Hoggard (pers. Comms)

Petrology and Geochemistry of the Mantle – Natural Samples

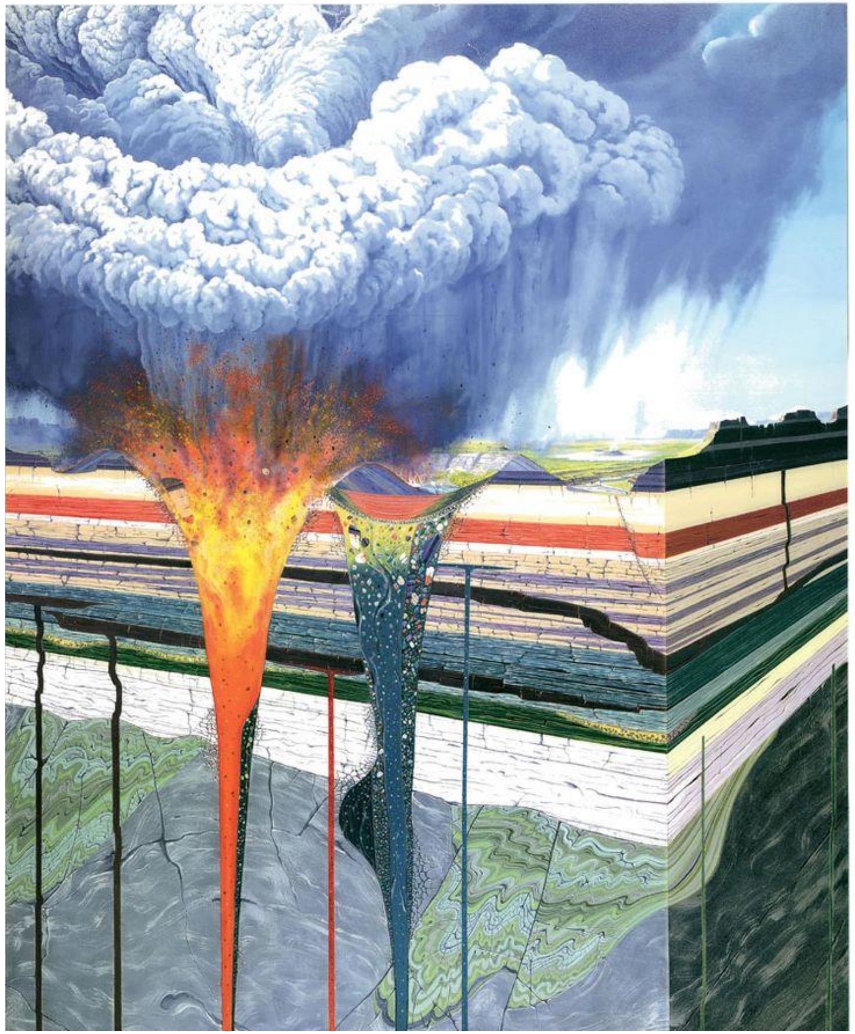
Mantle Xenoliths in Volcanic Rocks – Benefits

- Insights into continental and cratonic lithosphere
- Directly record temperature and composition of the mantle at time of eruption
- Easy to study and abundant publish data and access to new samples

Mantle Xenoliths in Volcanic Rocks– Challenges

- Limited insights into oceanic lithosphere
- Lack of samples beyond 1 Gyr (billion years)
- Entrainment mechanisms of xenoliths not fully understood

How representative are mantle xenoliths of the broader lithospheric mantle?



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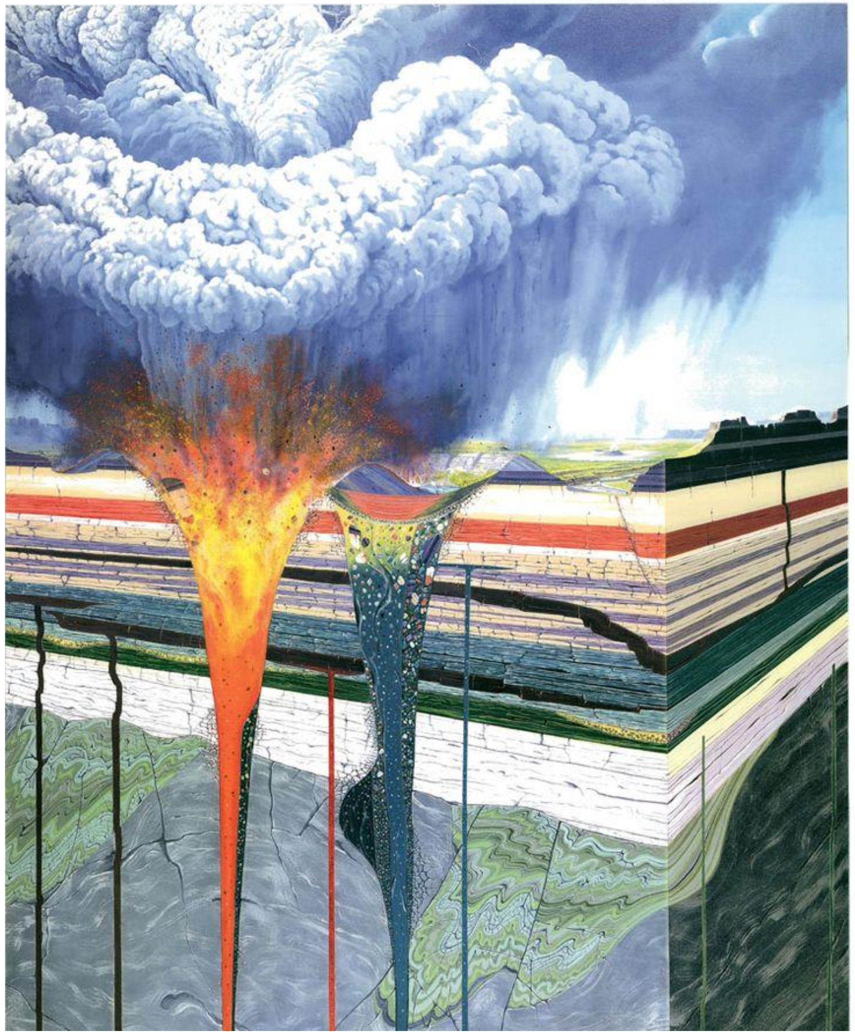


Quick break for Questions…..

What is the mantle made from?

What is the chemical composition?

(Fe, Mg etc.)

What is the mineralogy?

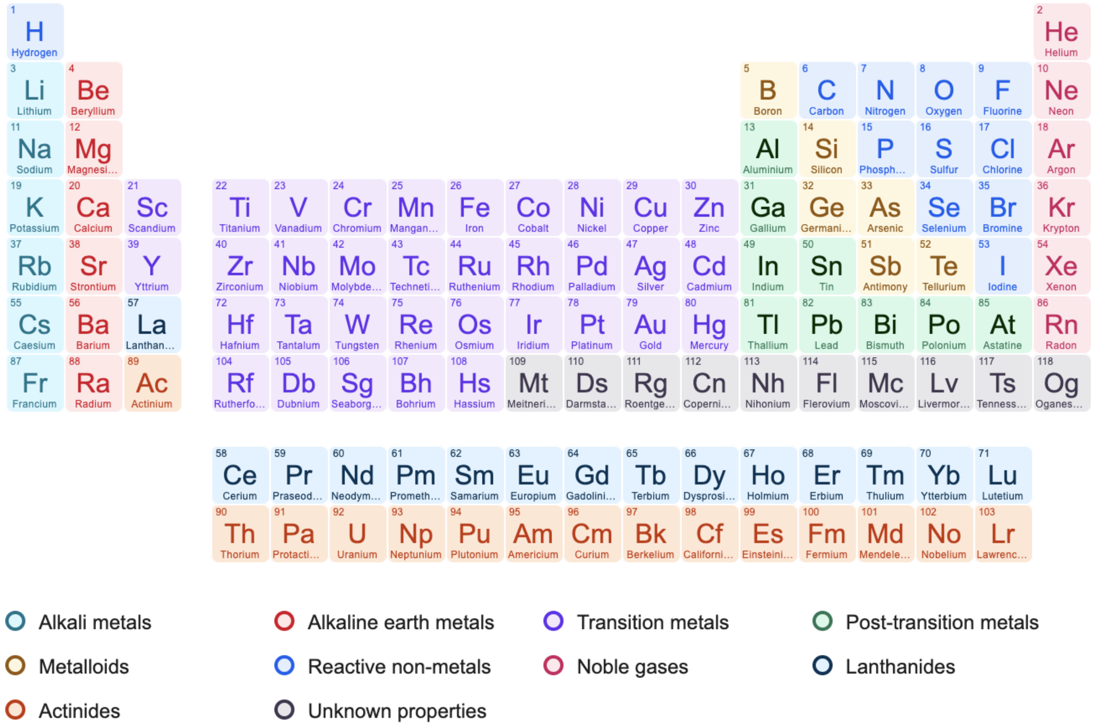
(Olivine, Pyroxene etc.)

What is the rock types (lithology)?

(Peridotite, Dunite etc.)

Constraints on what rocks and minerals make up the lithospheric has come from >60 years of inter-disciplinary research

Chemical composition/elements



1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesi...											13 Al Aluminium	14 Si Silicon	15 P Phosph...	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Mangan...	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germani...	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybde...	43 Tc Techneti...	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Caesium	56 Ba Barium	57 La Lanthan...	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfo...	105 Db Dubnium	106 Sg Seaborg...	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitneri...	110 Ds Darmsta...	111 Rg Roentge...	112 Cn Coperni...	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovi...	116 Lv Livermor...	117 Ts Tenness...	118 Og Oganes...
			58 Ce Cerium	59 Pr Praseod...	60 Nd Neodym...	61 Pm Prometh...	62 Sm Samarium	63 Eu Europium	64 Gd Gadolini...	65 Tb Terbium	66 Dy Dysprosi...	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	
			90 Th Thorium	91 Pa Protacti...	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californi...	99 Es Einsteini...	100 Fm Fermium	101 Md Mendele...	102 No Nobelium	103 Lr Lawrenc...	

○ Alkali metals
○ Alkaline earth metals
○ Transition metals
○ Post-transition metals
○ Metalloids
○ Reactive non-metals
○ Noble gases
○ Lanthanides
○ Actinides
○ Unknown properties

Periodic table of the elements

What is the mantle made from?

What is the chemical composition?
(Fe, Mg etc.)

What is the mineralogy?
(Olivine, Pyroxene etc.)

What is the rock types (lithology)?
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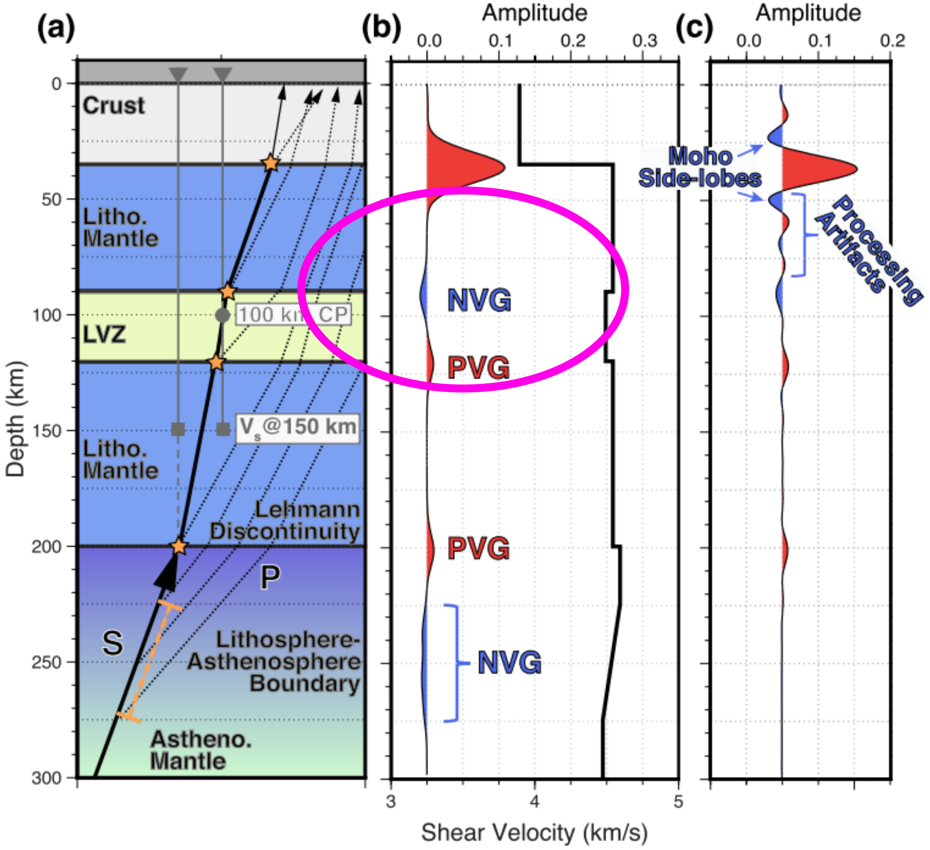
Understanding the lithology and mineralogy of the lithospheric mantle is crucial for several fields of research in petrology and geophysics:

- **Mantle discontinuities (cause of the MLD and LAB)**
- Thickness and stability of continental lithosphere
- Formation of ore deposits and mantle derived melts
- Geodynamics of the lithospheric mantle



Simplified illustration of synthetic receiver function for cratonic lithosphere. NVG are difficult to explain by assuming a homogenous and anhydrous lithospheric mantle. Krueger et al. (2021).

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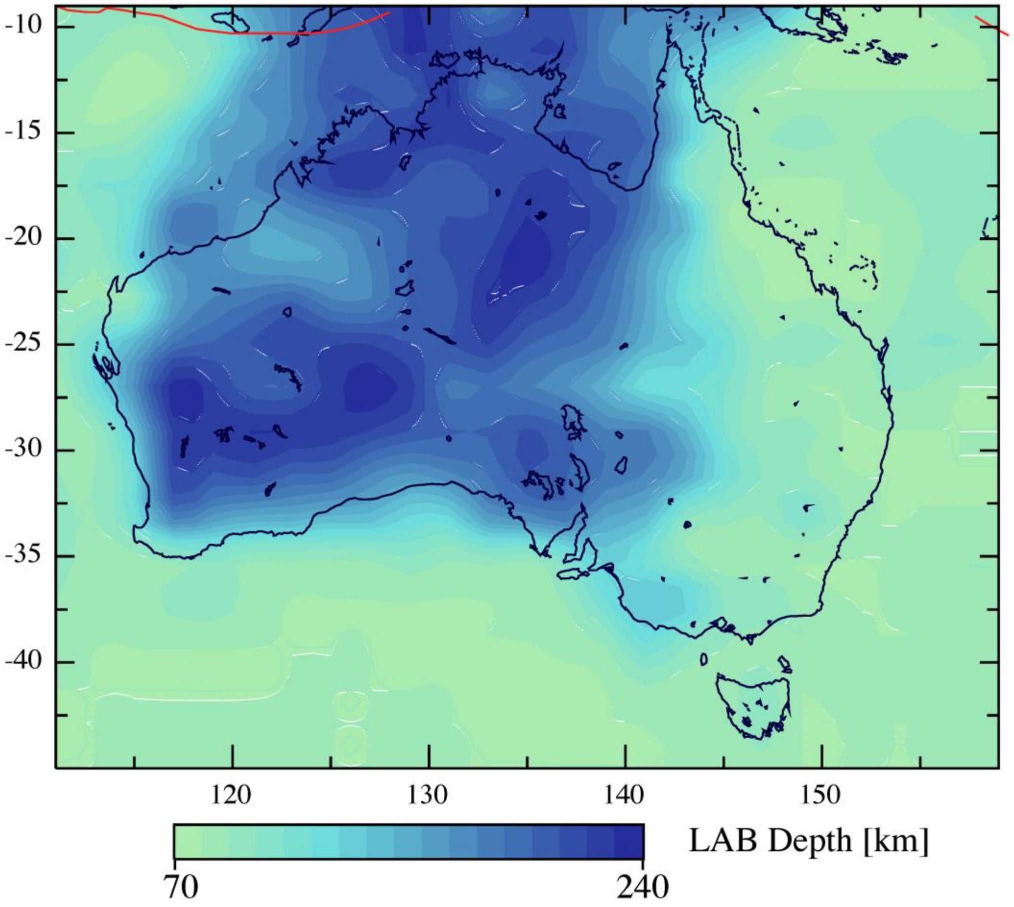

LAB map of Australia (AusMantle)

What is the mantle made from?

After Howell et al. (2019)

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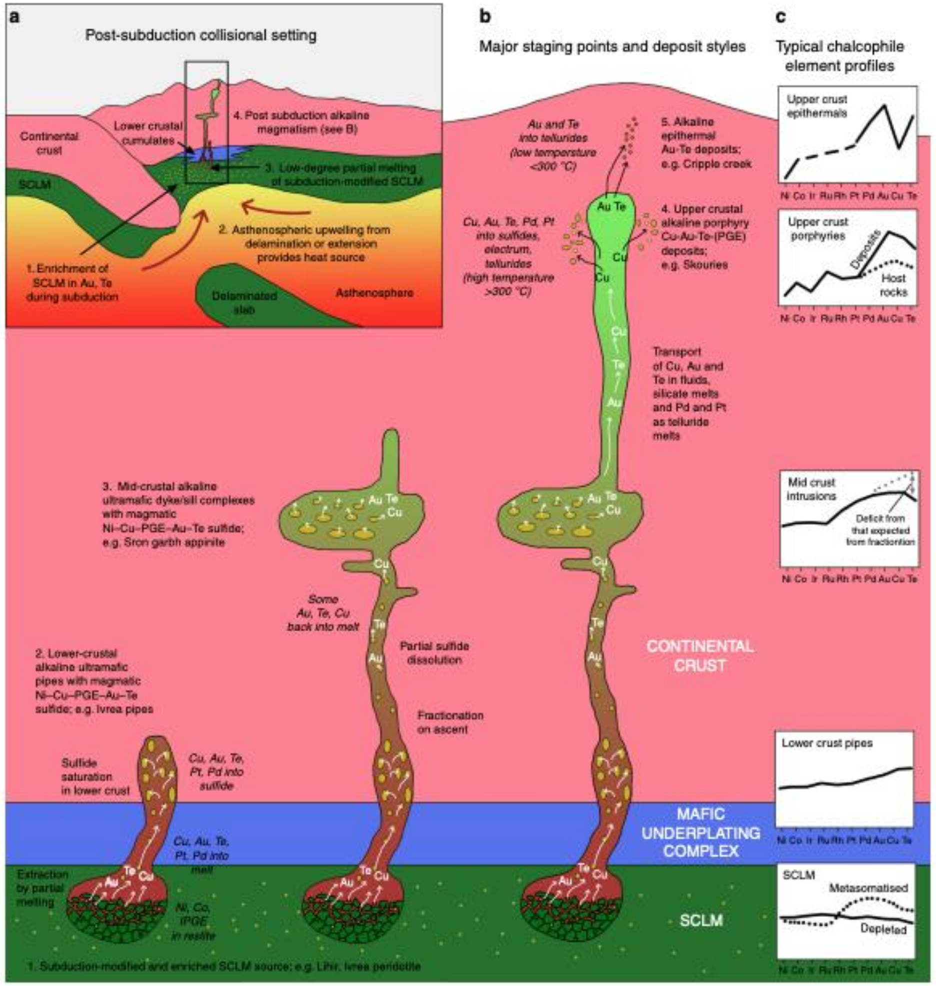

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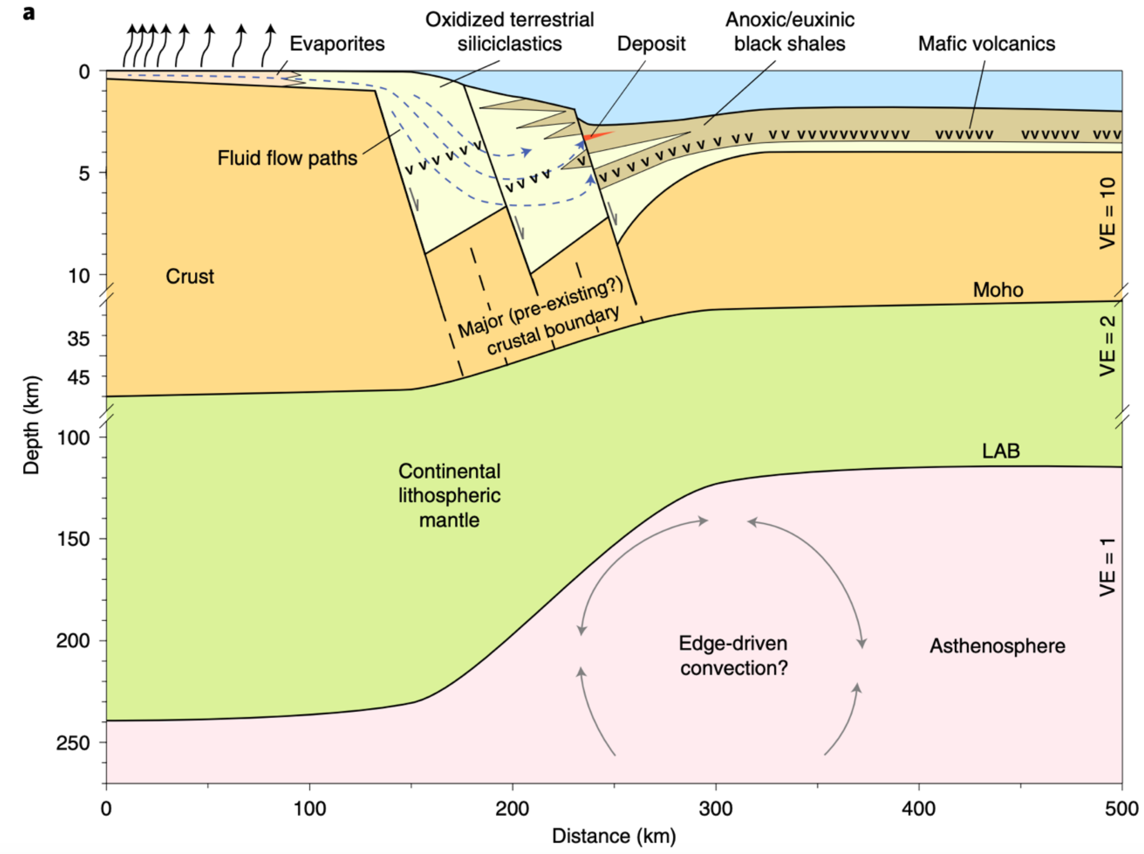


After Hoggard et al. (2020)

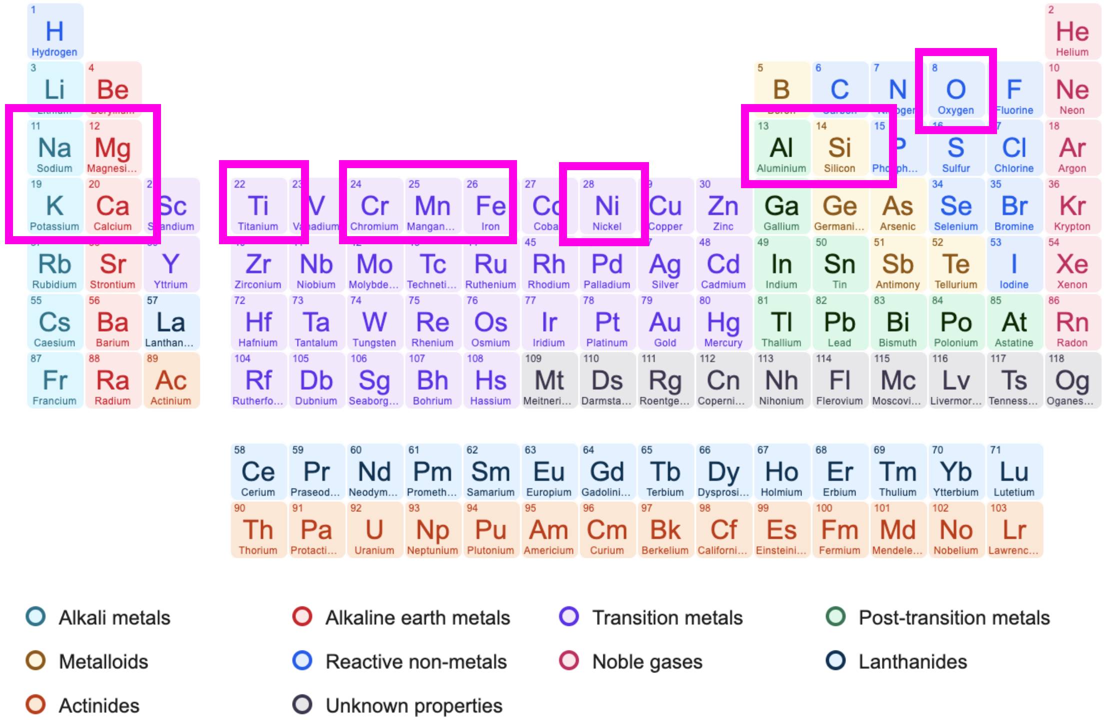
Basic chemistry of the lithospheric mantle

Geochemist and petrologist often refer to elements within the mantle in their oxide form:

Si, Ti, Al, Cr, Fe, Mn, Mg, Ca, Na, K and O

These elements have different physical properties which govern how minerals and rocks behave in the mantle:

- Density of rocks and minerals (i.e., Fe-rich)
- Electro-negativity
- Compatibility (preference for forming a fluid or solid)



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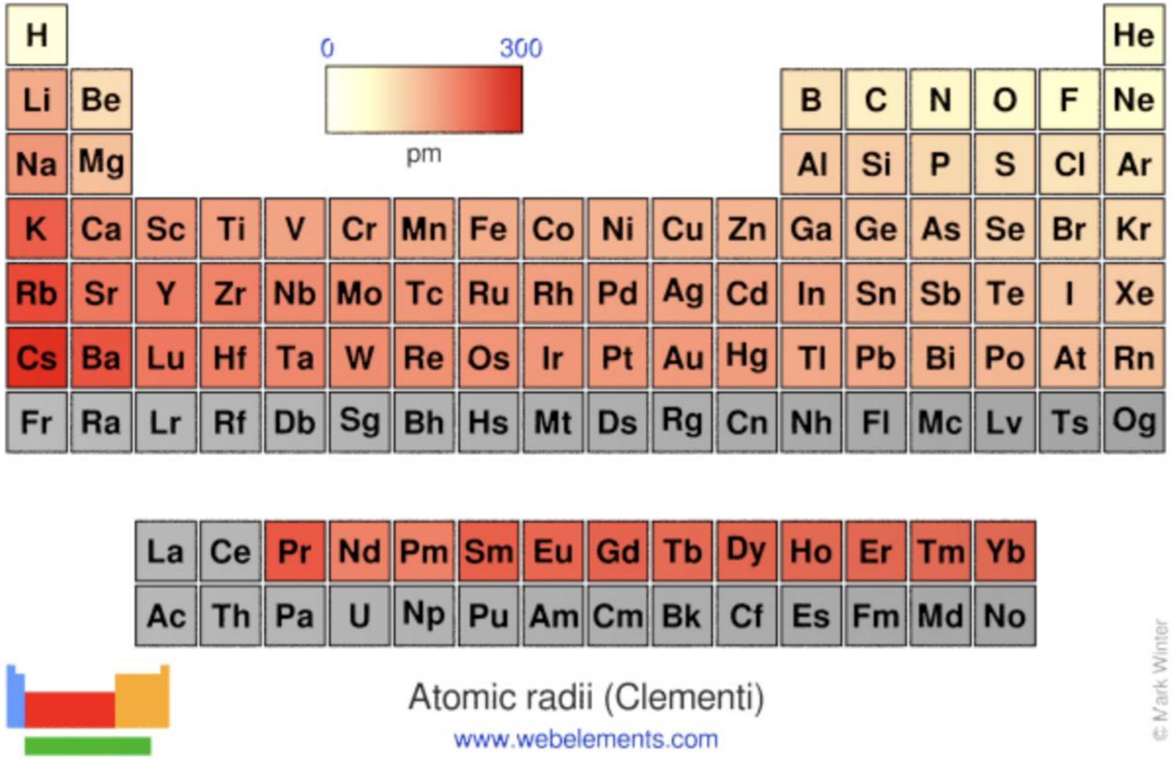

Atomic radii (Clementi)

www.webelements.com

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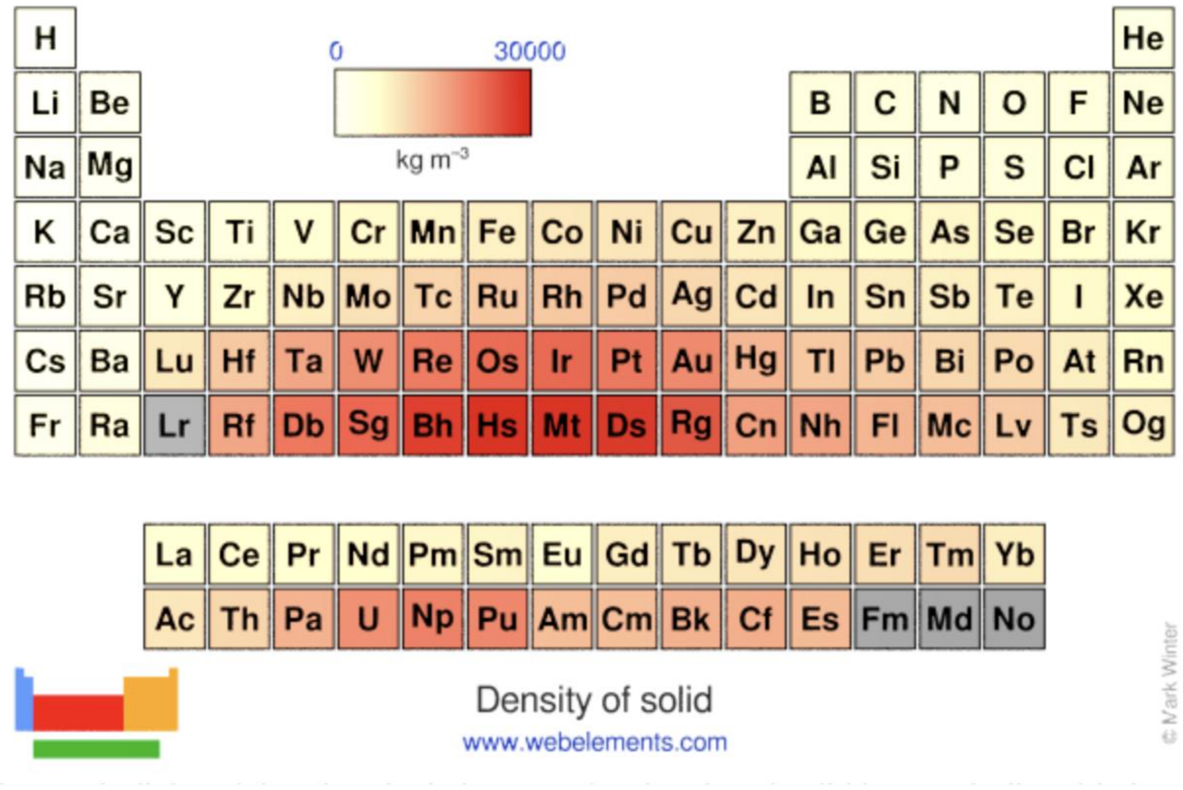


Density of solid
www.webelements.com

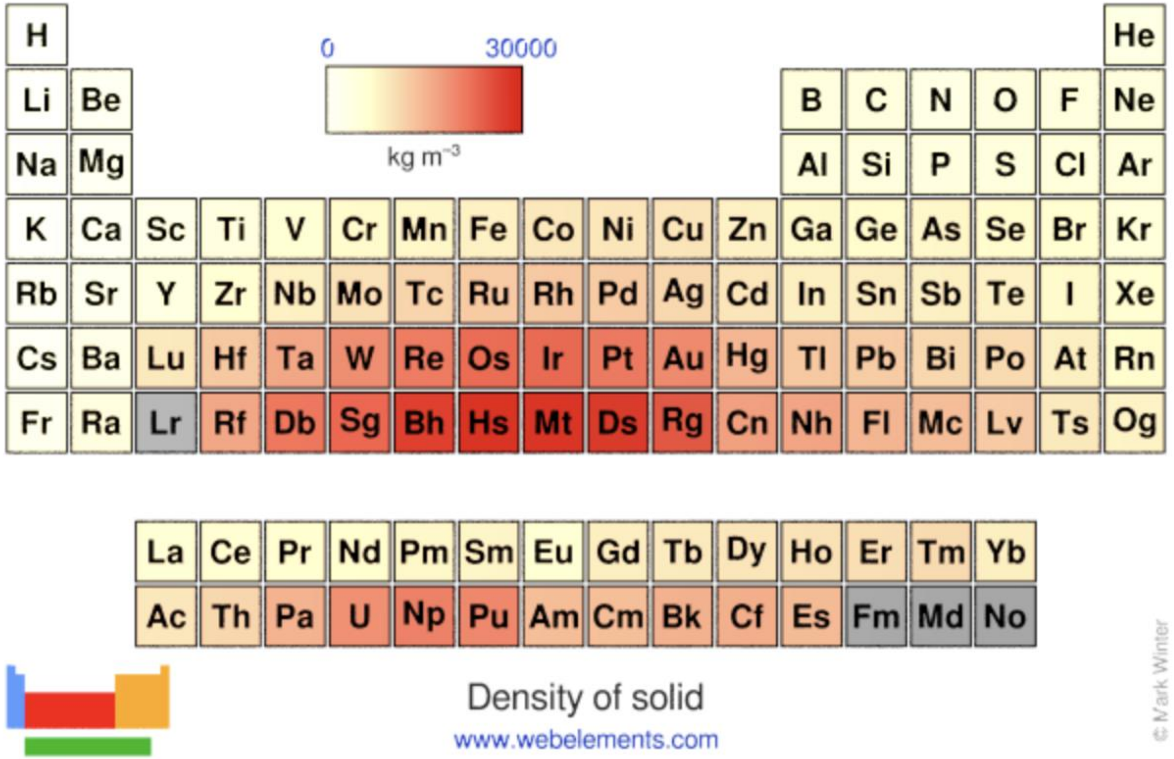
Basic chemistry of the lithospheric mantle

Less Dense Elements

K (0.86 g/cm^3)
Na (0.97 g/cm^3)
Ca (1.55 g/cm^3)
Mg (1.73 g/cm^3)
Si (2.33 g/cm^3)
Al (2.70 g/cm^3)
Ti (4.54 g/cm^3)
Cr (7.19 g/cm^3)
Mn (7.43 g/cm^3)
Fe (7.87 g/cm^3)

More Dense Elements

Density of elements measured at SLC



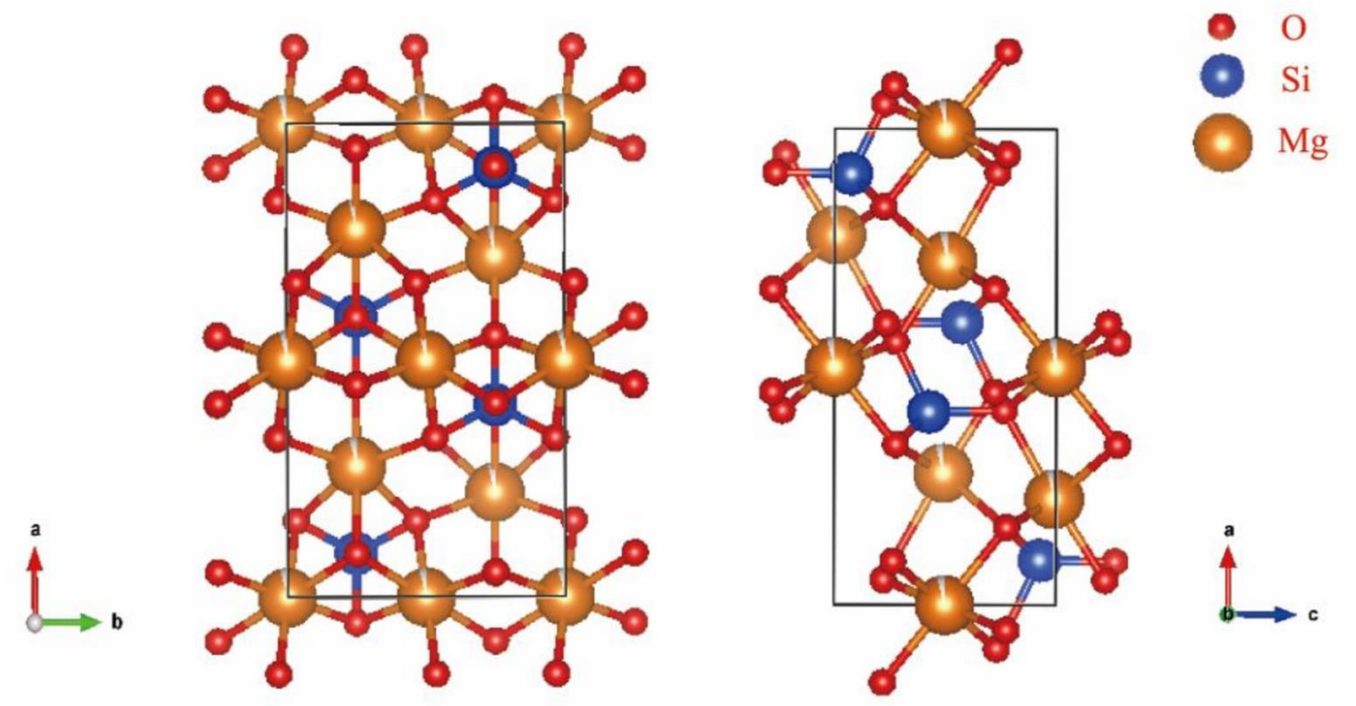
Density of solid
www.webelements.com

Basic mineralogy of the lithospheric mantle

Elements are arranged into stable crystalline solids – *minerals*

The elements are oxides are connected to form minerals by different chemical bonds which have varying strength

There are 6062 official minerals on Earth – **however, the lithospheric mantle has ~8 major minerals**



Simplified illustration of the arrangement of elements that form a forsterite (olivine) crystal. Olivine contains an Mg and Si cation that are bonded with oxygen anions. After Peng (2022)

Basic mineralogy of the lithospheric mantle

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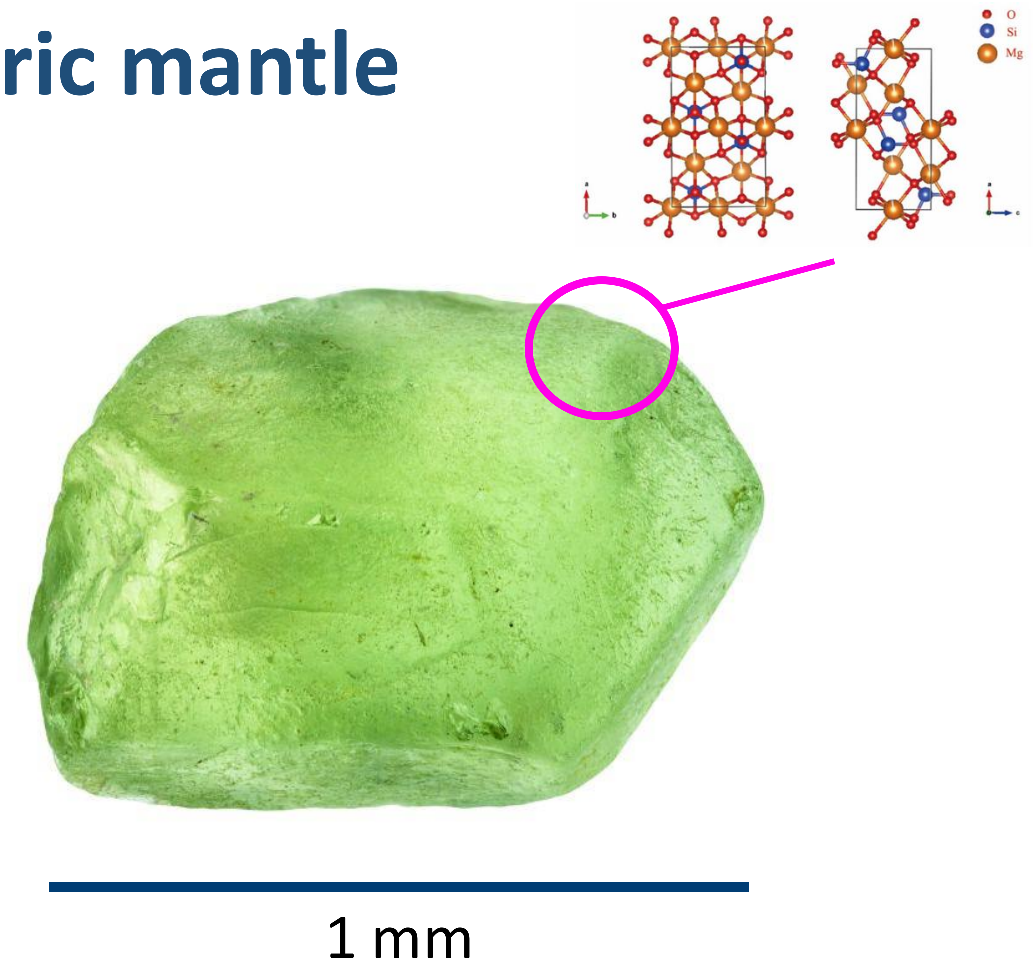


Olivine crystal (not to scale) made up of millions of repeated Mg2SiO4.

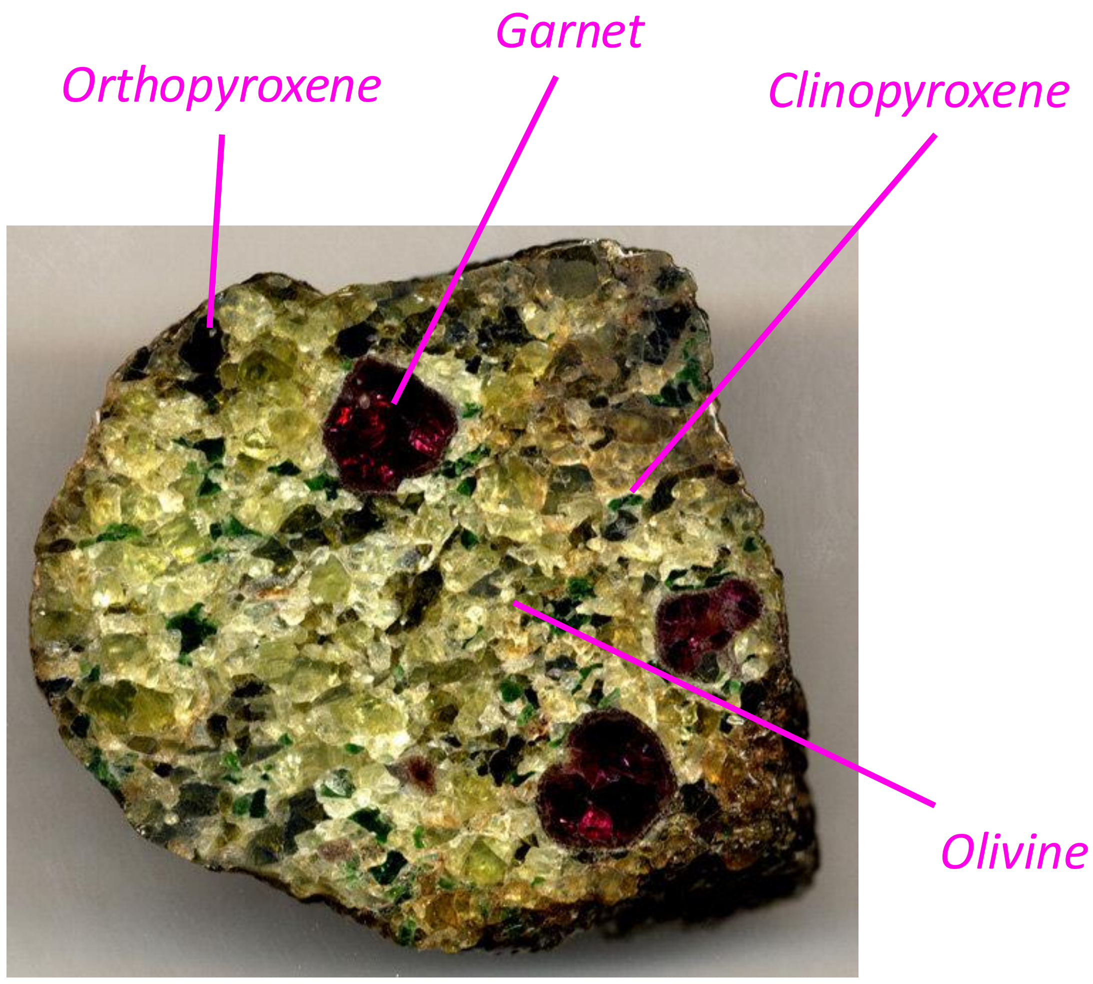
Basic mineralogy of the lithospheric mantle

The mineralogy of the mantle is surprisingly simple:

Olivine	$(Mg,Fe)_2SiO_4$
Clinopyroxene	$(Ca,Mg,Fe,Na)(Mg,Fe,Al)(Si,Al)_2O_6$
Orthopyroxene	$(Mg,Fe)_2Si_2O_6)$
Garnet	$(Mg,Fe,Ca,Mn)_3(Al,Cr)_2(SiO_4)_3$

These minerals have different properties such as density, melting T, and electronegativity.

Minerals occur in different abundances to make up rock types in the lithospheric mantle - largely due to changes in pressure and temperature



Mantle xenolith containing the main mantle minerals

Basic mineralogy of the lithospheric mantle

Olivine **(Mg,Fe)$_2$SiO$_4$**

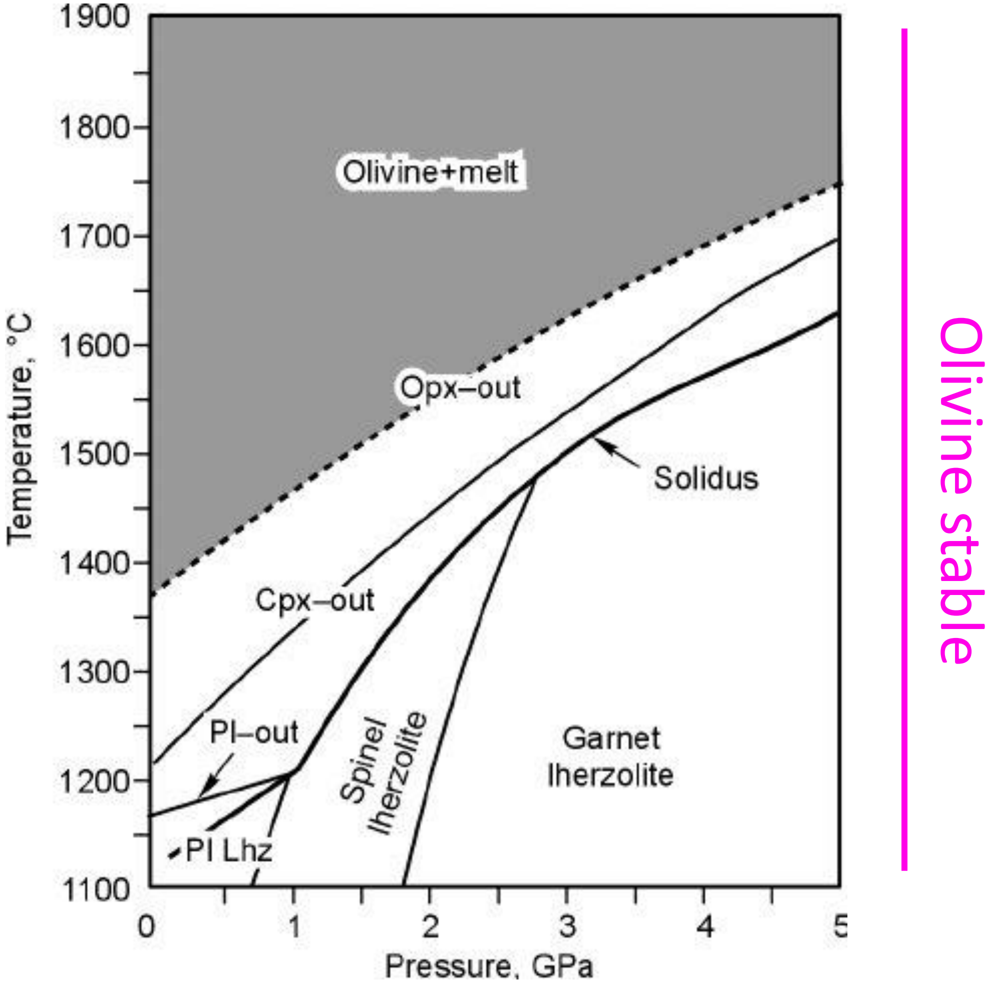
Makes up about 50% to 70% of lithospheric mantle by volume. Stable in mantle across a wide range of PT until phase transformation to Wadsleyite (410 km)

Stable across entire lithospheric mantle PT range: Last mineral to melt in mantle rocks

Density: 3.21–3.33 g/cm^3 (Mg$_2$SiO$_4$)
Density: 4.30–4.40 g/cm^3 (Fe$_2$SiO$_4$)

Mg-rich olivine is common within thick and cold cratons

Phase diagram of peridotite



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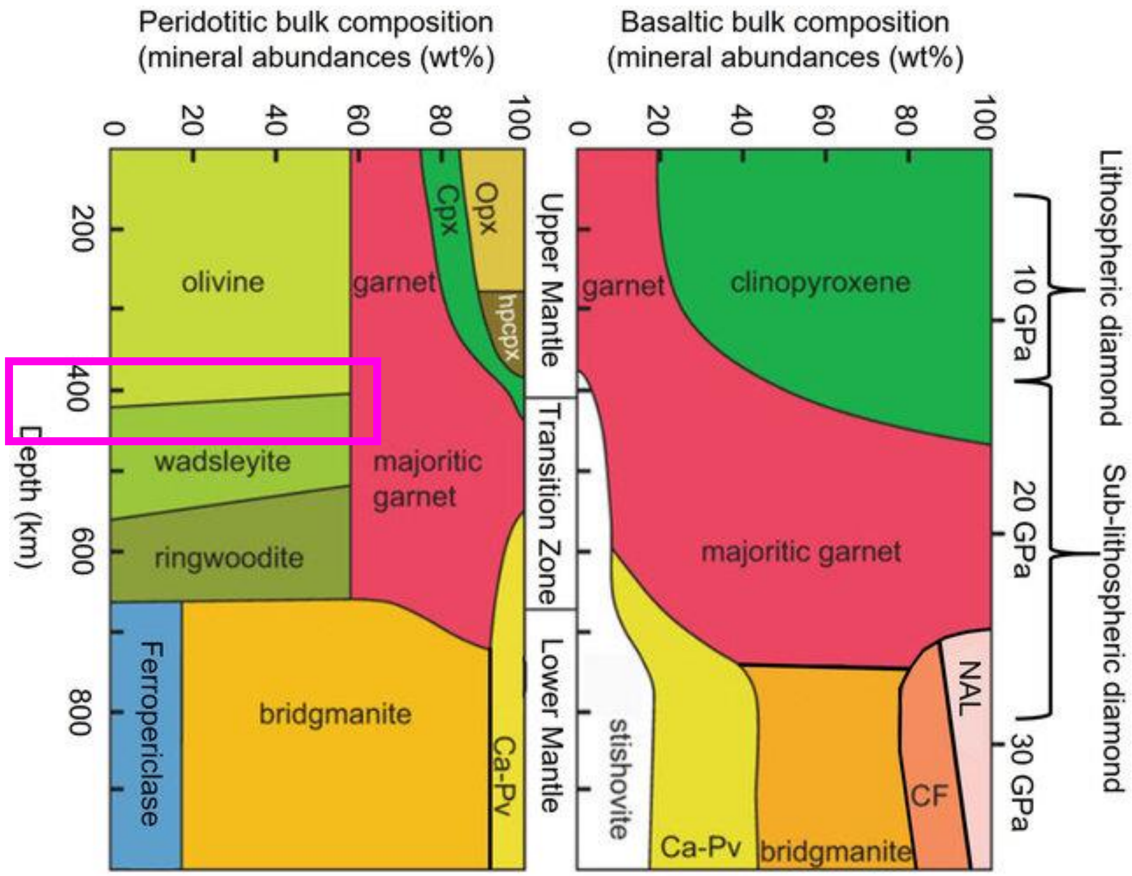


Basic mineralogy of the lithospheric mantle

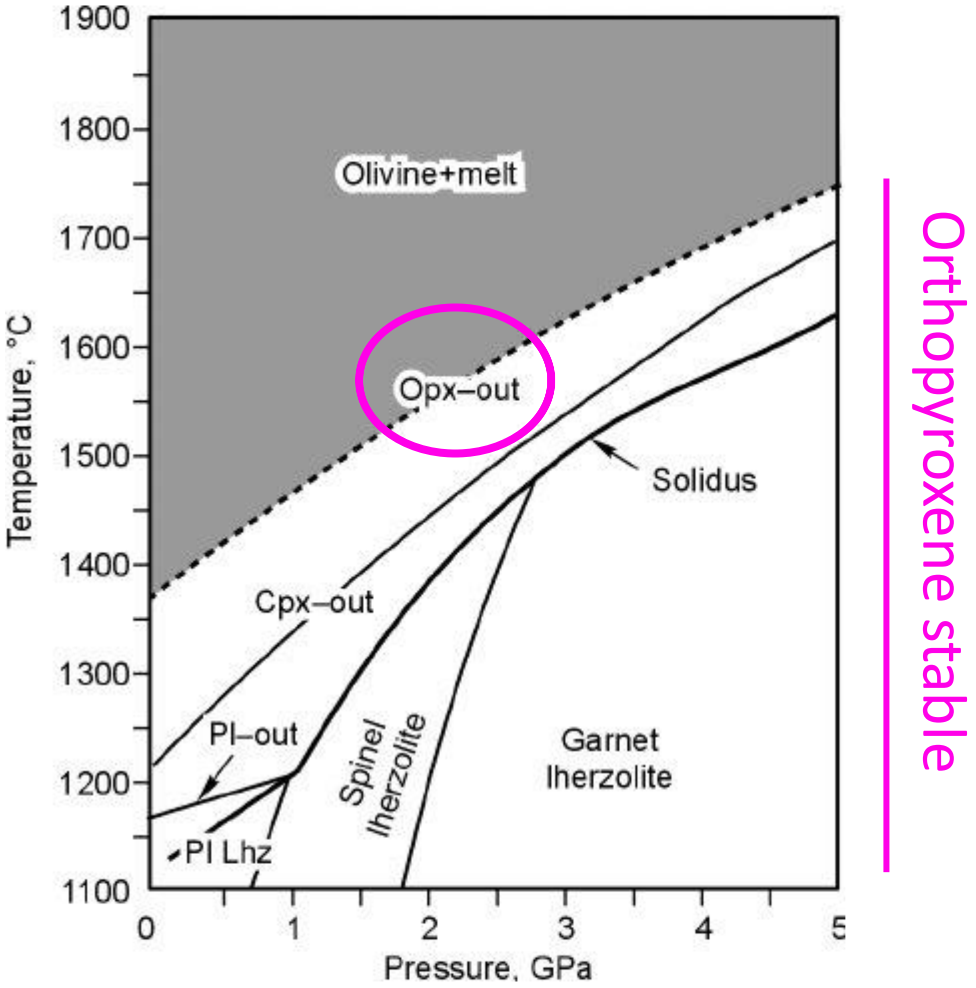
Orthopyroxene **$(Mg,Fe)_2Si_2O_6$**

Makes up <25% of lithospheric mantle by volume. Begins to break-down at high PT

Stable across most lithospheric mantle PT range: <u>Second last mineral to melt in mantle rocks</u>

Density: 3.10–3.30 g/cm^3 ($Mg_2Si_2O_6$)

Also common within thick and cold cratons along with high-Mg olivines



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Basic mineralogy of the lithospheric mantle

Clinopyroxene

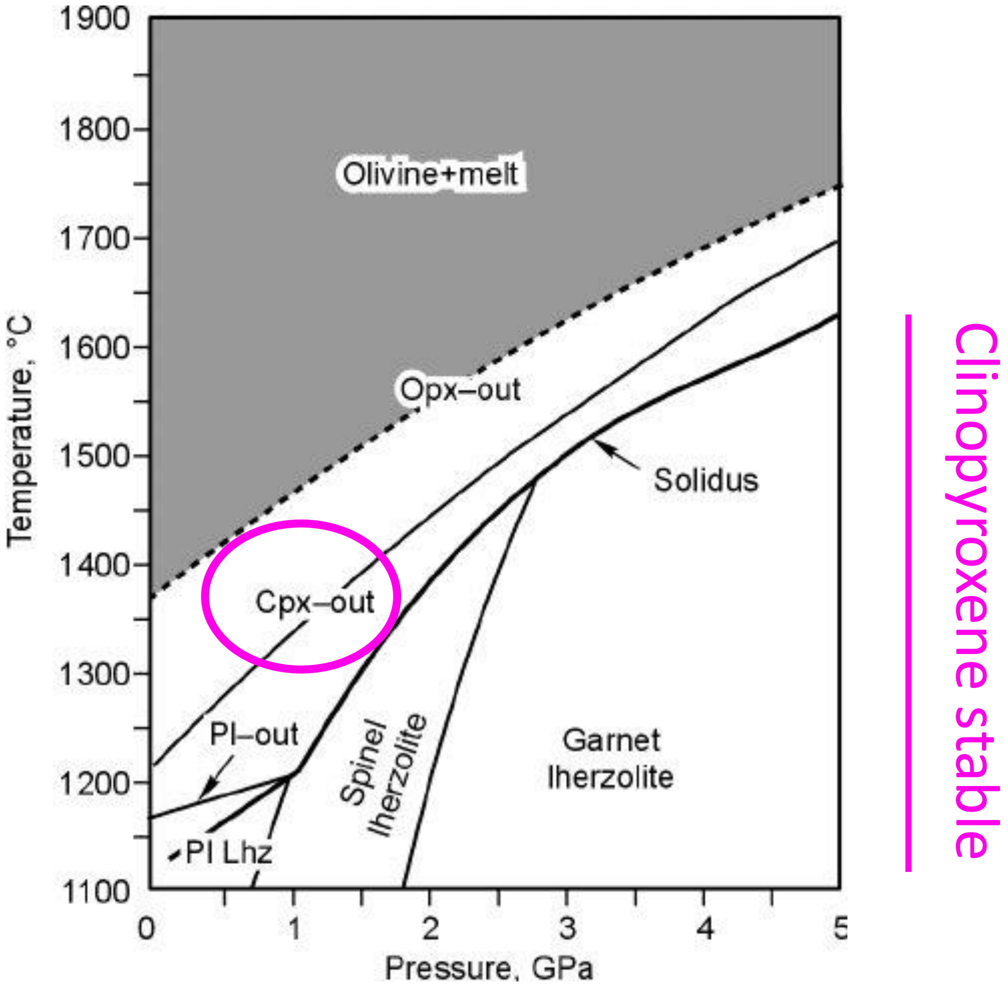
$(Ca,Mg,Fe,Na)(Mg,Fe,Al)(Si,Al)_2O_6$

Makes up <25% of lithospheric mantle by volume.
Begins to break-down at high-PT

Stable across moderate PT in lithospheric mantle:
<u>First major silicate mineral to melt in mantle rocks</u>

Density: 3.22–3.38 g/cm^3 ($CaMgSi_2O_6$)

Uncommon within thick and cold cratonic regions of continents…



Basic mineralogy of the lithospheric mantle

Garnet

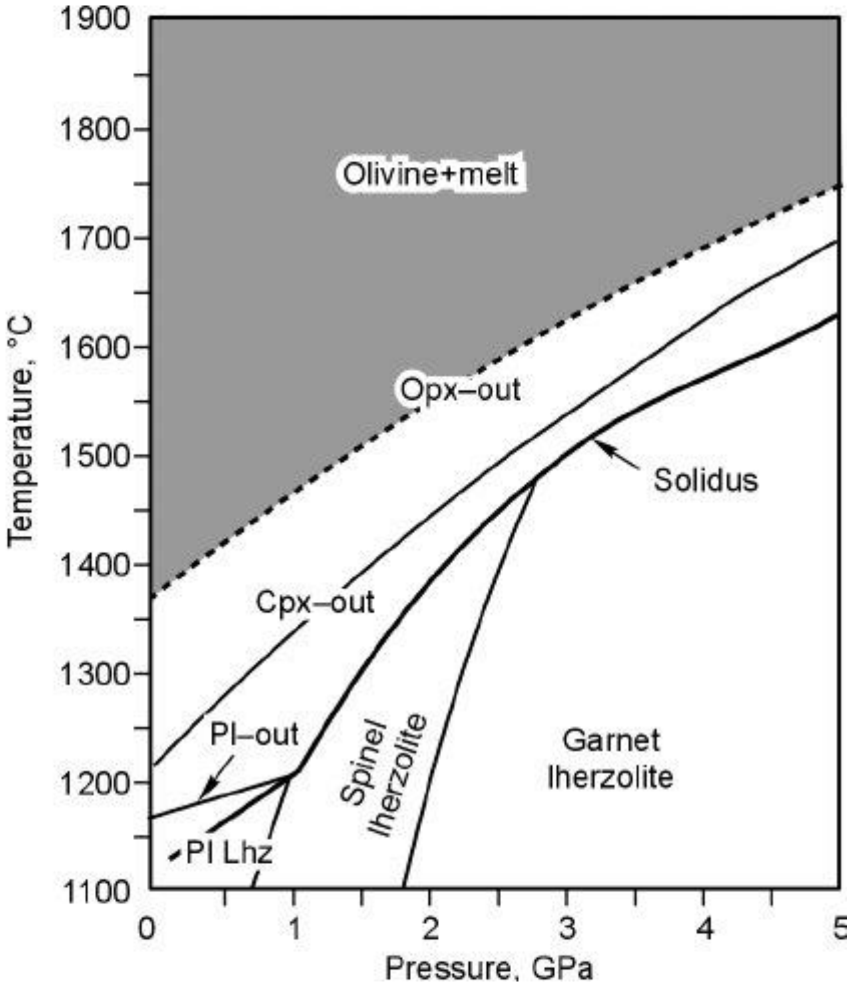
$(Mg,Fe,Ca,Mn)_3(Al,Cr)_2(SiO_4)_3$

Makes up <10% of lithospheric mantle by volume.
Stable beyond ~2 GPa following spinel breakdown

Stable across large PT in lithospheric mantle
<u>breaks down at similar PT to orthopyroxene</u>

Density: 3.45–3.55 g/cm^3 $Mg_3Al_2(SiO_4)_3$

Common within thicker (>60 km) regions of continental lithosphere (shallow regions = spinel)



Quick break for Questions…..

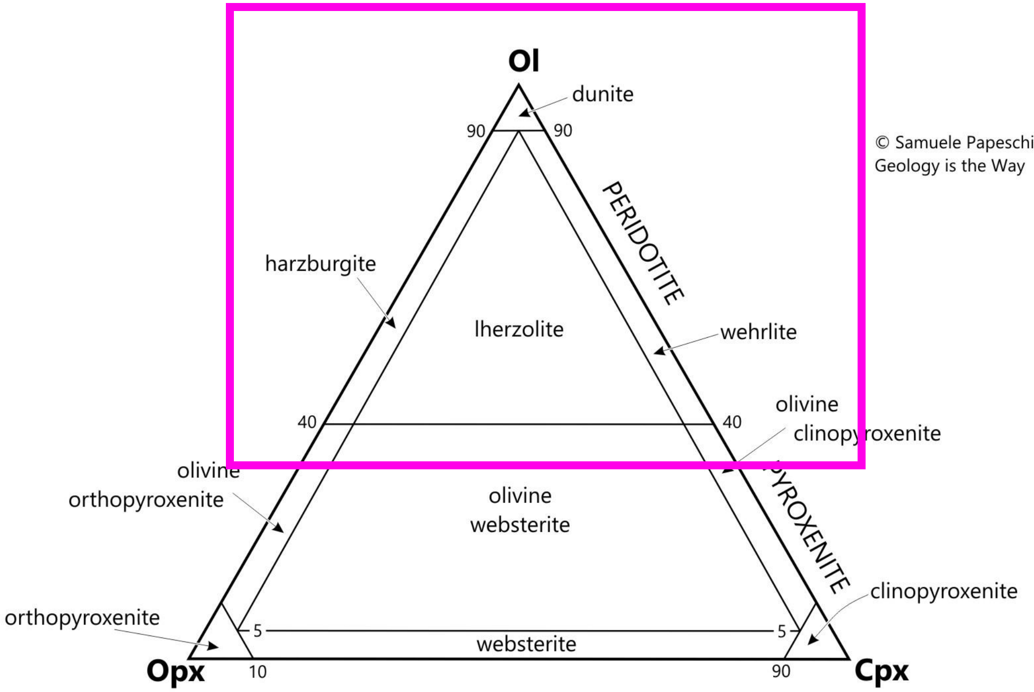
What is the mantle made from?

Experimental and geochemical studies suggest that the lithospheric mantle is ***mostly*** comprised of ***peridotite***

The mineralogy of peridotite is:
Olivine
Clinopyroxene
Orthopyroxene
Garnet or Spinel

Several ‘flavors’ of peridotite may occur depending on the modal abundances of these minerals. These are closely related to the PT variations discussed on previous slides:

Dunite **Lherzolite**
Harzburgite **Wehrlite**



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Ternary diagram showing different rock types that occur within the lithospheric mantle and their modal percentage of olivine (Ol) clino- (Cpx) orthopyroxene (Opx)

What is the mantle made from?

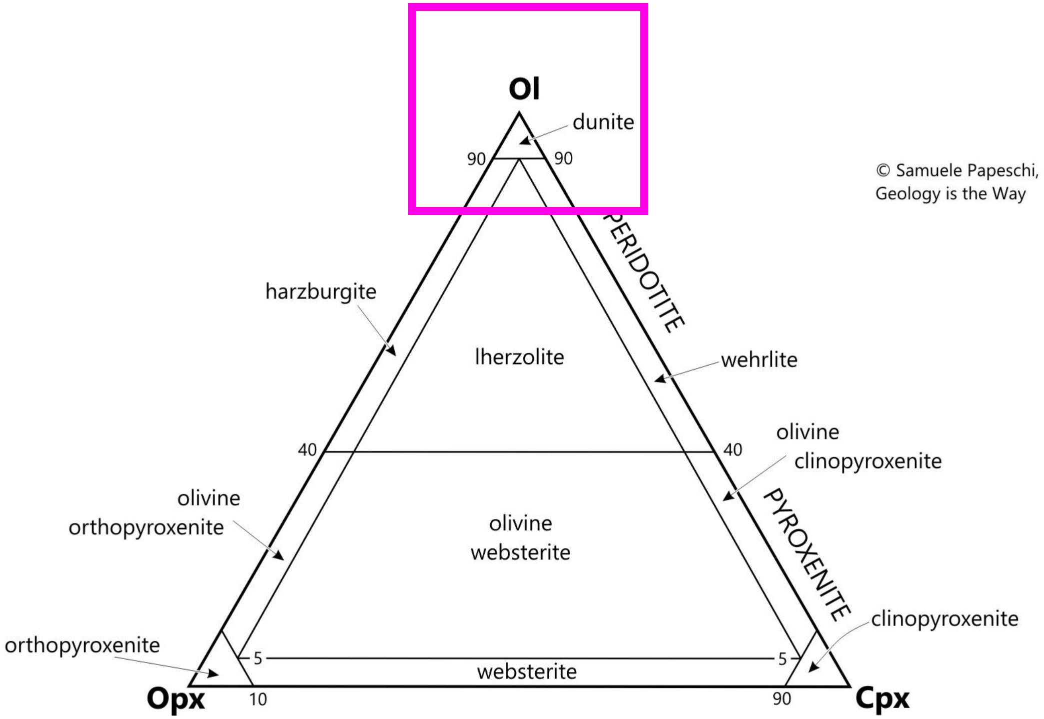
Dunite:

90% olivine with minor (<10 %) clinopyroxene and/or orthopyroxene (and garnet/spinel)

Named after Dun Mountain: New Zealand

Formation requires melting past cpx-out and opx-out (high-degree melting): 1500–1700 °C and 2–5 GPa

Relatively uncommon within the mantle although known to occur beneath cratons and in settings with high-degree melting (M.O.R)



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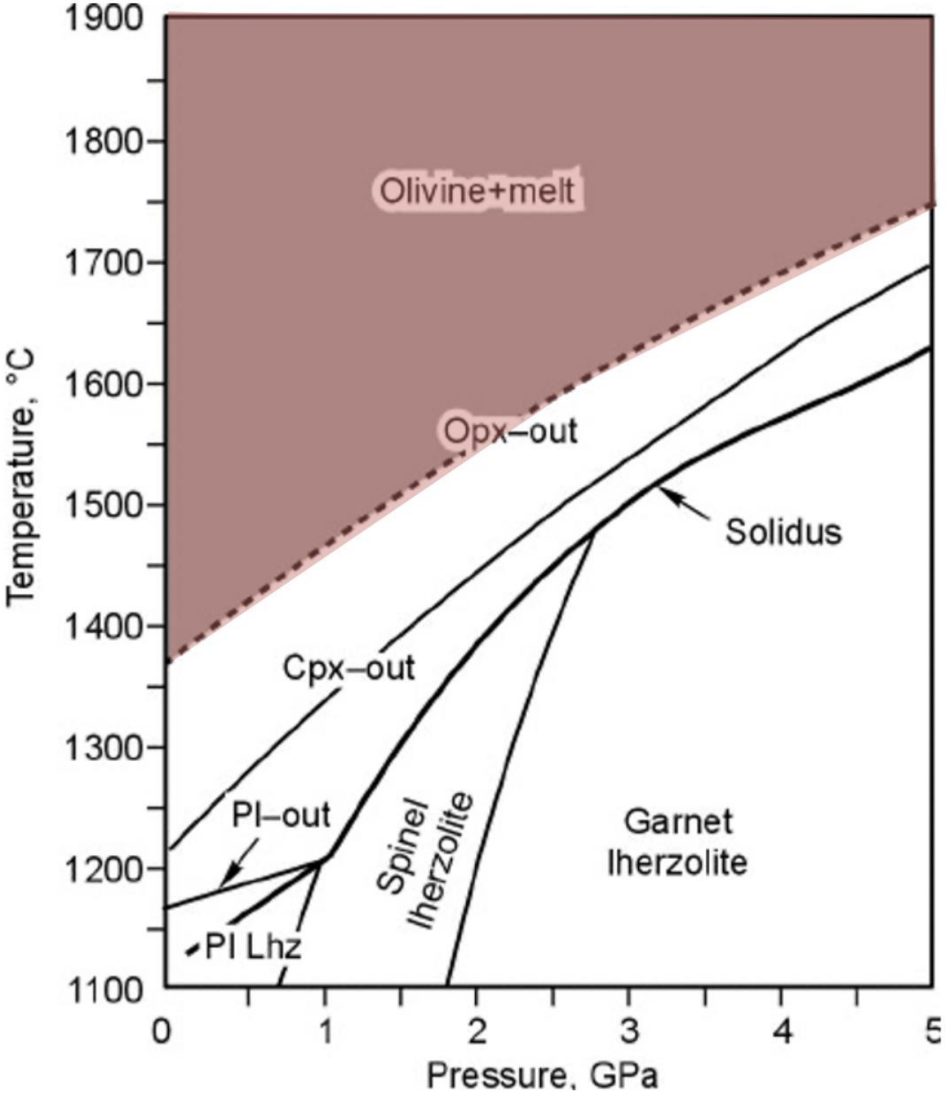


What is the mantle made from?

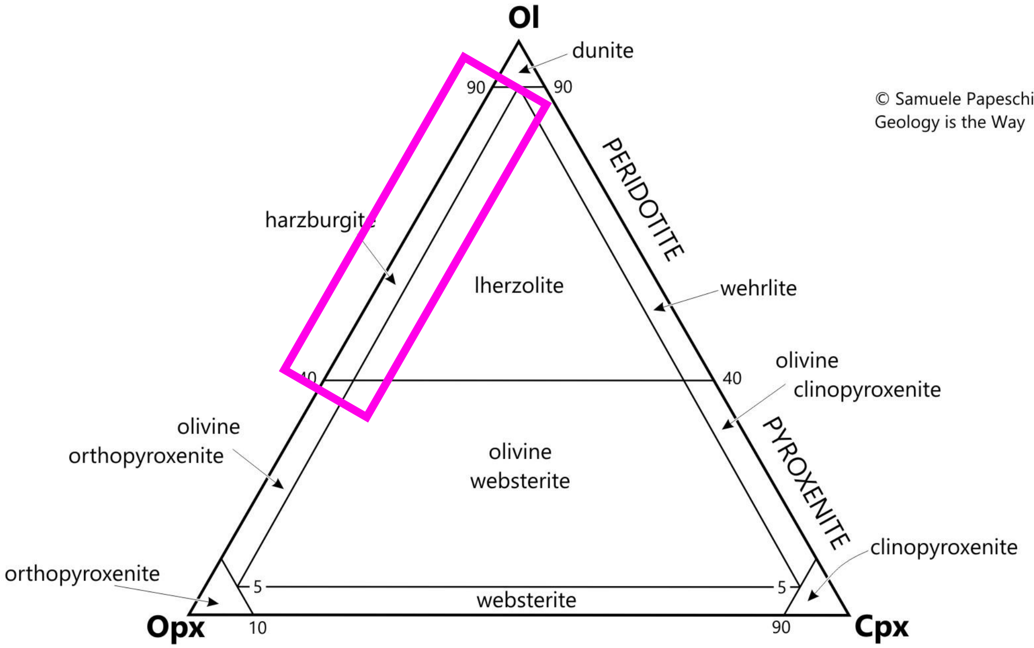
Harzburgite:

Orthopyroxene and olivine with <5% clinopyroxene

Named after Harz Mountain (Germany)

Minor clinopyroxene: Formation requires melting past cpx-out (high-degree melting): 1400–1600 ℃ and 3–5 GPa

Common within the mantle beneath ancient cratons, M.O.R settings, and some subduction zones. Relatively less dense and geochemically depleted in comparison to other mantle rocks



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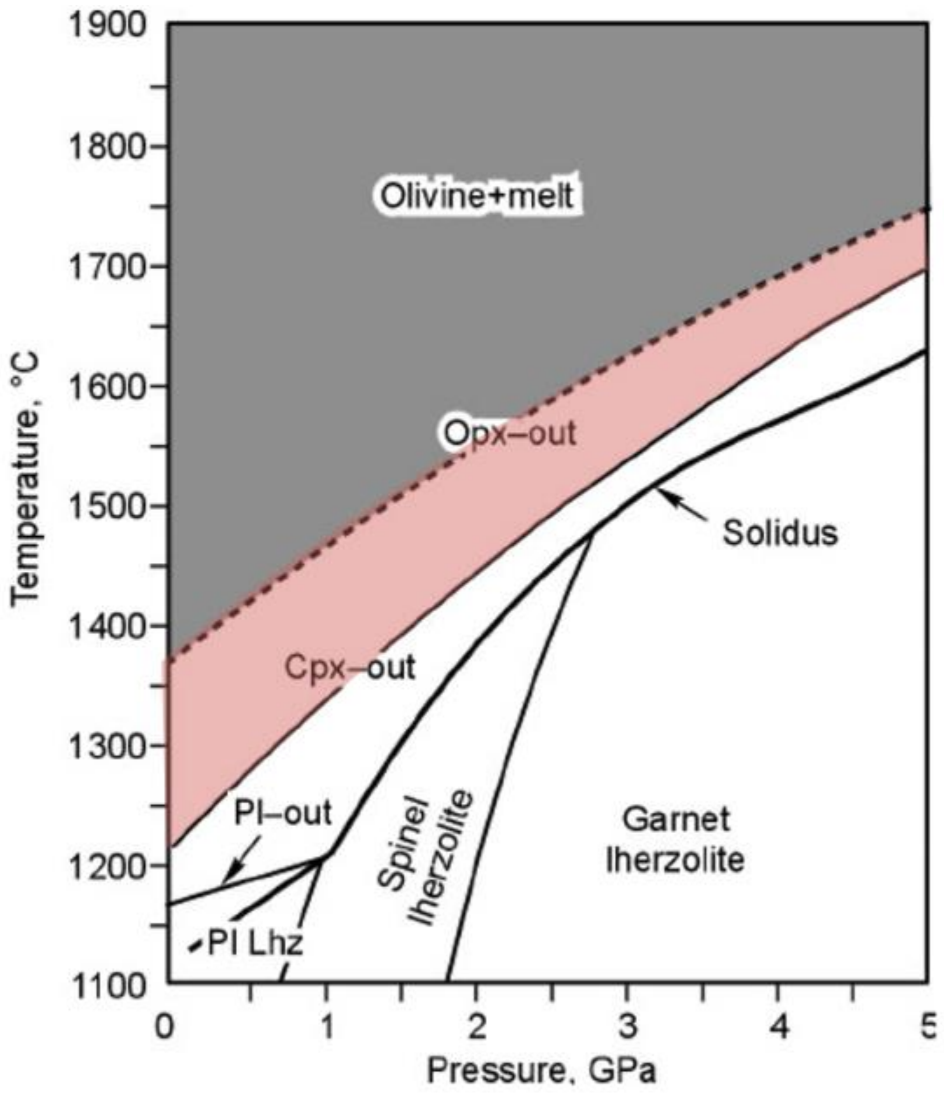


What is the mantle made from?

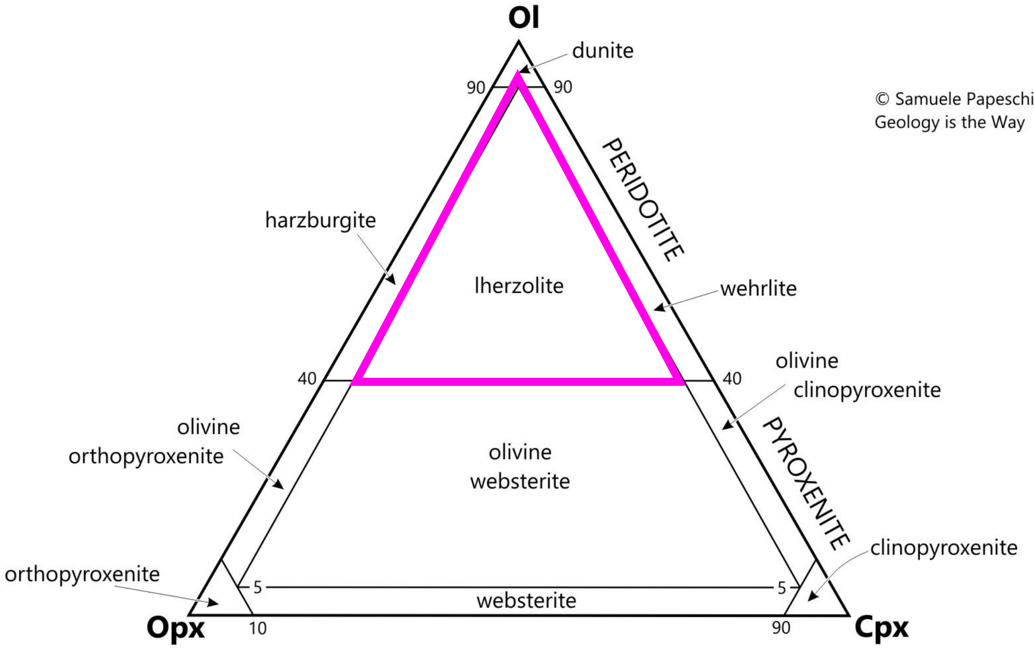
Lherzolite:

Orthopyroxene, olivine and clinopyroxene (+/- garnet and/or spinel)

Lherz Massif: North Pyrenees (France)

Most common rock type within the lithospheric mantle. Occurs beneath most settings (i.e., cratons, M.O.R settings, subduction zones etc.)

Most geothermal gradients do not reach the temperatures required to melt orthopyroxene and clinopyroxene. Therefore, Lherzolite is most common.



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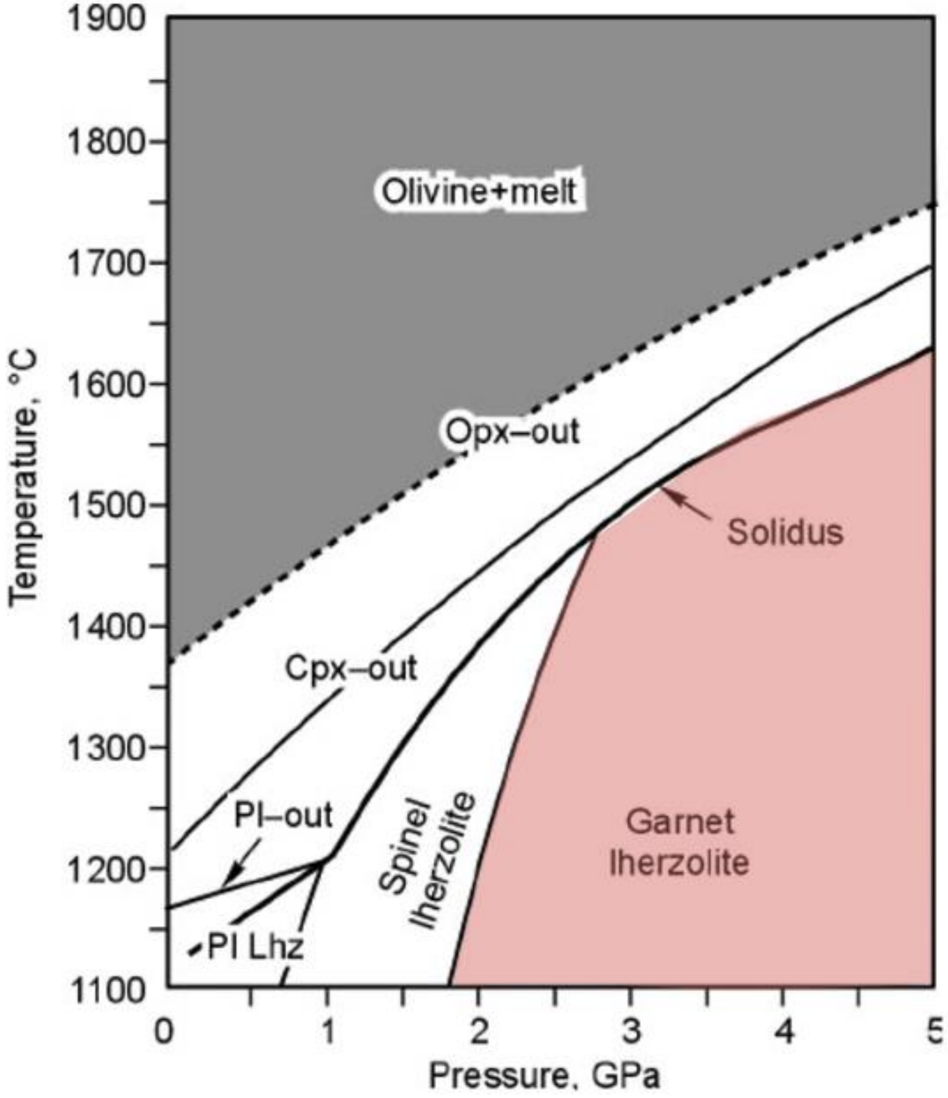
Most geothermal gradients do not reach the temperatures required to melt orthopyroxene and clinopyroxene. Therefore, Lherzolite is most common rock in most mantle settings!

Garnet Lherzolite



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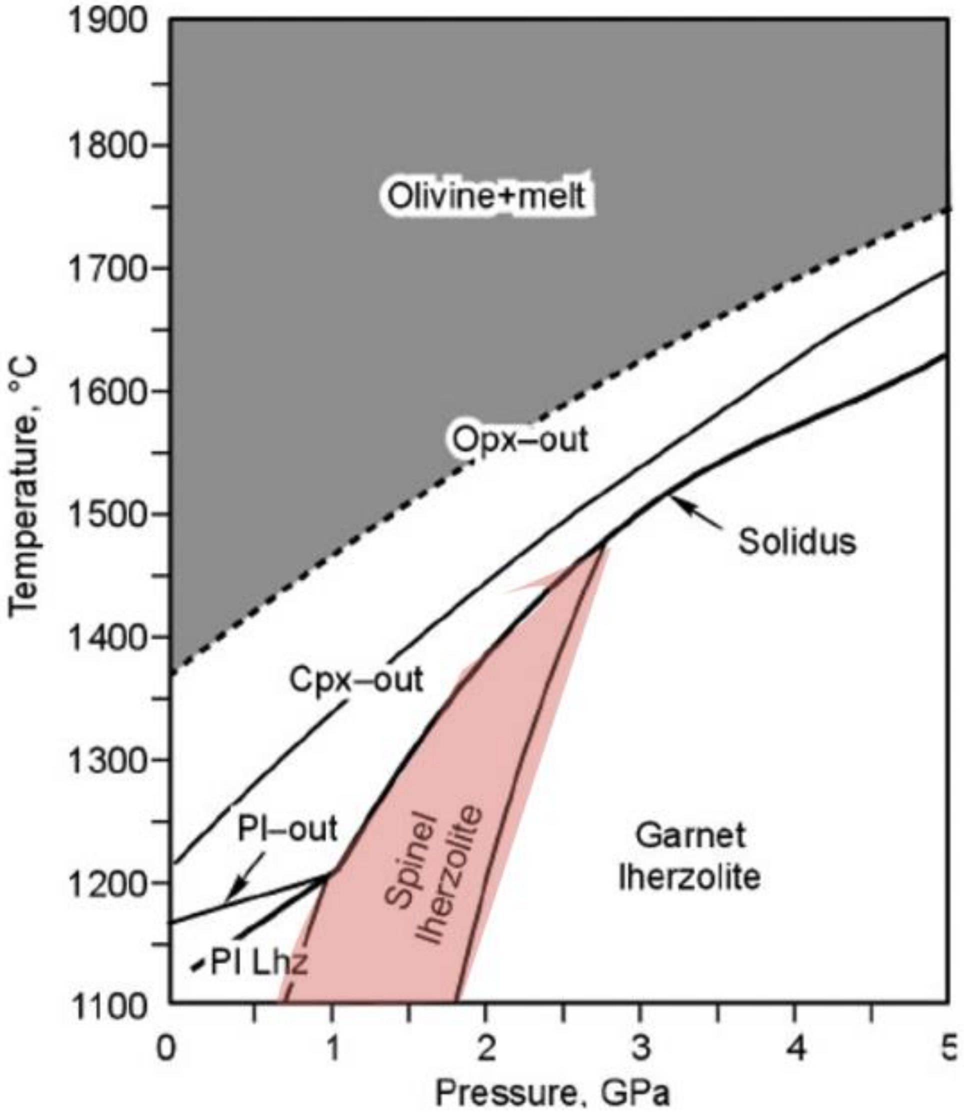
Spinel Lherzolite



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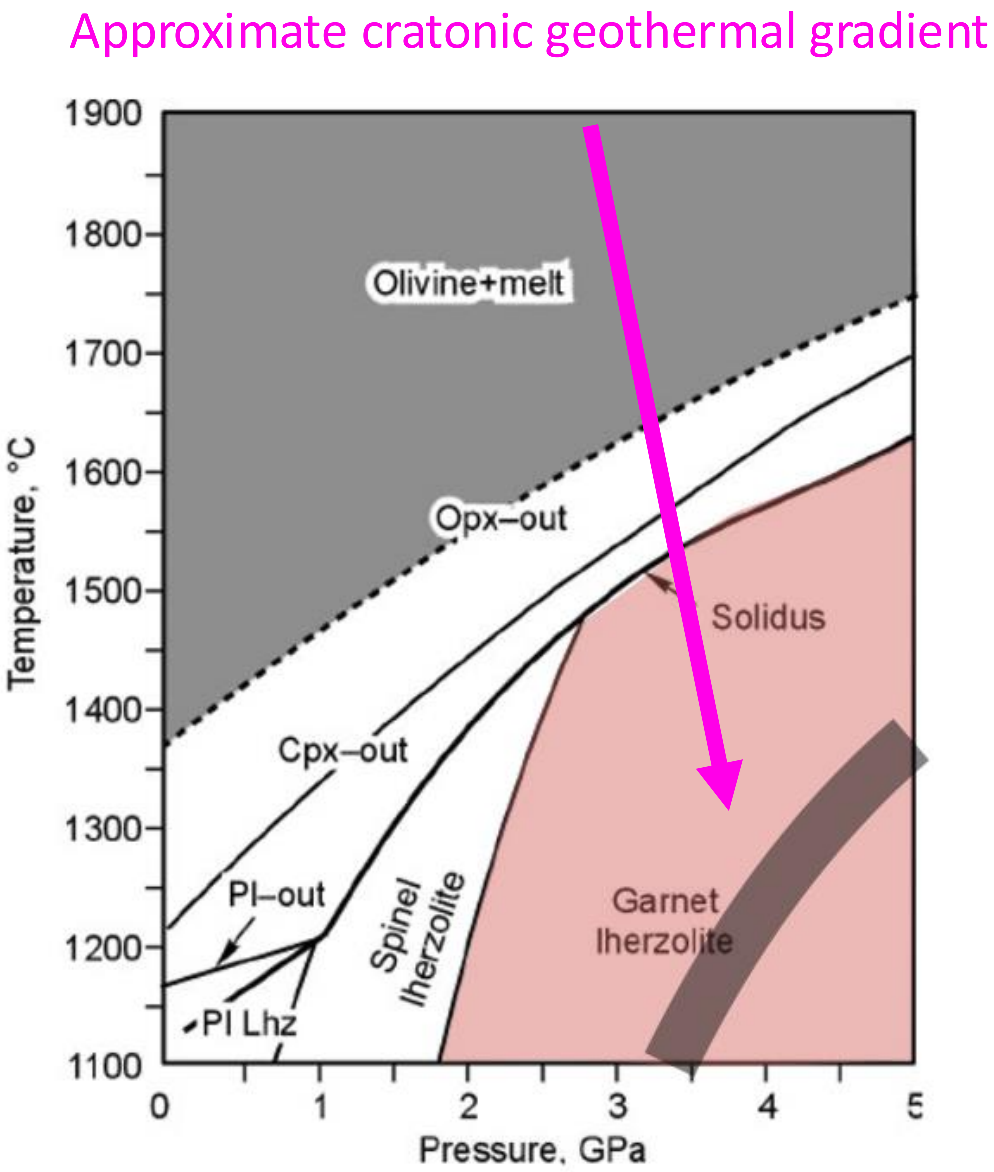


What is the mantle made from?

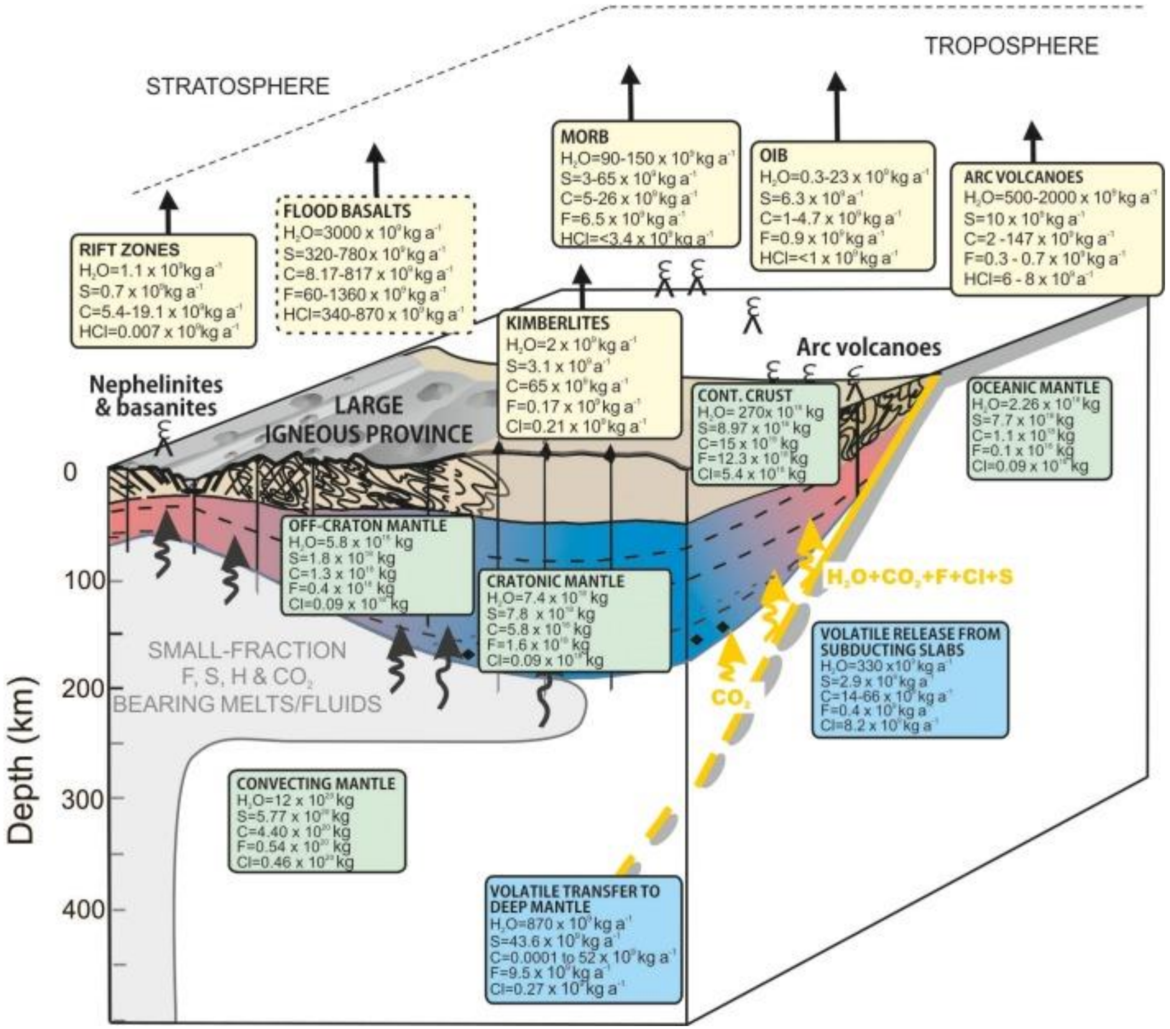
- The previous rock types and their minerals describe most of the lithospheric mantle **BUT cannot explain all complexity**
- These rocks and minerals are anhydrous and volatile free (they assume a dry mantle), which is true for most of the lithospheric mantle
- Additional complexities within the lithospheric mantle relate to very small changes in composition and mineralogy **caused by the presence of very small amounts of H_2O and CO_2**
- The addition of these components helps to **form new 'secondary' minerals which have unique properties** compared to 'dry' minerals

The role of volatiles in mantle heterogeneity

There needs to be some volatiles present (CO_2, H_2O) within the lithospheric mantle:

- **Mass balance calculations of volatiles entering and exiting subduction zones**
- Seismology and magnetotellurics
- Composition of erupted lavas and isotope geochemistry

Volatiles are mostly added by subduction of oceanic crust but may be mobilized during melting, convection and mantle plumes



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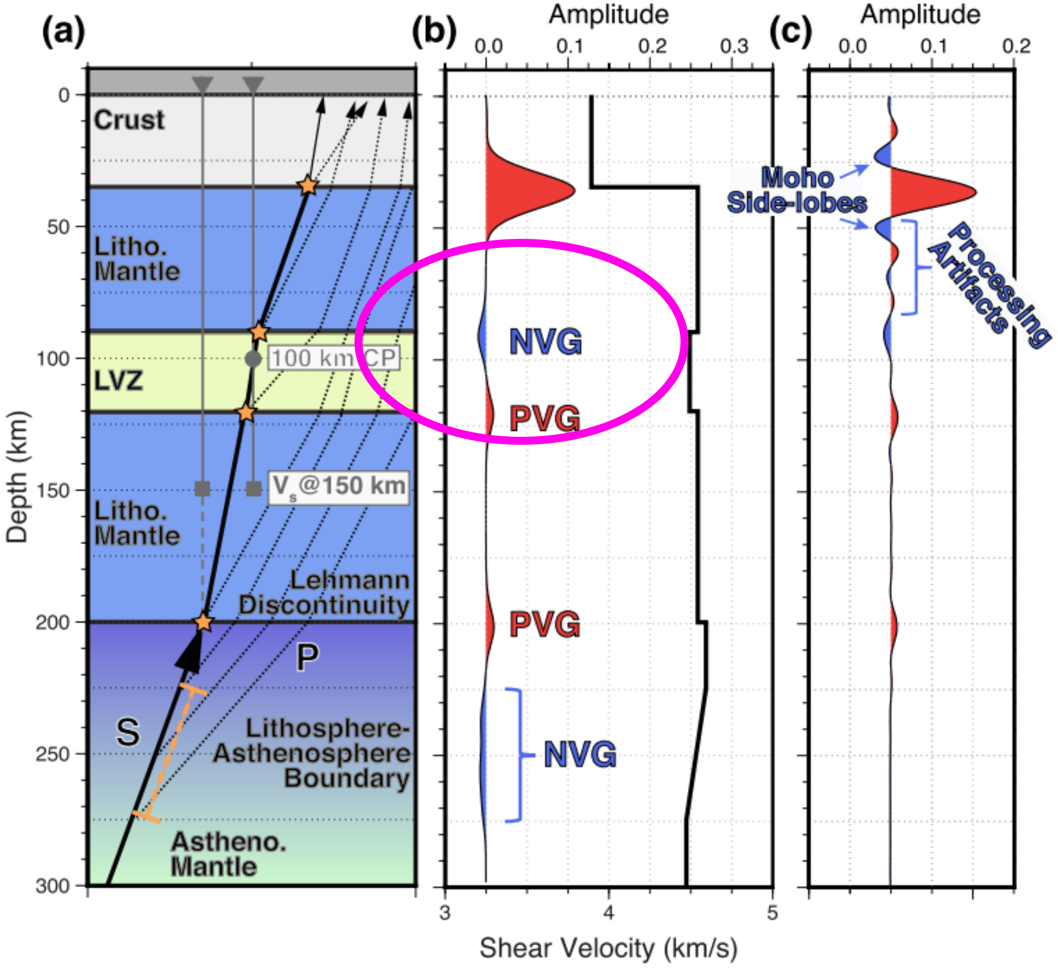

Simplified illustration of synthetic receiver function for cratonic lithosphere. NVG are difficult to explain by assuming a homogenous and anhydrous lithospheric mantle. Krueger et al. (2021).

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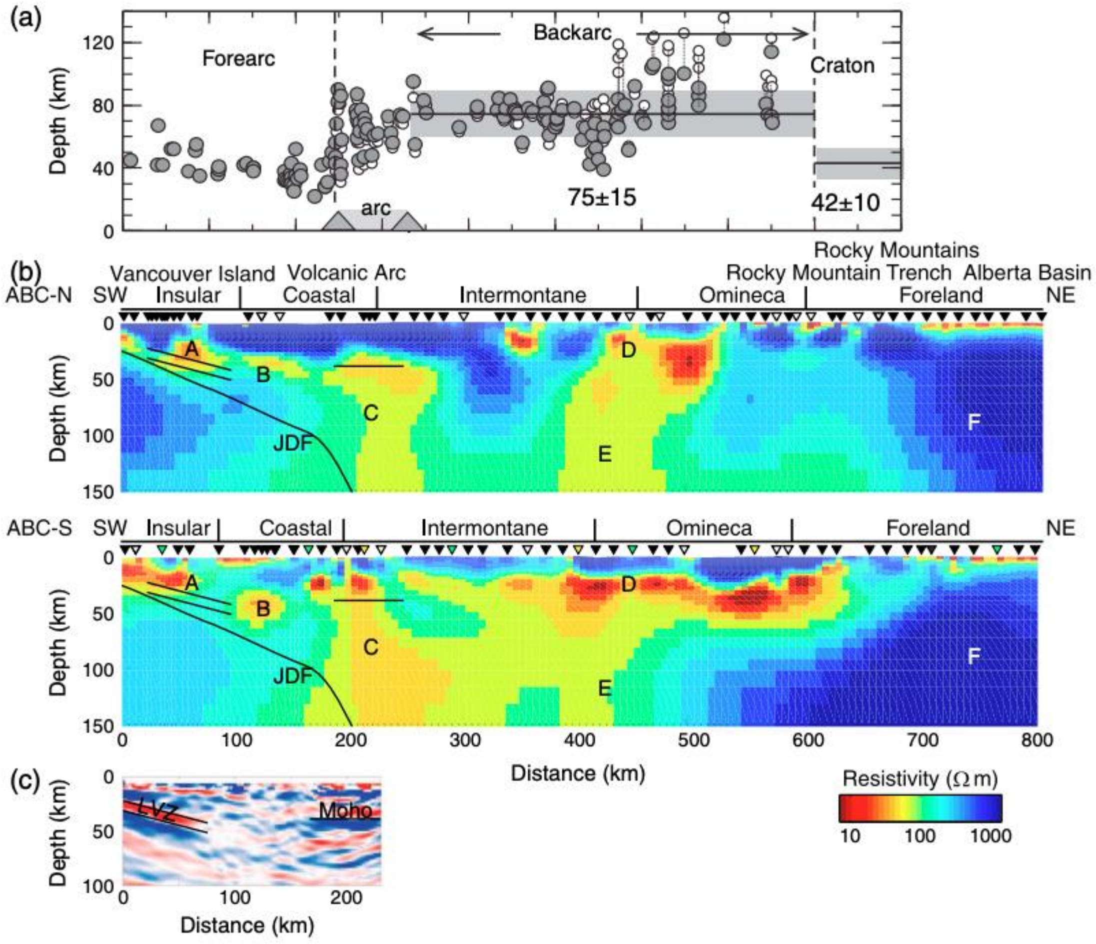

(a) Heat flow map after Currie and Hyndman (2006). (b-c) electrical resistivity model along two different traverses at Canadian Cordillera. Note the significant variations in the EC within lithospheric mantle. After Rippe et al. (2013).

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Volatiles are mostly added by subduction of oceanic crust but may be mobilized during melting, convection and mantle plumes

Professor Marie Edmonds sampling volcanic rocks. These samples can be quantitively analyzed for their compositions to determine the amounts of volatiles within their mantle source region.

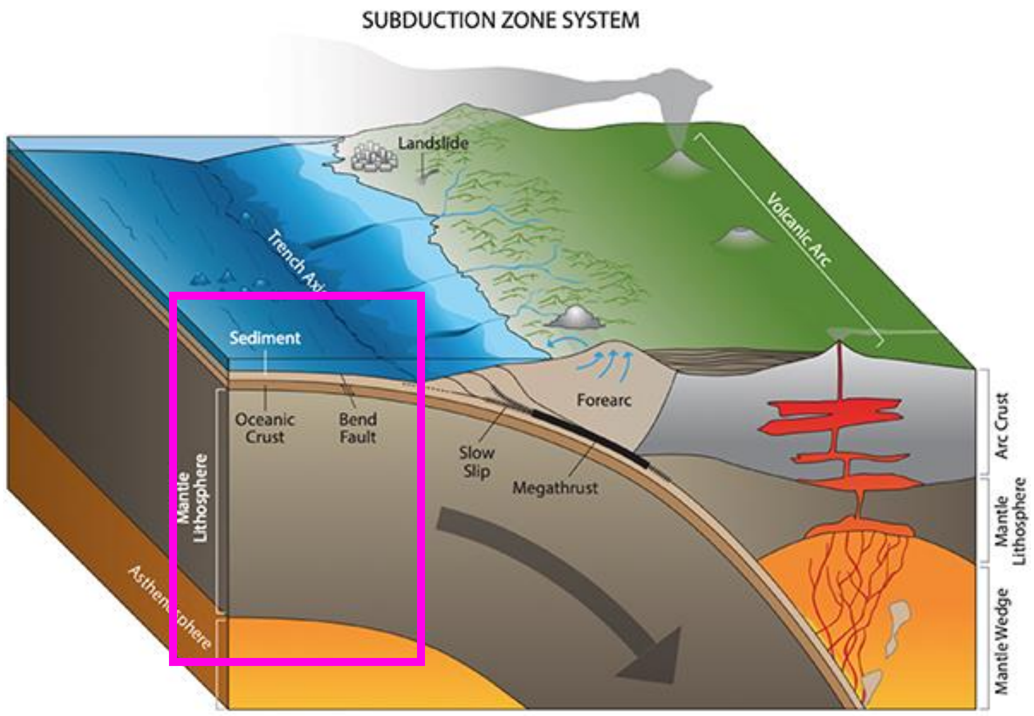
The role of volatiles in mantle heterogeneity

Dense- water-rich oceanic crust (basalt) and sediments can enter the lithospheric mantle at subduction zones and add heterogeneities in mantle composition at the mantle wedge

Water and other volatiles are mostly expelled off the slab into volcanoes, but some enter long-term cycles in mantle

Some volatiles will enter the crystal latices of minerals or form new water-rich minerals (micas and amphiboles). Very small concentrations!

Water-bearing minerals result in extreme changes in the geophysical properties of the lithospheric mantle



Simplified illustration of a subduction zone. Basalt is converted to eclogite which drives the slab-pull process. Water and other volatiles are expelled off the slab into the surrounding mantle wedge.

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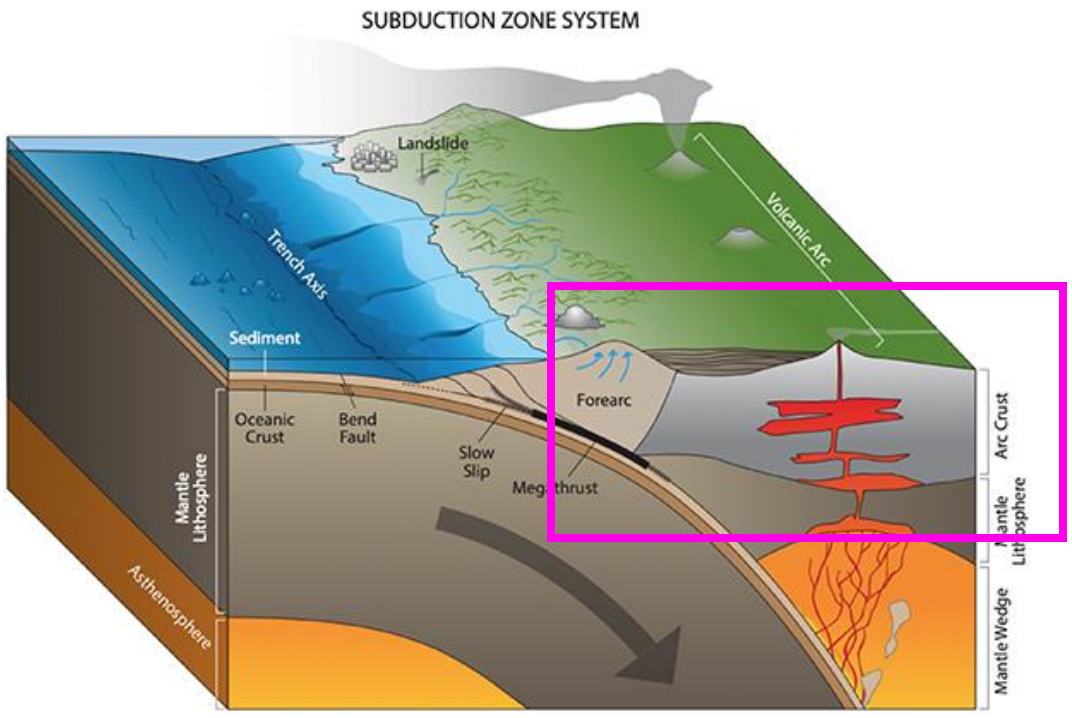

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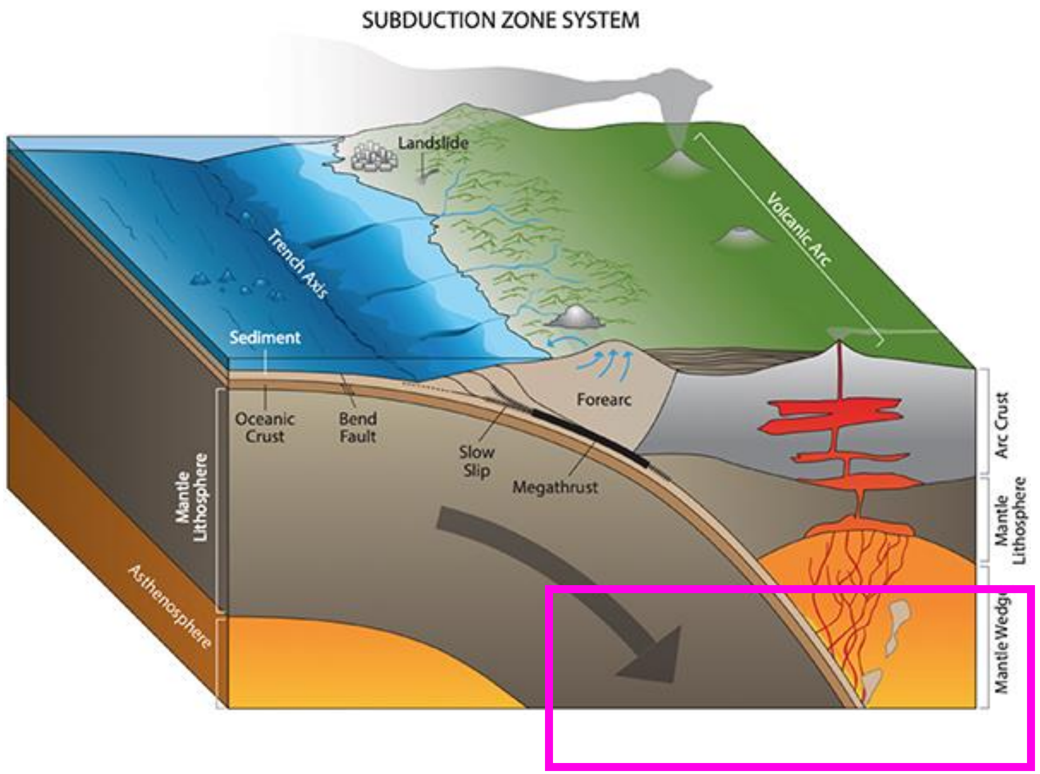

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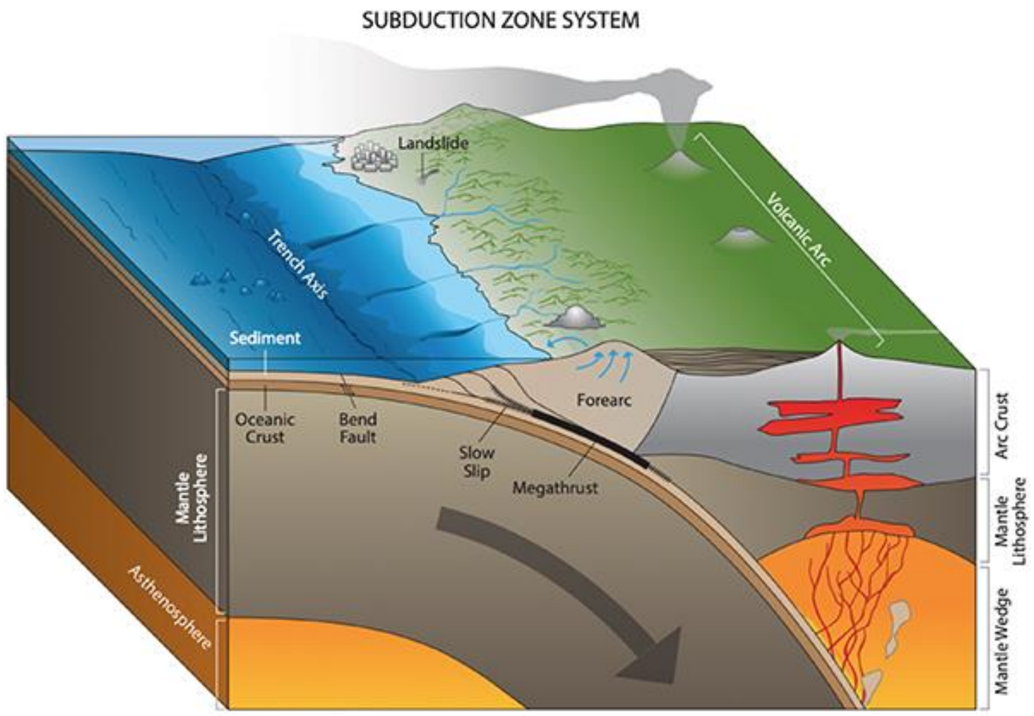

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The role of volatiles in mantle heterogeneity

Addition of volatiles into the lithospheric mantle helps to form new 'secondary' minerals:

- Phlogopite
- Amphibole
- Ca-Mg Carbonate

These minerals occur in extremely low abundances (<5%) but are responsible for a significant amount of the heterogeneity and complexity of the lithospheric mantle

Due to their volatile contents these minerals have relatively narrow stability fields in the lithospheric mantle and can re-melt easily

Phlogopite occurring in vien in lherzolite. Phlogopite may have been added during peculation of fluid within the mantle wedge of a subduction zone. Photo: Alex Strekeisen.

Quick Summary:

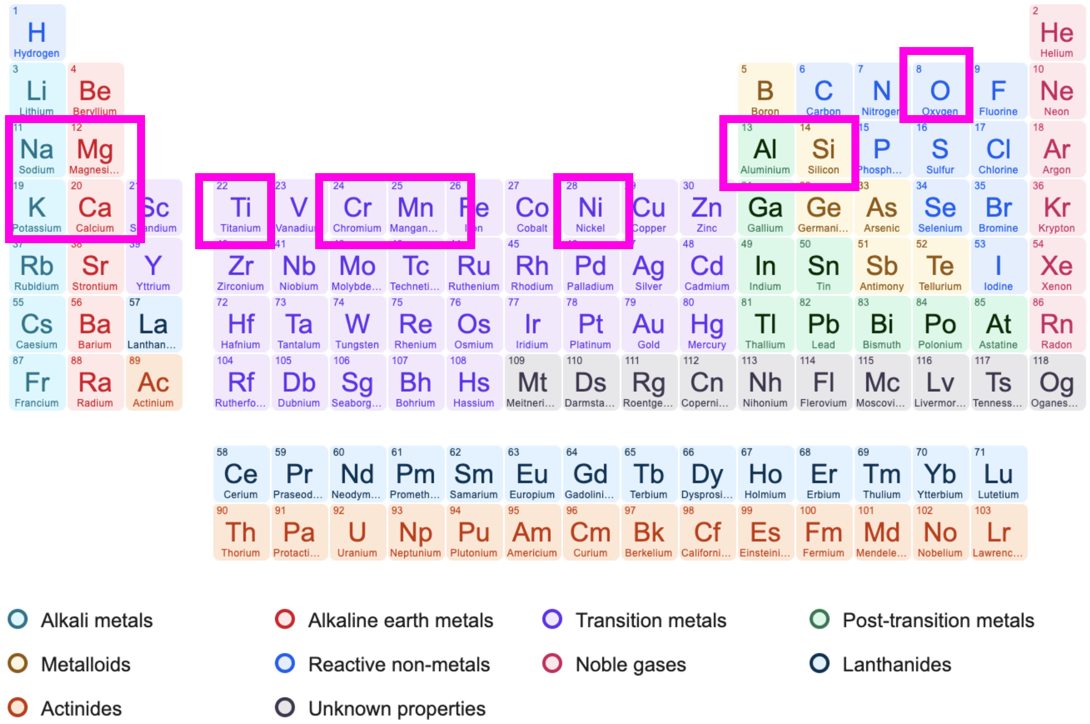
>99% of lithospheric mantle is made up of <10 geochemical building builds (oxides)

Si, Al, Ti, Cr, Fe, Mn, Mg, Ca, Na, K and O

These elements are arranged into crystal structures (minerals):

Petrological studies show that most of the lithospheric mantle is peridotite. Peridotite contains the minerals:

Olivine **Garnet**
Clinopyroxene **Orthopyroxene**



Periodic table of elements. Areas with pink square represent the most common elements that occur within the lithospheric mantle. These elements mostly commonly occur in stable compounds with oxygen which are referred to as oxides.

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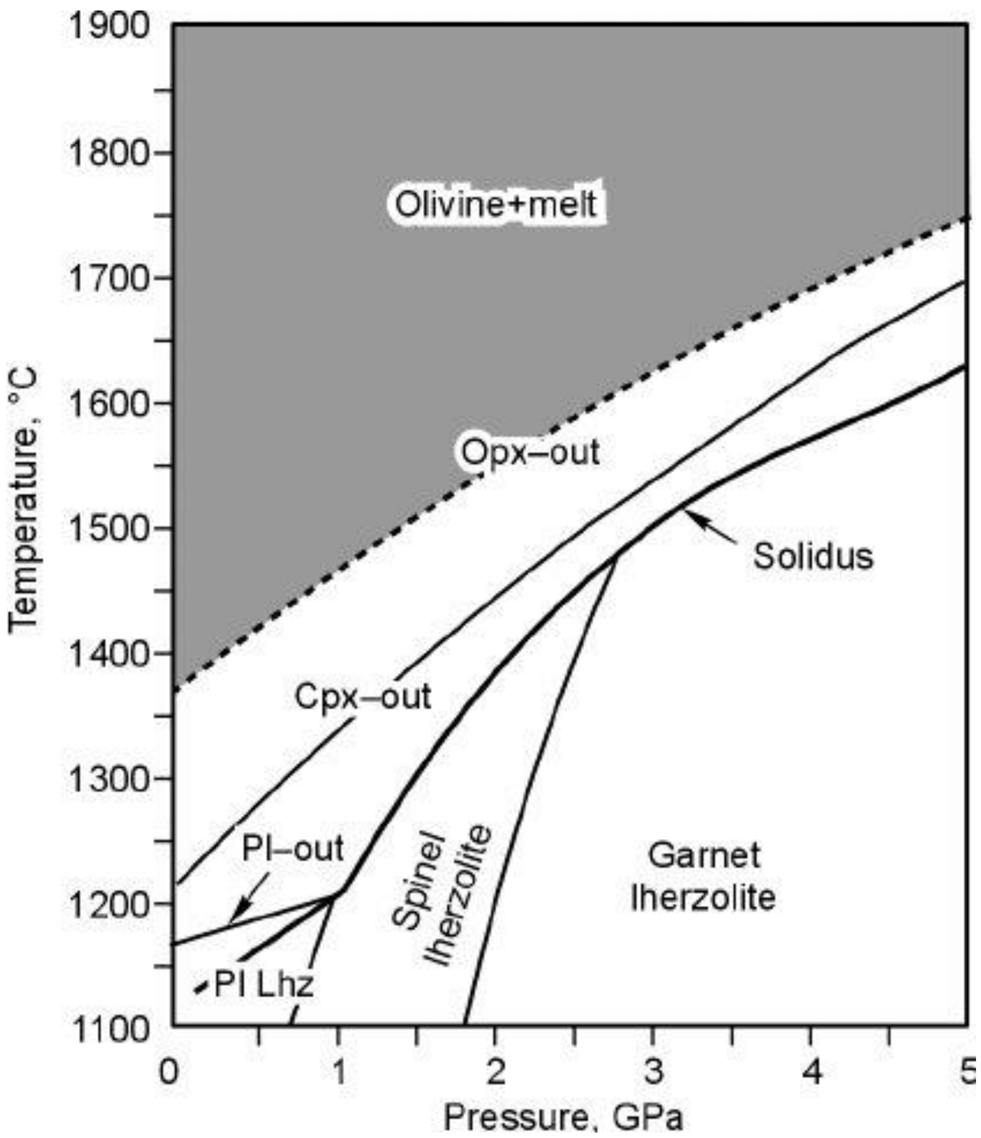


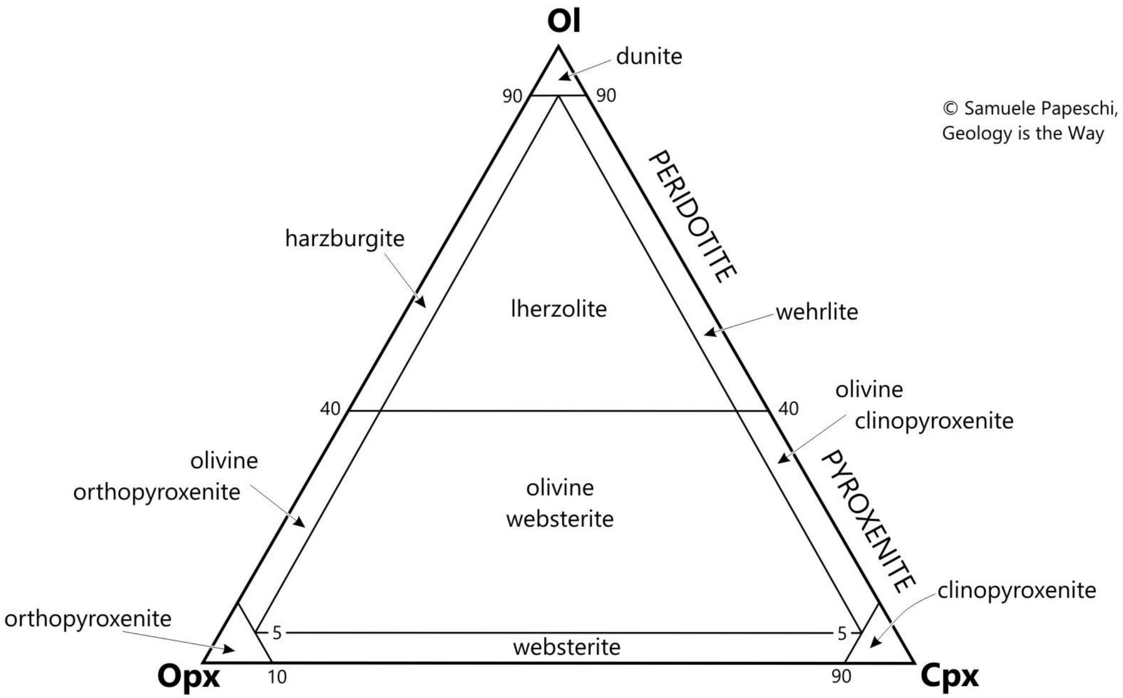
Quick Summary:

These minerals most commonly occur in a rock type called peridotite

Different modal proportions of these minerals occur due to changes in pressure and temperature and result in different types of peridotite:

Dunite	**Lherzolite**
Wehrlite	**Harzburgite**

The most common of these 'types' of peridotite are lherzolite, although dunite and harzburgite occur commonly within cratons



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Ternary diagram showing different rock types that occur within the lithospheric mantle and their modal percentage of olivine (Ol) clino- (Cpx) orthopyroxene (Opx)

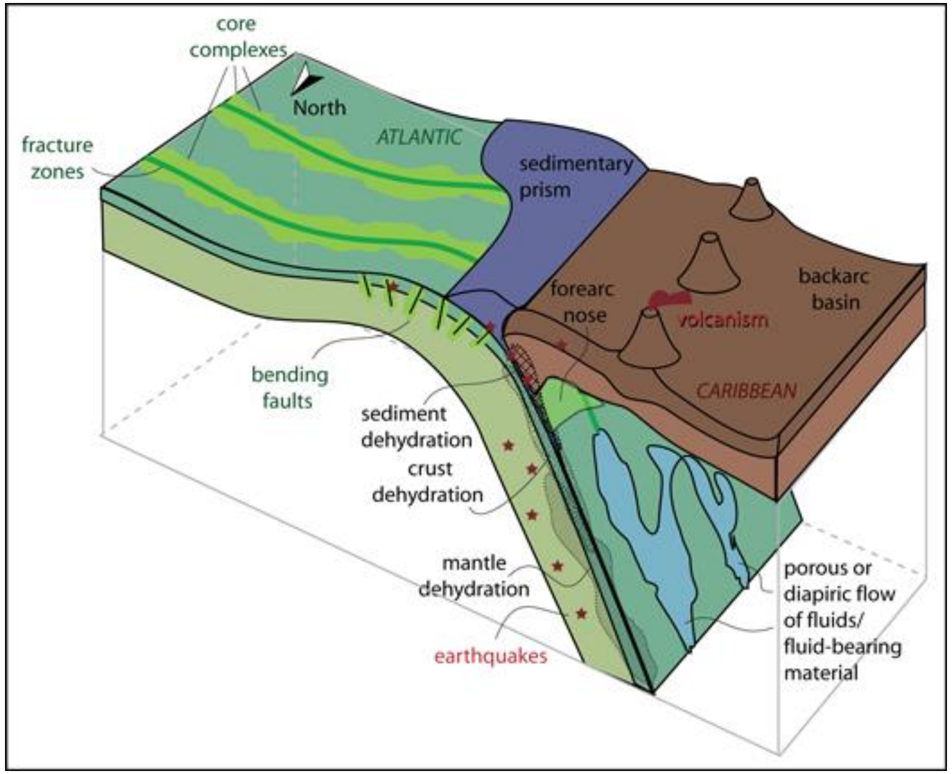
Quick Summary:

In addition to variations in types of peridotite that occur due to changes in PT, heterogeneity may also result due to the addition of volatiles (CO_2, H_2O)

Volatiles are added during subduction of oceanic crust

Volatiles lead to the formation of new ‘secondary’ mantle minerals such as **phlogopite and amphibole**

These minerals occur in very small abundances but can result is very strong changes in the physical properties of the mantle



Simplified illustration of water and other volatiles entering the lithospheric mantle during the subduction of ocean crust. Many of the volatiles will exit back to the surface in melts but some will enter the mantle wedge to form hydrous minerals. Photo: S. Goes.

Questions to think about..

- Cratons are thick and cold blocks of continental lithosphere – however, petrological and geophysical studies have shown that many cratons have large amounts of dunite and harzburgite. What is a possible explanation for this paradox?

- Volatile-bearing minerals in mantle rocks can be easily remobilized at high temperature because they melt at much lower temperatures compare to most other minerals. How might we explain the occurrence of volatile-bearing minerals, such as Phlogopite or Pargasite, occurring in a harzburgite, which requires very high temperatures to form?

- What setting might we expect spinel bearing lherzolites to be the dominate rock type occurring in the lithospheric mantle?

Answers will be discussed in the following lecture