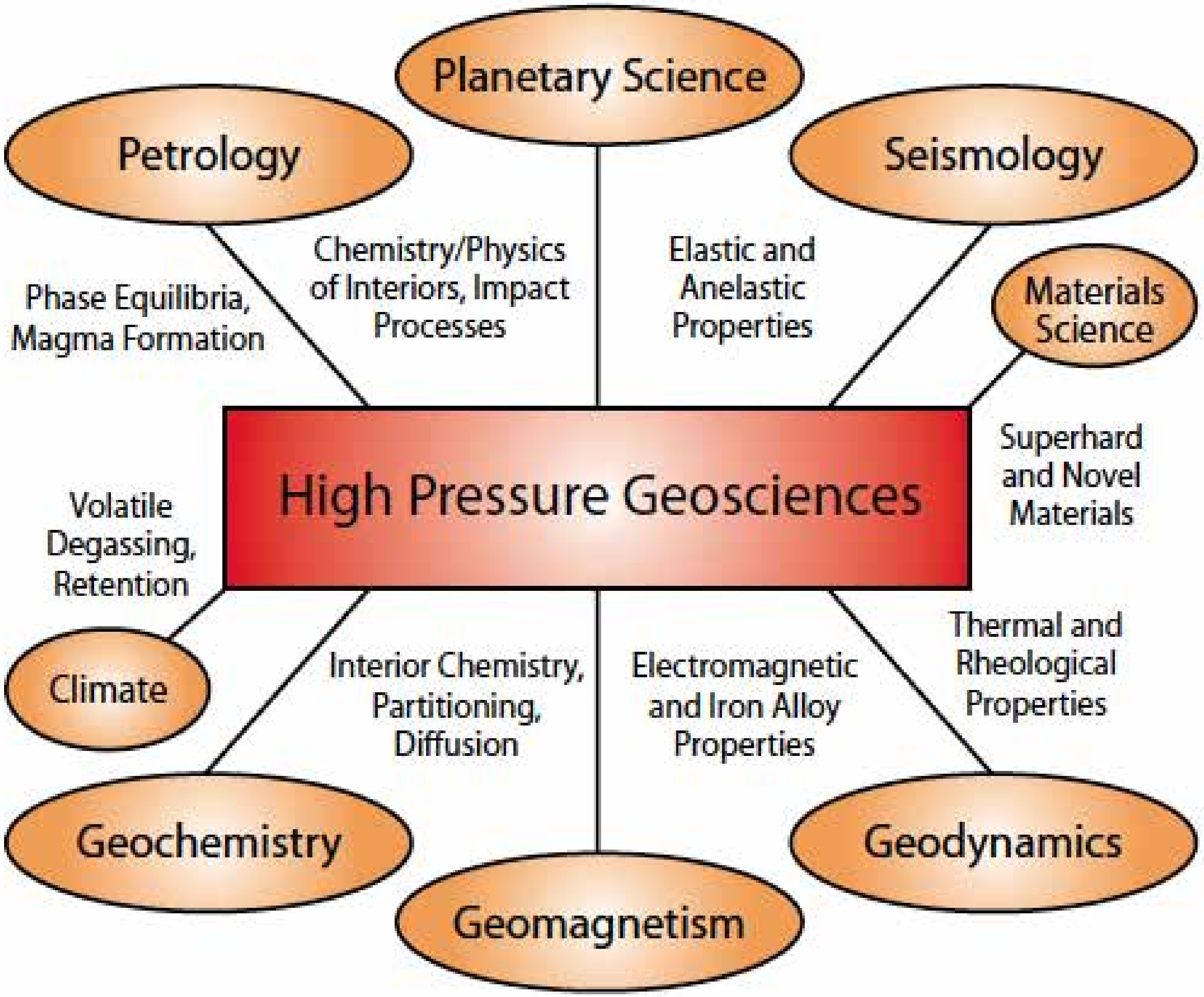
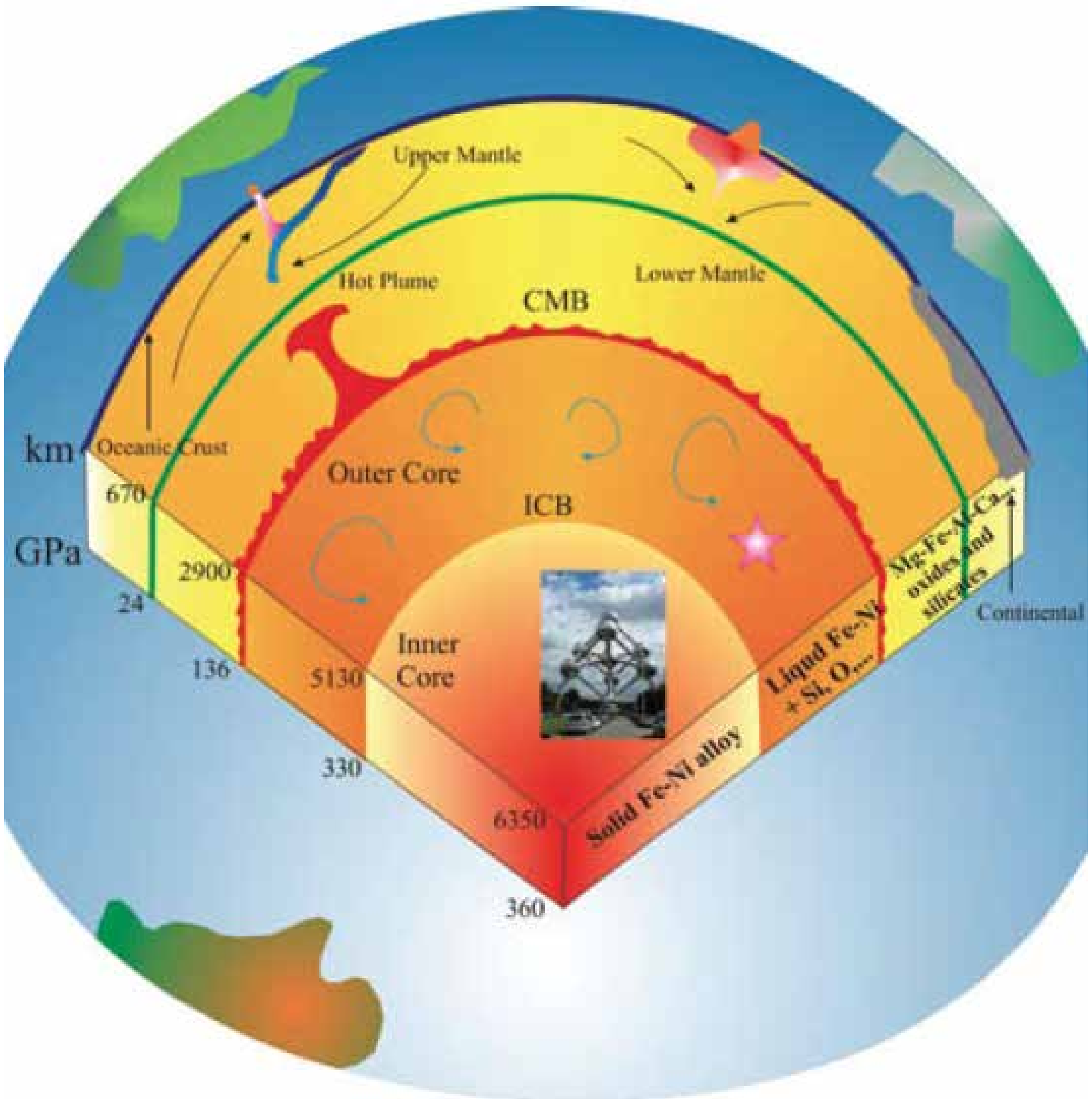
Understanding Dynamic Earth: Insights from the Experimental Laboratory

Tracy Rushmer, Simon Clark

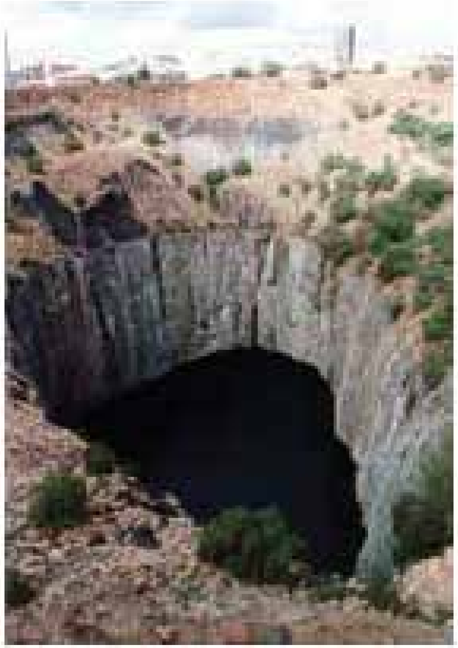
Macquarie University

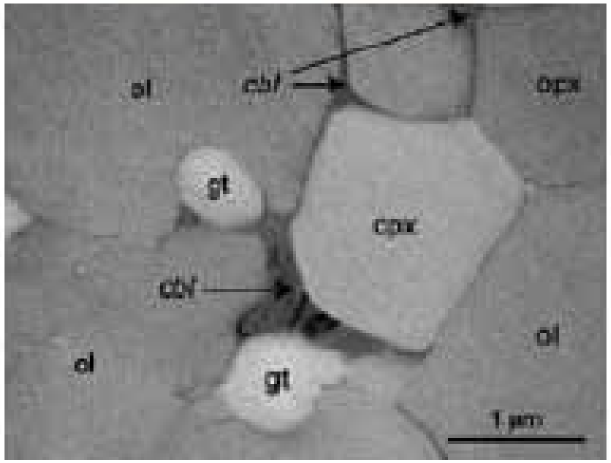


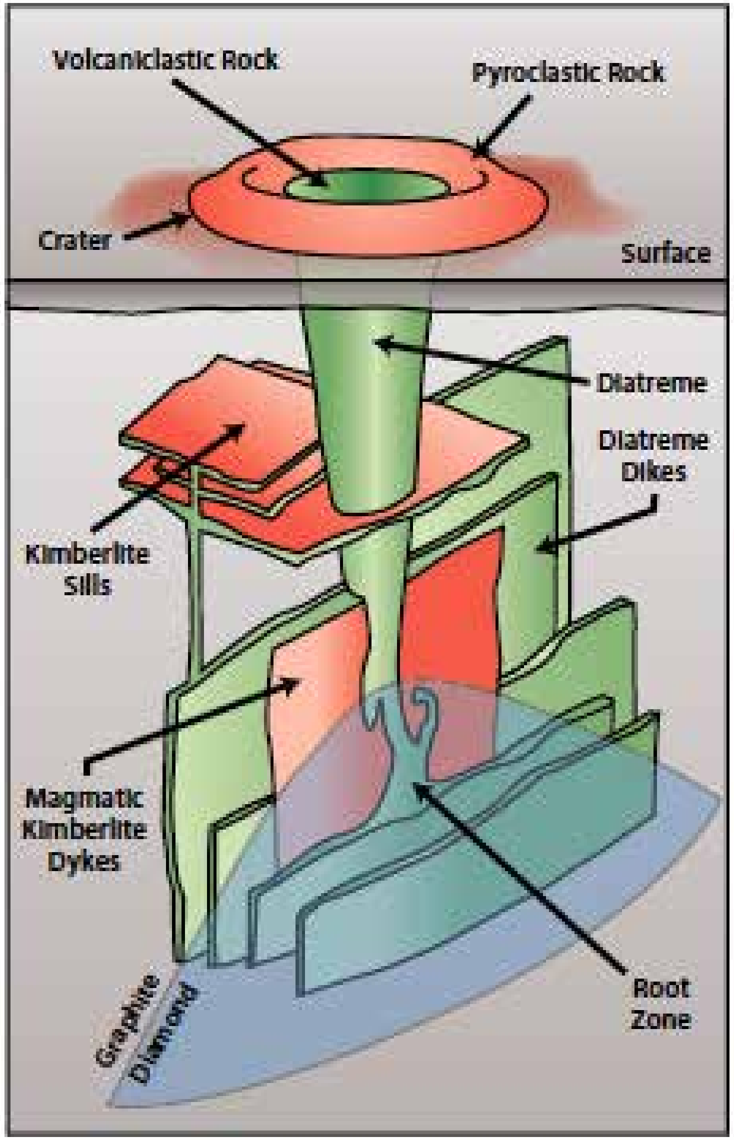
Understanding the Building Blocks of the Earth: Long-range Planning for High Pressure Geoscience NSF COMPRES workshop 2009



Our challenge as experimentalists: Designing ways to test our ideas about the dynamic deep Earth (from upper mantle to core).

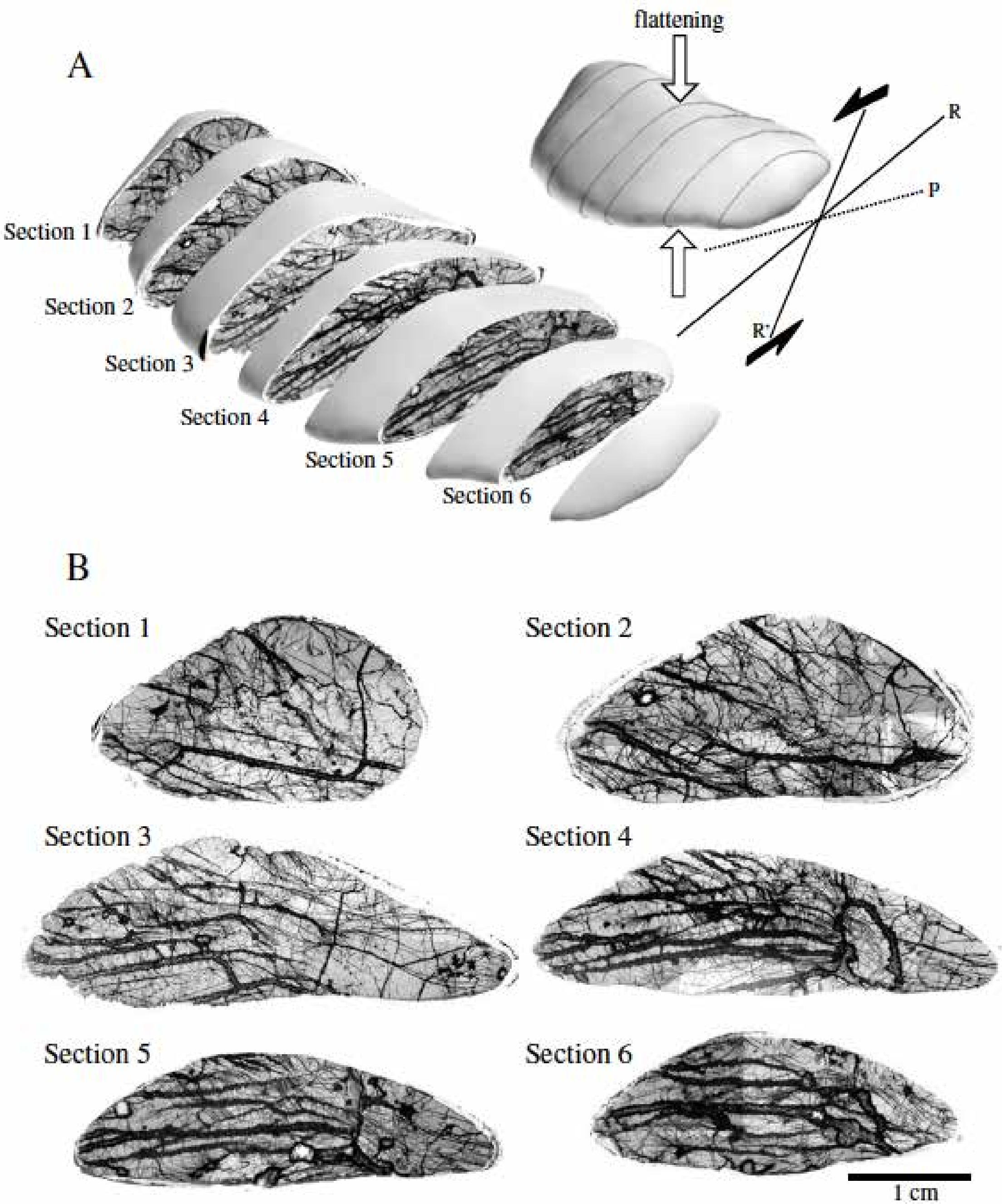






Major focused challenges (why we are here!) make links to the lithosphere – magmas, fluid, heat sources, rheology

(COMPRES, 2009)



We can gain important information about the dynamics of the lithosphere-asthenosphere boundary from natural samples from kimberlites. Here is a highly deformed garnet from the work of Samatha Perritt (University of Johannesburg). These garnets were deformed at ~1330^{o}C and 58 Kbars.

(Thank you Hielke Jelsma)

Some principal challenges and key questions for modern day geodynamics:

- The melting and phase relations of mantle materials in the lithosphere and the chemistry and physical properties of melts generated at different depths.

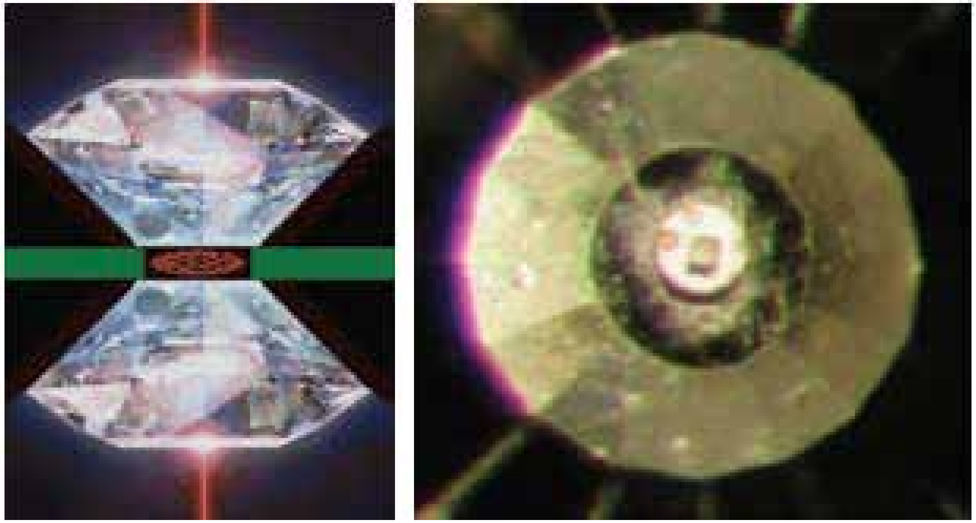
- Determining the viscosity of solid rocks in situ at high pressures and temperatures to provide experimental constraints on the vigor of mantle convection (and on plate tectonics itself!). Must also measure other physical properties.

- How are thermal and electrical conductivities influenced by pressure, temperature, and composition?

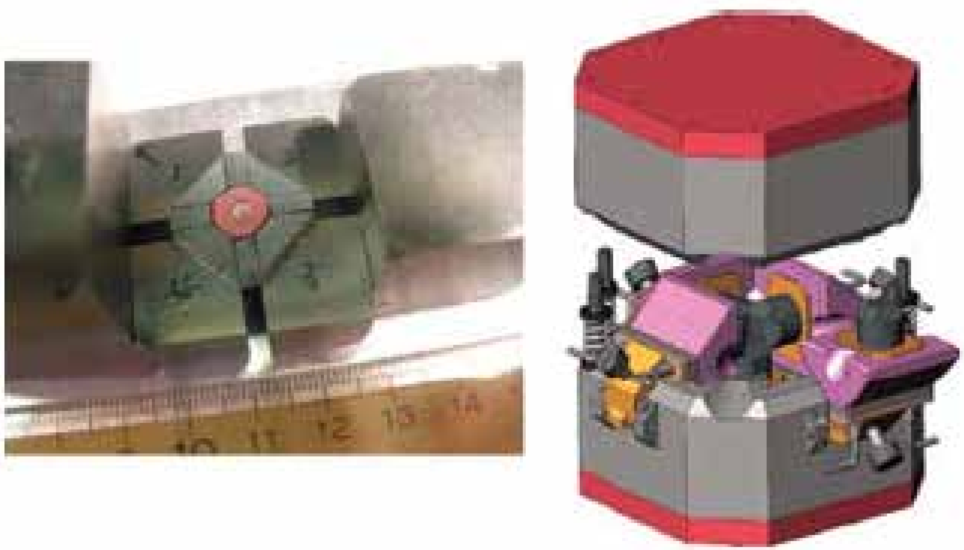
- How do aqueous and carbon-rich fluids behave at depth, and how do fluids and rocks interact, particularly in subduction-zone environments?

With new experimental techniques approaches, we can address these challenges.

Work horses of high pressure experimentation. Becoming routine!

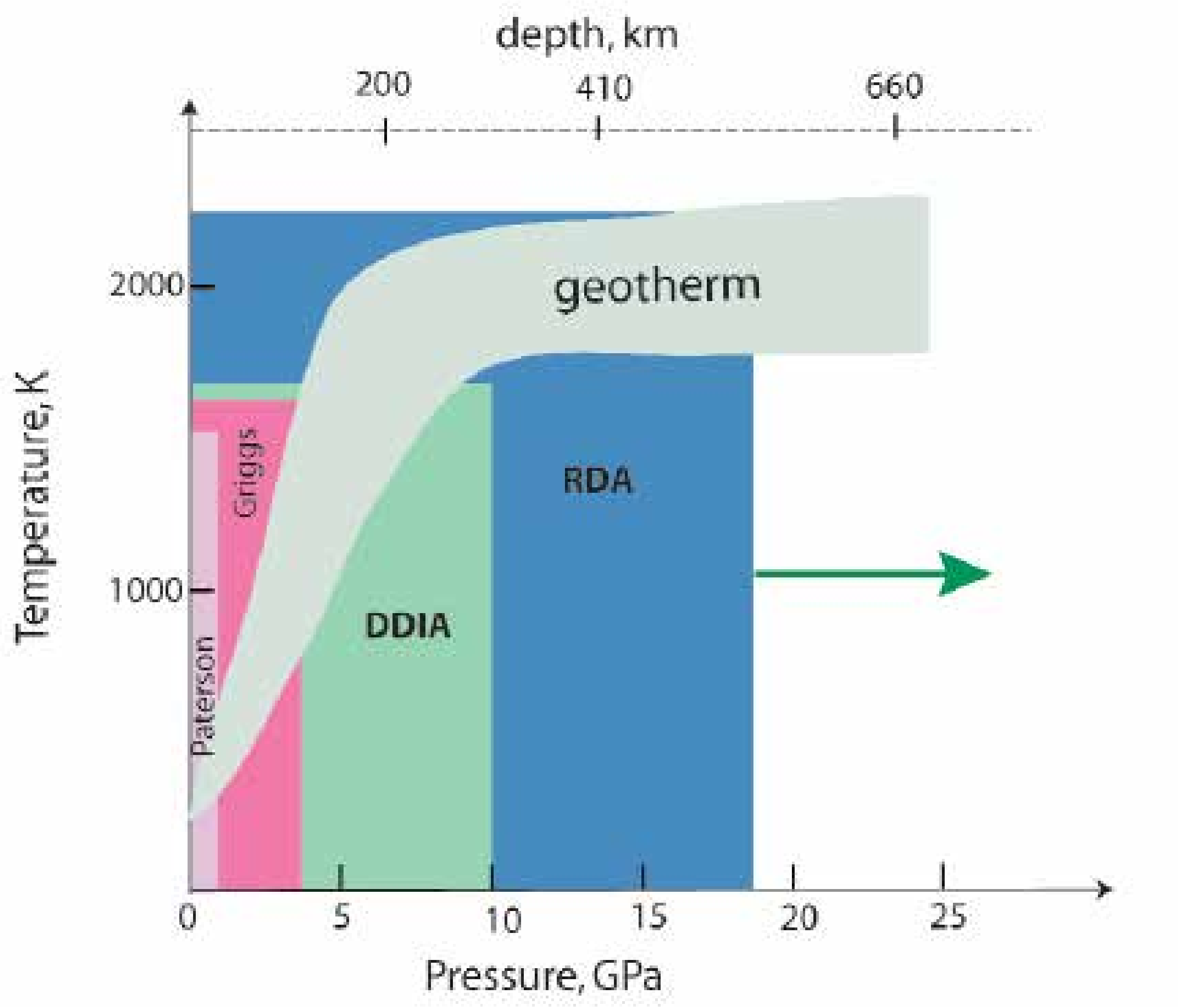


Diamond-Anvil



Multi-Anvil assembly
and module

Pressure and temperature ranges we can now achieve with new developments in high pressure technology



But the most important advance is the combination of the high pressure equipment and high energy x-rays (and neutrons) for in-situ work

Funded by LIEF (MQ, Monash and ANU) and MQ DVCR Discretionary funds, we now have a D-DIA at the Australian Synchrotron that can achieve pressures and temperatures to the base of the lithosphere (and into the transition zone with further development)

What has been done and what can we do now?

Some major questions and challenges:

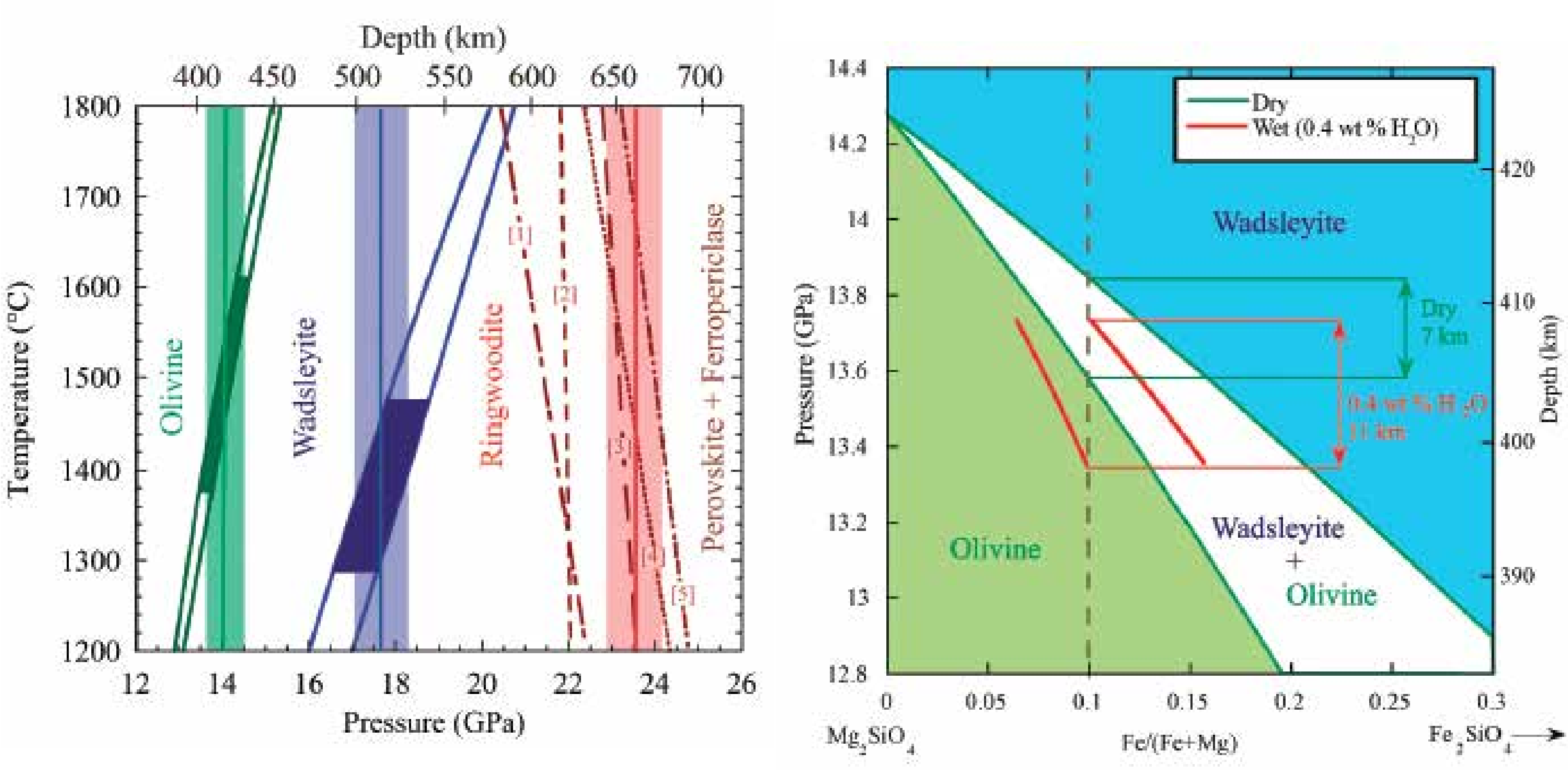
1) The melting and phase relations of mantle materials in the lithosphere and the chemistry and physical properties of melts generated at different depths.

Determining the stability range of mantle phases into the transition zone

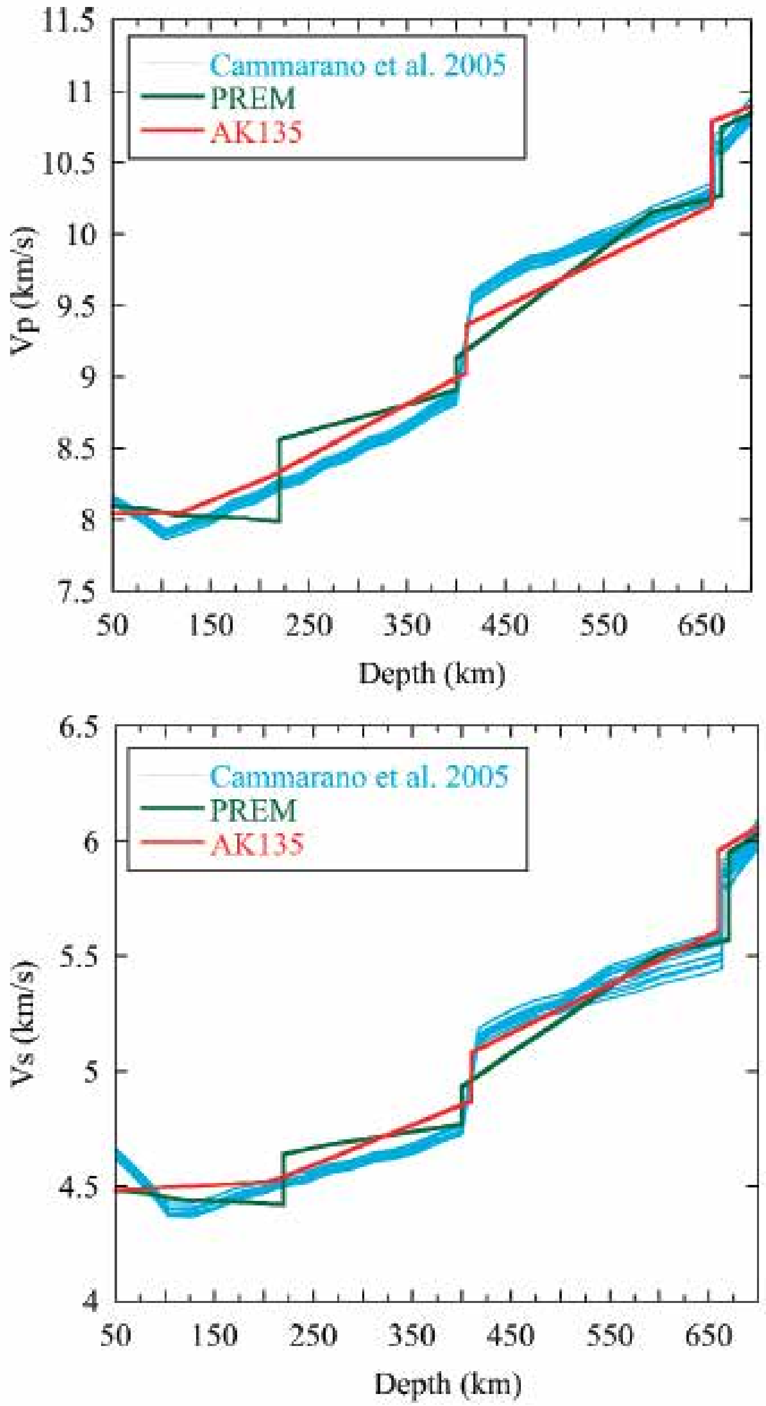
a) pressures at which transitions initiate, and the width of the pressure interval depend on both temperature and composition

b) seismic characterizations of the depth and sharpness of these discontinuities can, when coupled with accurate laboratory measurements of these transitions, provide a particularly accurate gauge of the temperature and composition through lithosphere into the transition zone. Water?

c) Physical properties of hydrous silicate melts at high pressure.

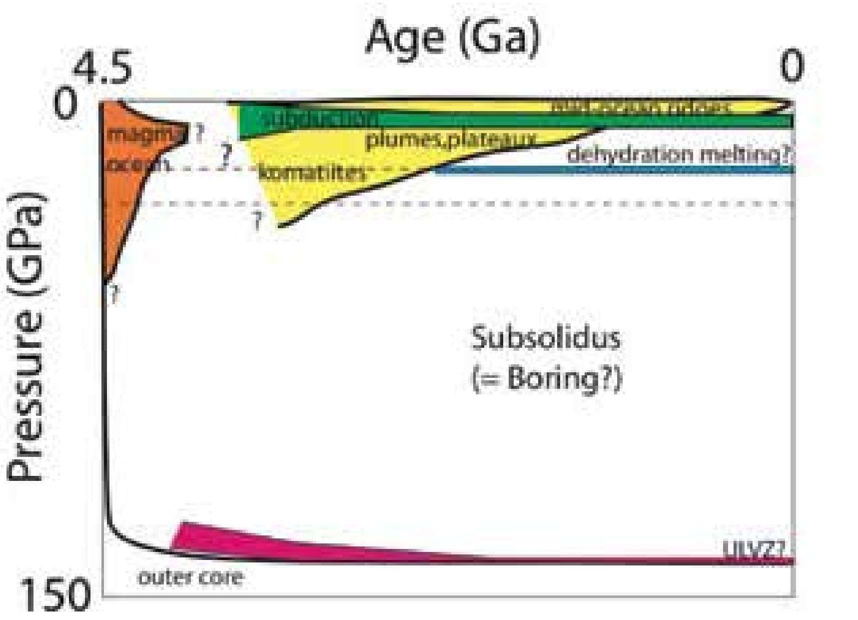


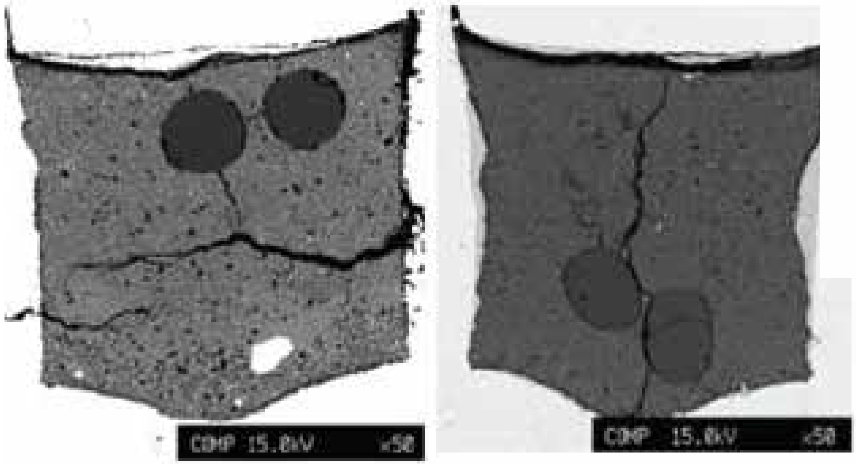
Experimentally determined phase transitions and the location of the major discontinuities in the Earth (eg. Shim, 2001; Fei et al., 2004; Frost, 2006) and Frost & Dolejs 2007 show calculated phase diagram with water.



Cammarano et al. (2005) shows S- and P-wave velocity structure in the upper mantle and transition zone. These were obtained by fitting similar global seismic data, as used in PREM, for example, to 1-D velocity models calculated for a pyrolite mineral assemblage by adjusting mineral elastic properties within the range of their uncertainties.

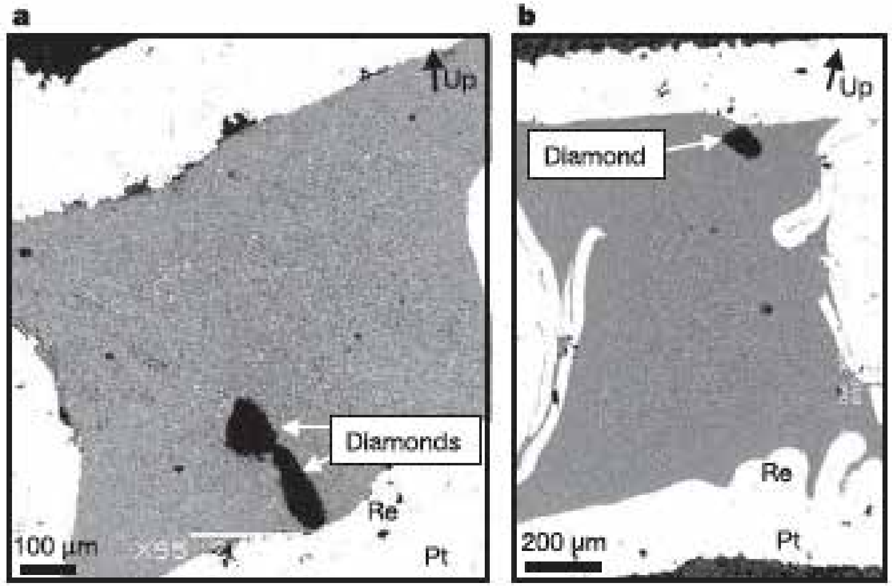
The numerous acceptable fits from this approach which can be now further tested and refined in the future due to the continual improvements in mineral-physics measurements in-situ at high pressure.





Garnet (Py69 Al17Gr14) Float
at 80 Kb, 1750C

Garnet (Py58Al34Gr08) Sink
at 90.7 Kb, 1800C

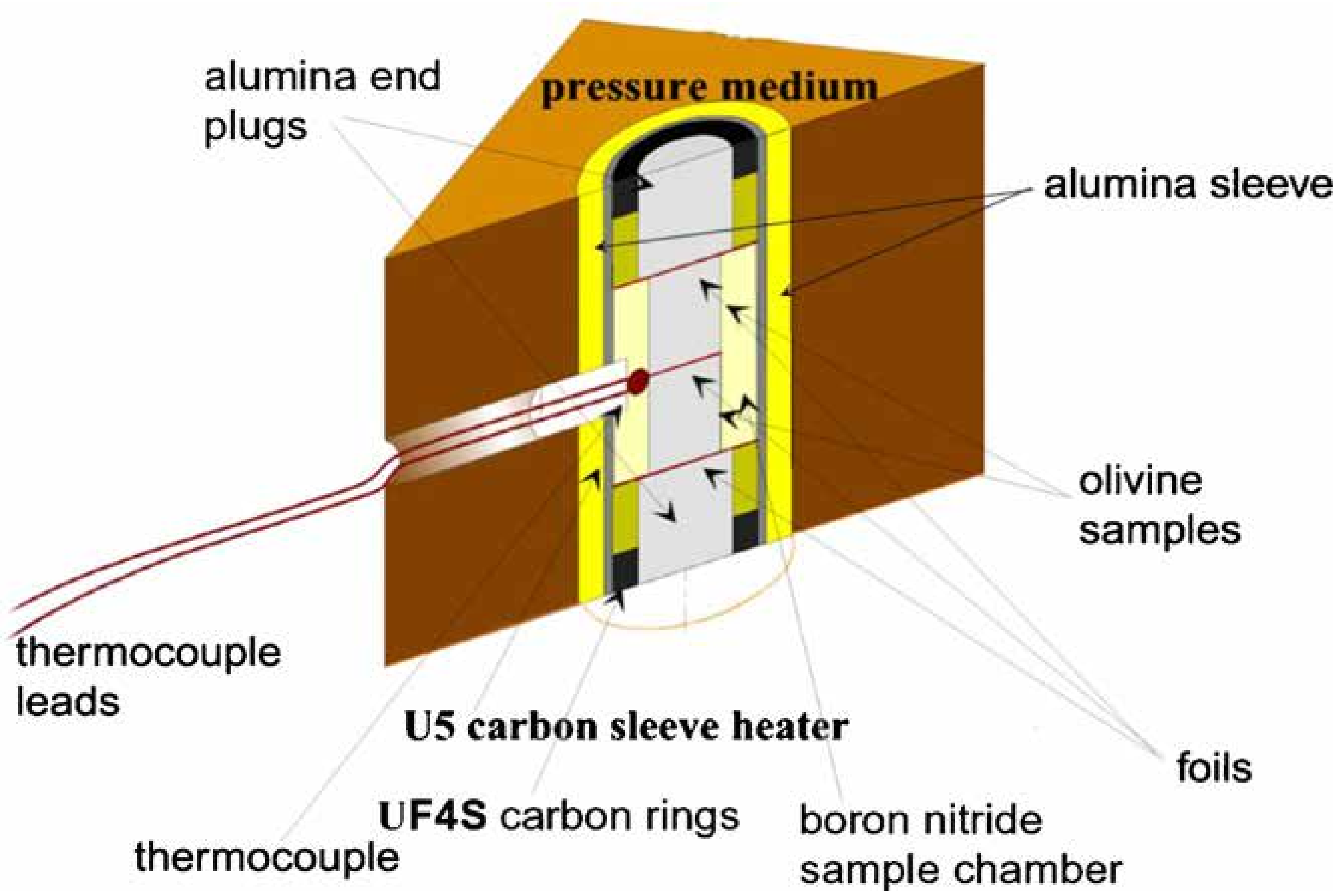


A) Density measurements at 240 km; 270km. B) Silicate melt at 410 km
(Agee, 2006; Matsukage et al., 2005)

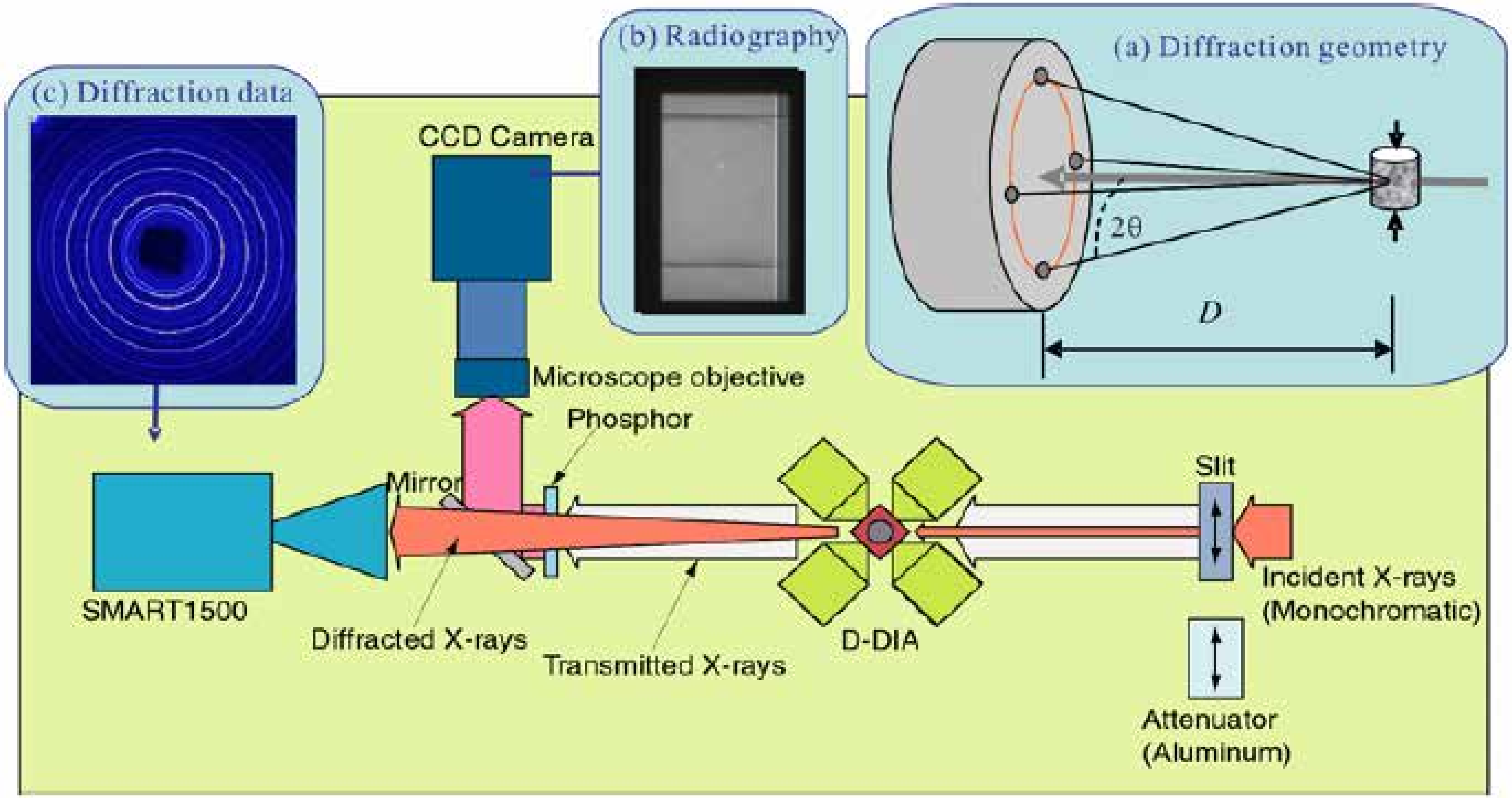
2) Determining the mechanical properties of mantle materials (density, viscosity, thermal conductivity) in situ, at high pressures and temperatures.

The D-DIA is a sophisticated apparatus that when combined with imaging technology, we can do time series analyses that will allow measurement of the physical properties of mantle materials at a range of pressures and temperatures, along with more traditional measurements.

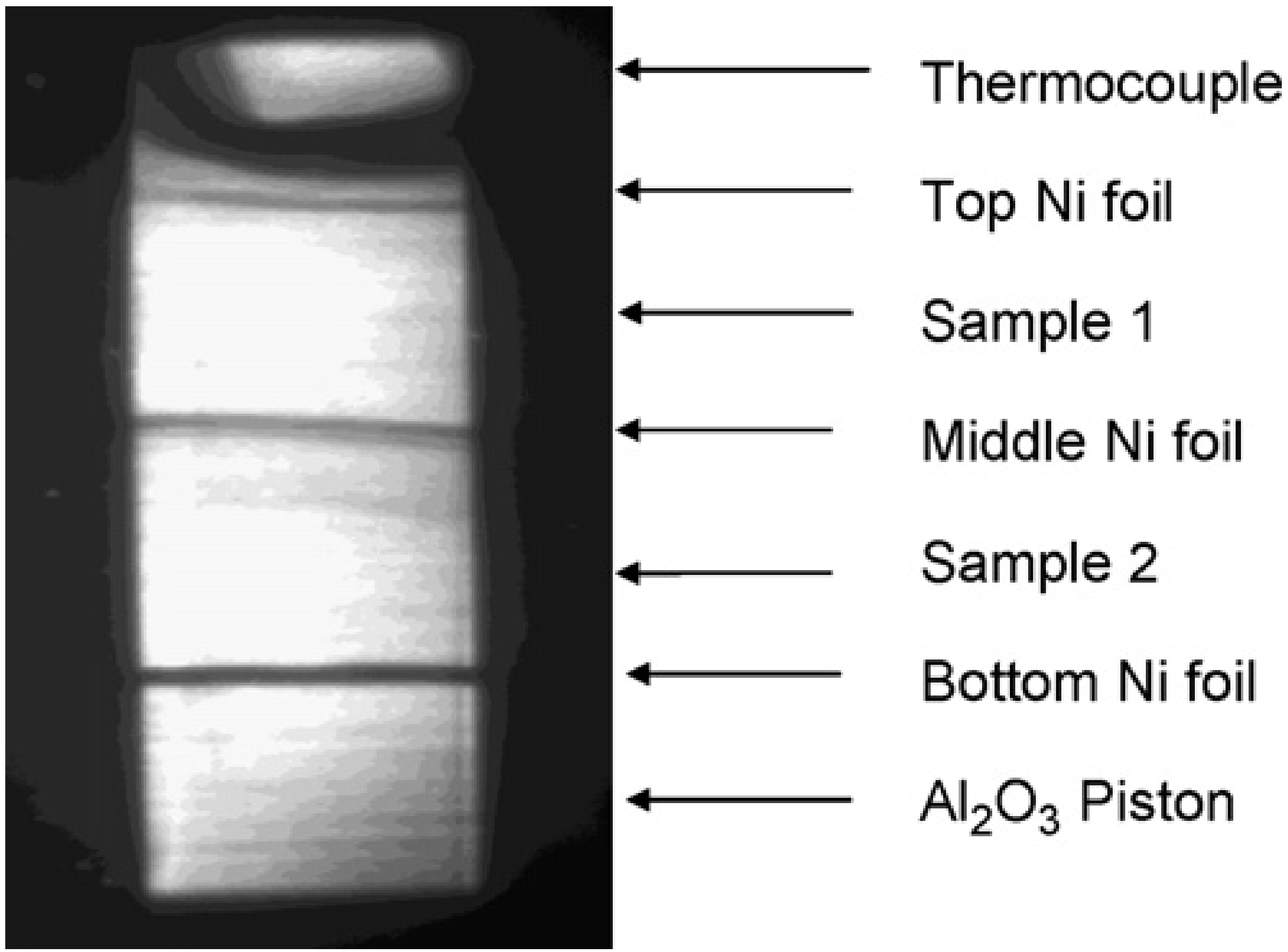
D-DIA at the Australian Synchrotron. Press, alignment system, module.



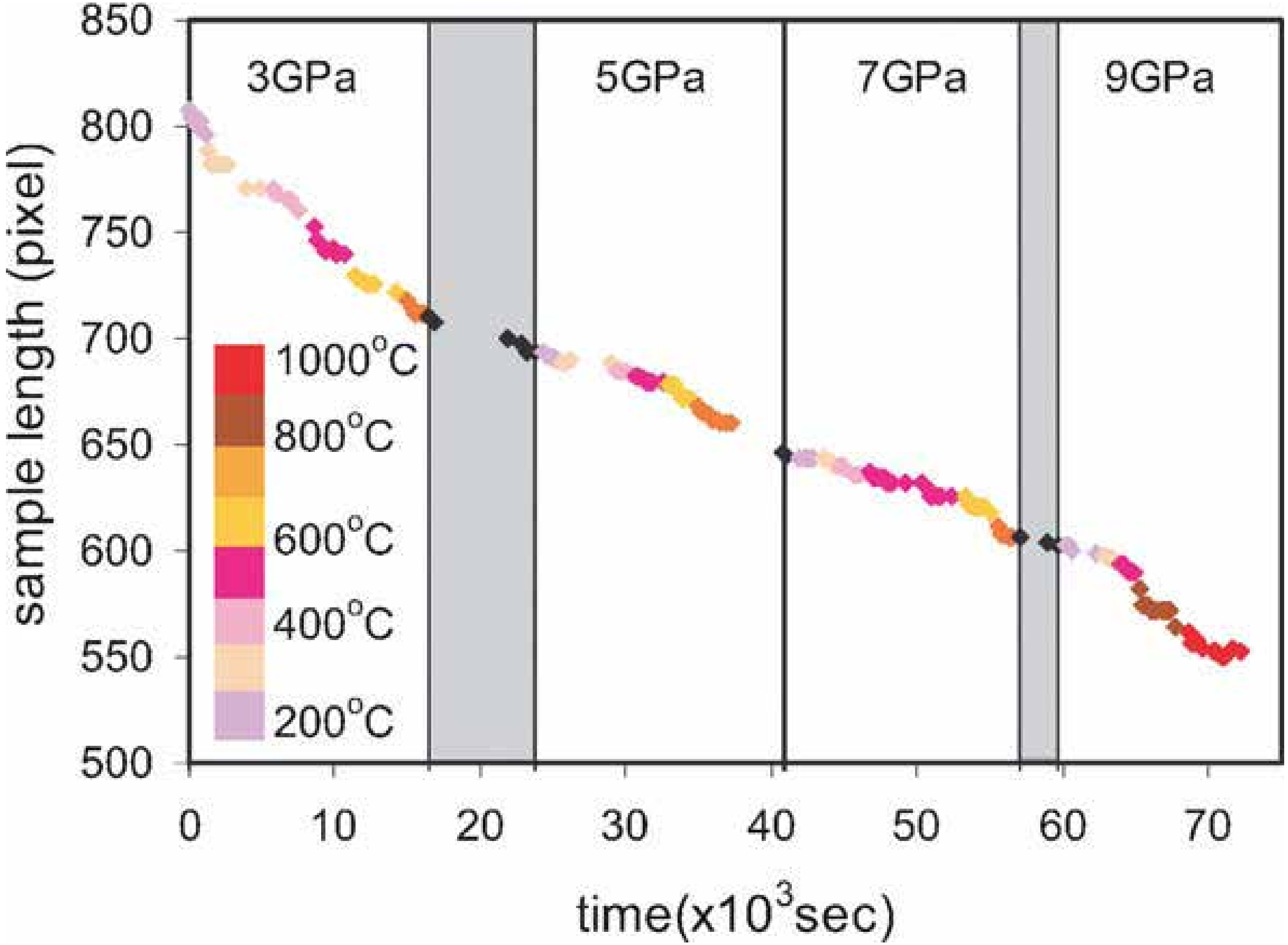
(Long et al., 2011)



Detector and imaging system at APS Chicago (Wang et al., 2004)

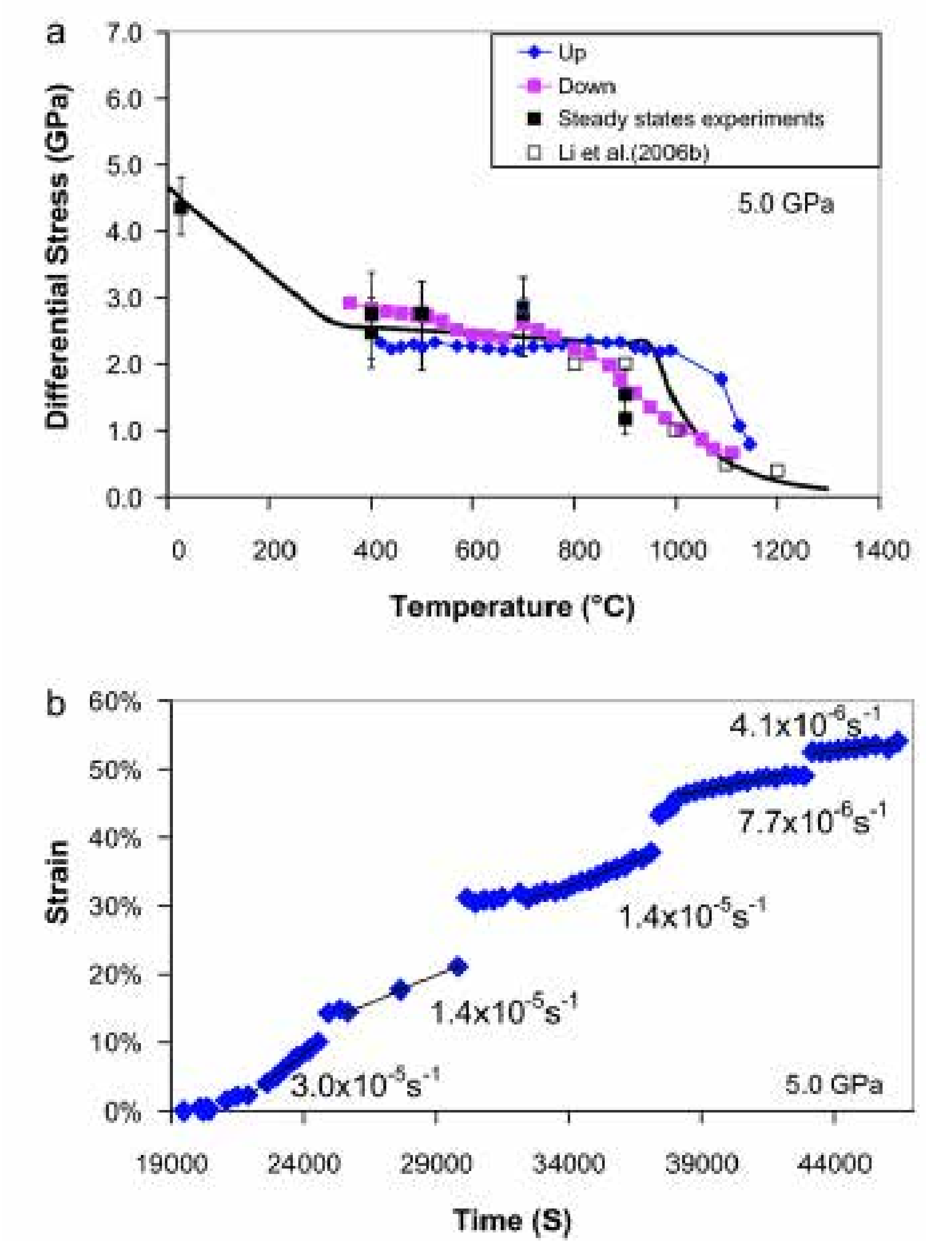


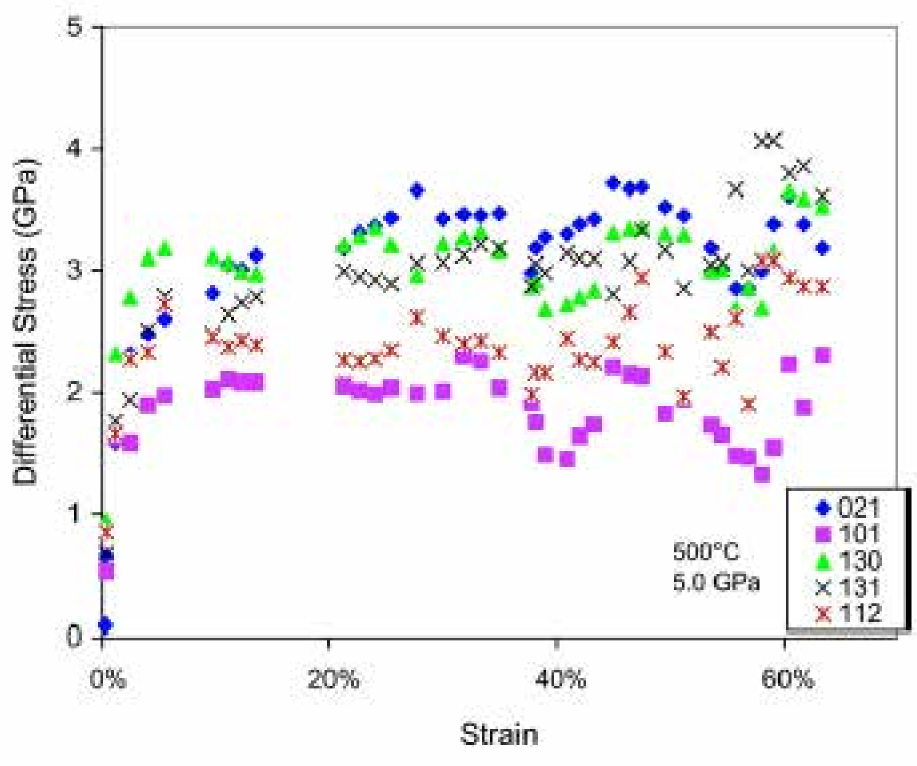
Sample image (San Carlos Olivine) taken by the in situ X-ray radiograph technique during deformation. The dark shadow surrounding is the gap of the anvils (Long et al., 2011).



Direct measurements of the strain and stress through sample (in this case olivine) imaging (sample length changes) and X-ray diffraction eliminate the uncertainty introduced in the modeling of indirect measurements at high pressures (Chen 2004).

From Long et al. (2011). San Carlos olivine flow law at 150 km depth

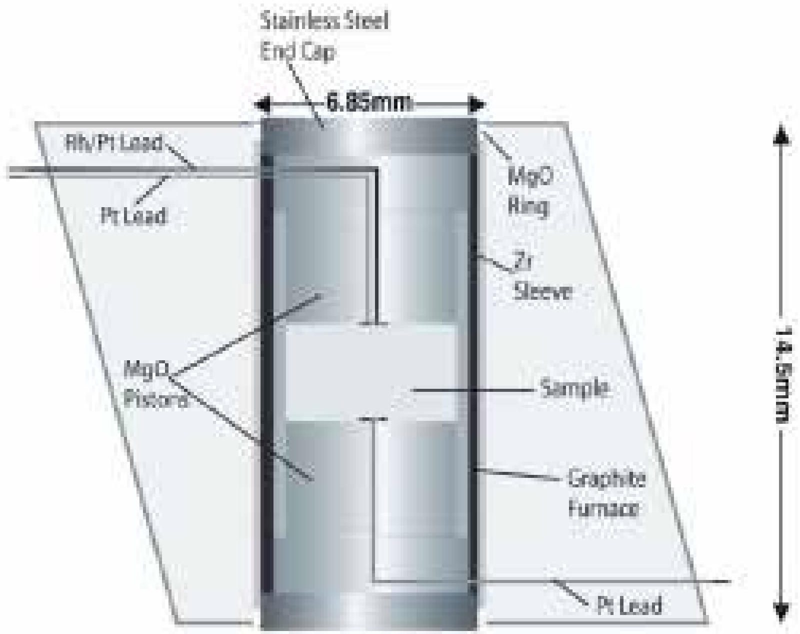




Data show that by using a combination of imaging and diffraction in-situ, the experiments provide strength data as a function of strain for individual lattice planes in the olivine (relevant to seismic anisotropy).

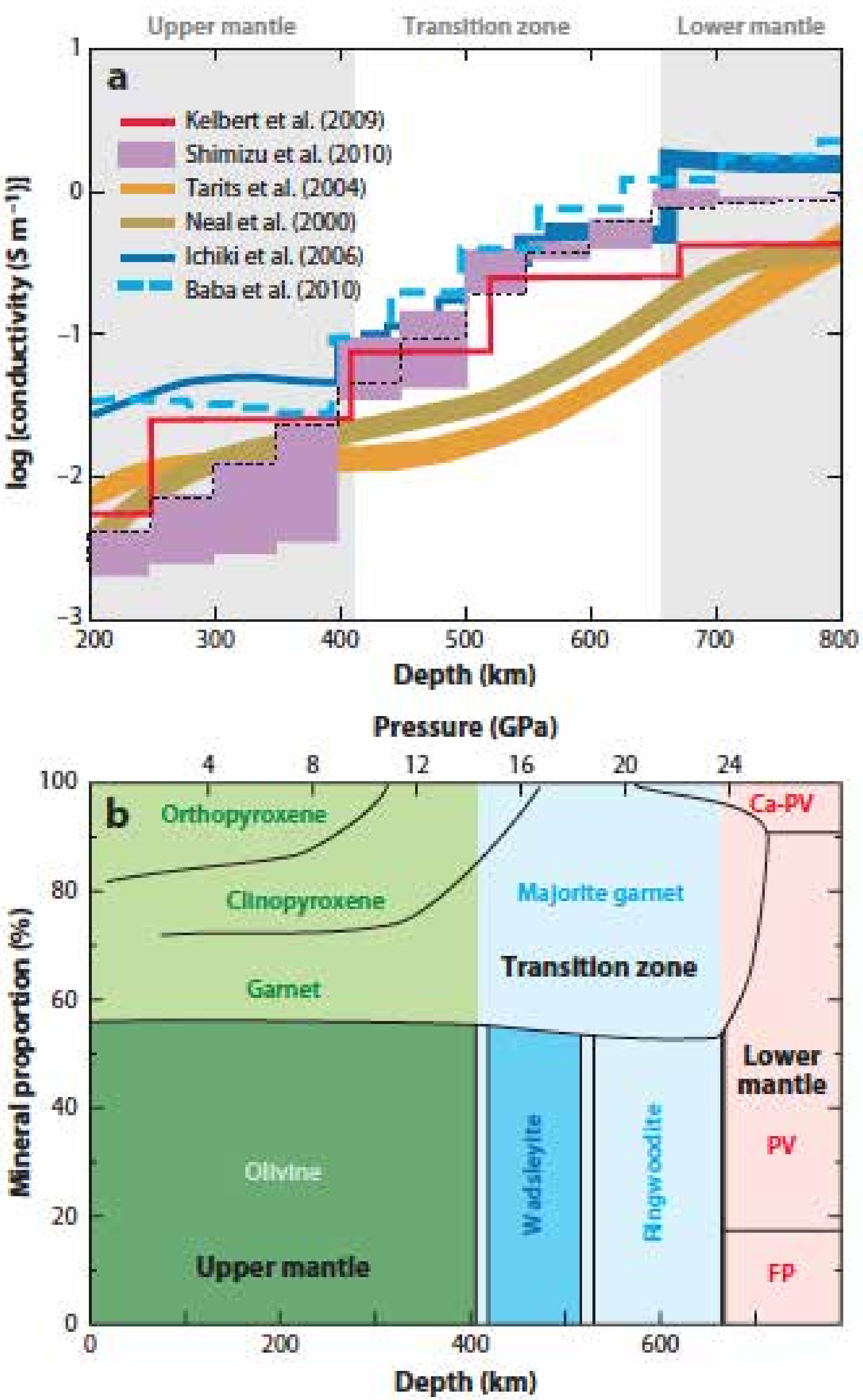
3) How are thermal and electrical conductivities influenced by pressure, temperature, and composition? Can we use electrical conductivity to determine water content at depth?

- Although seismic waves provide good representations of elastic properties, they are not unambiguously sensitive to temperature, partial melt, chemical compositions, or presence of volatiles within the Earth



Cross Section of Conductivity Cell

This is a conductivity cell designed at Manchester University for use in the multi-anvil at Daresbury synchrotron facility. We plan to use electrical conductivity for experimental partial melting studies at Macquarie University and on the D-DIA at the AS.



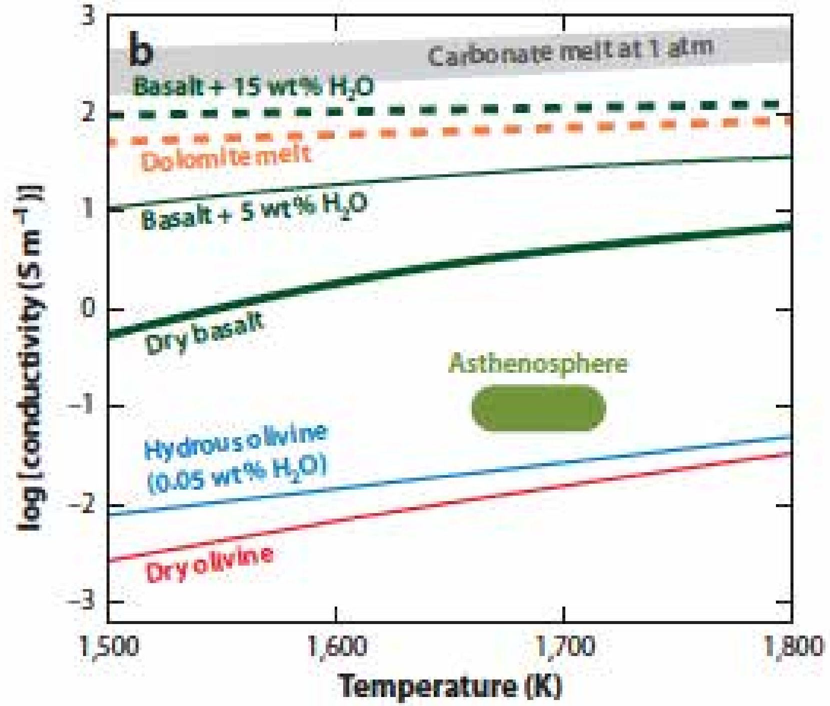
Background:

Electrical conductivity- what is it good for?

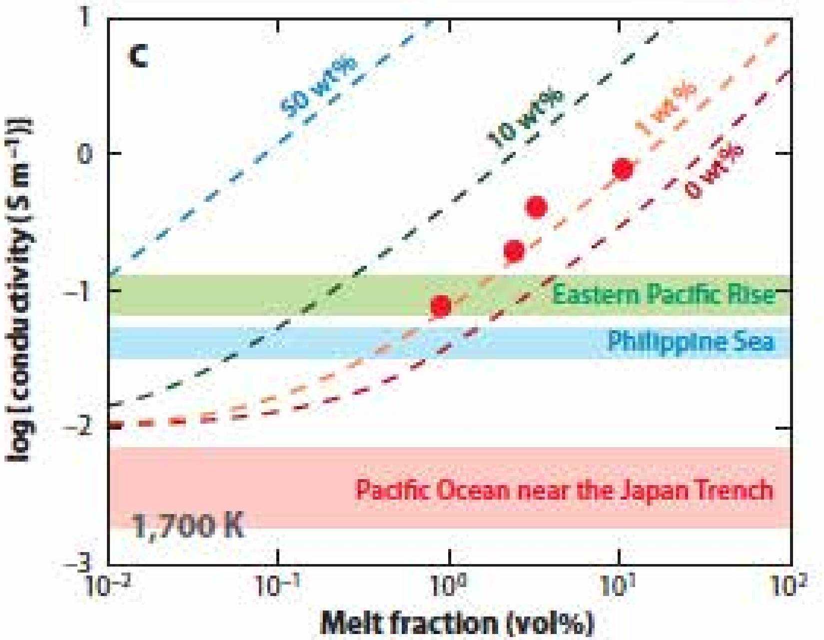
a) Shows the increase in detail of data sets in the recent studies - mainly the jumps in the transition zone.

b) Shows associated mantle mineral phases and their mode. Note, transition zone phases can take up H in their structures quite easily.

(Yoshino and Katsura; 2013)

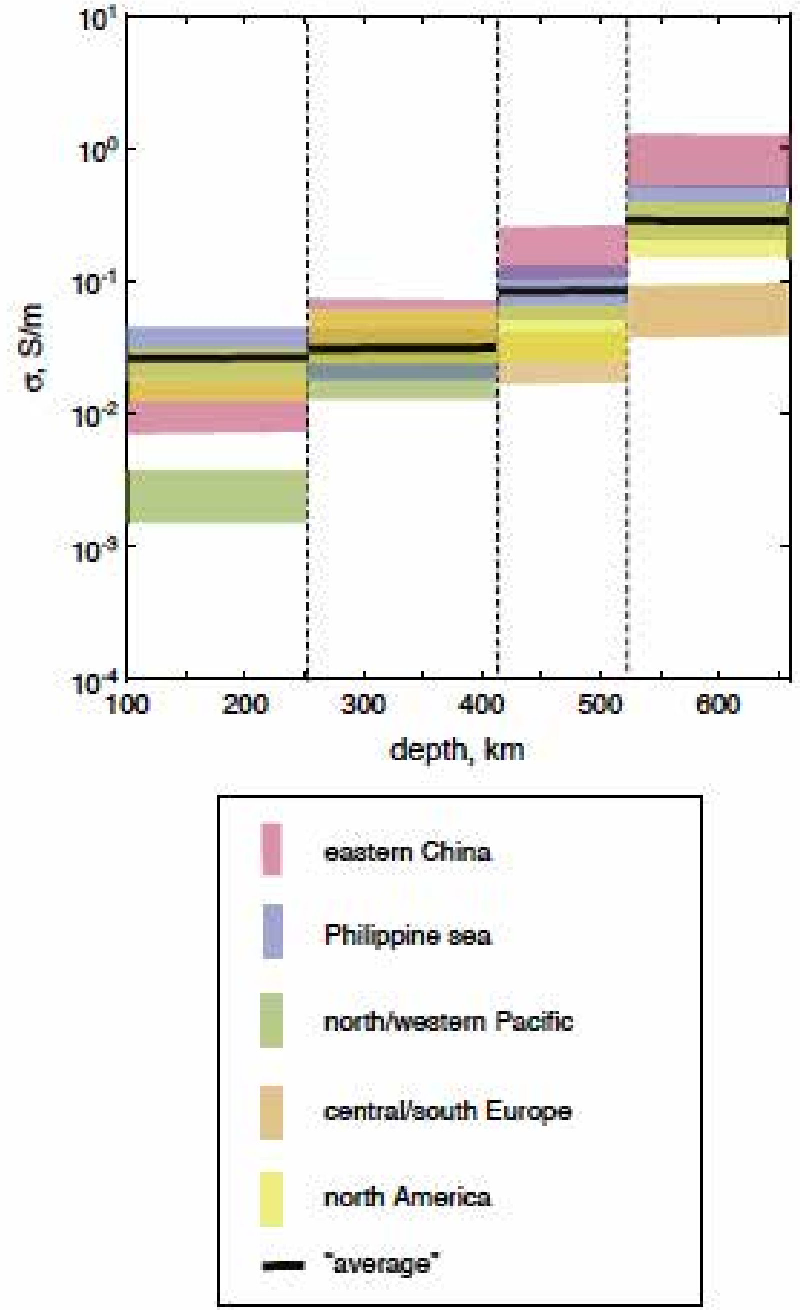


Electrical conductivity vs. temperature for dry and hydrous olivine, basaltic melt with various amounts of water added and carbonate melt (1 atm). Green area shows the conductivity anomaly in the oceanic asthenosphere



Electrical conductivity vs. partial melt fraction in partially molten peridotite for various amounts of water in the basaltic melt (predicted dashed lines; red dots are data from Yoshino et al., 2010).

(Yoshino and Katsura; 2013)



From Karato, 2011

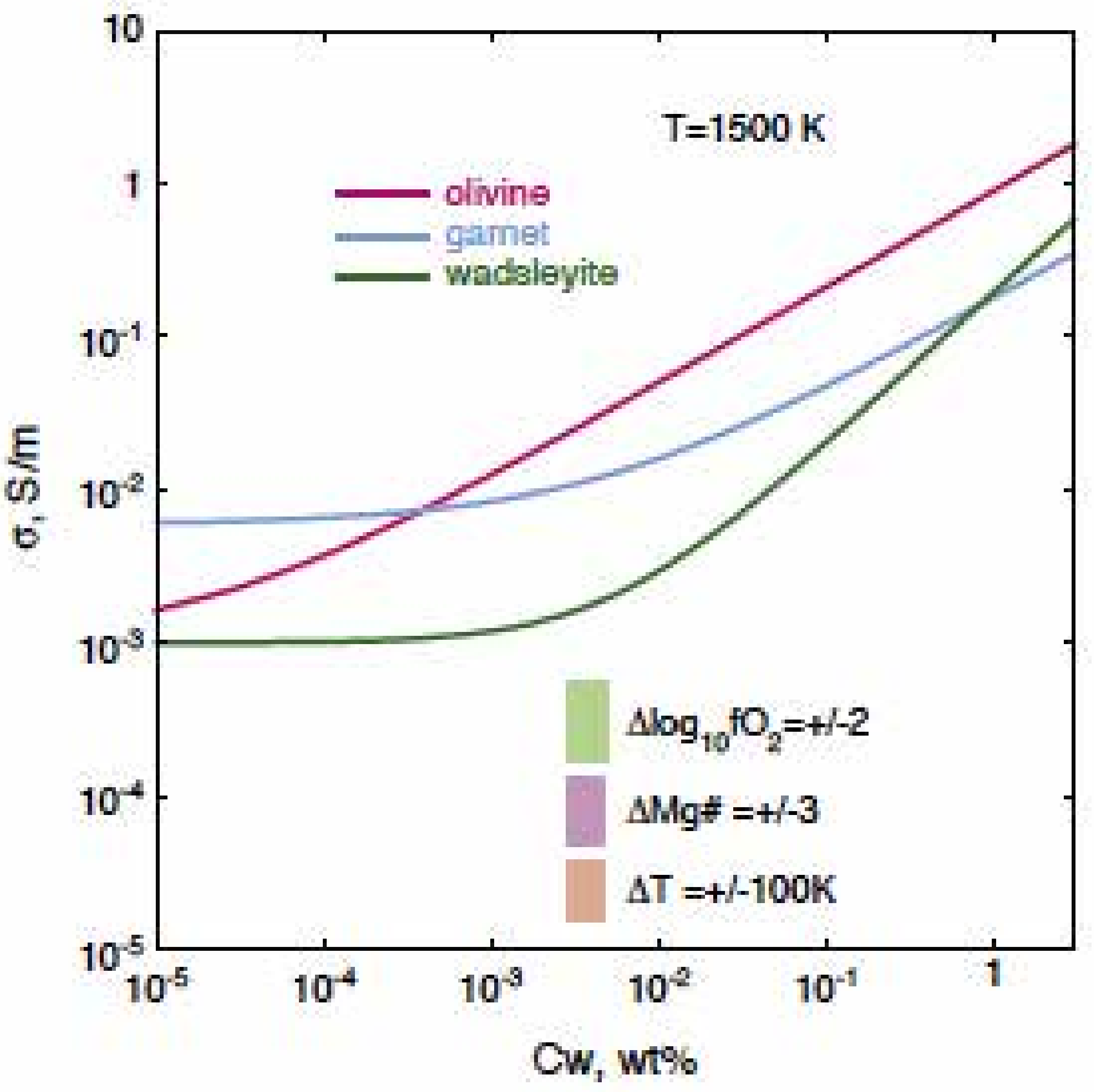
Recent electromagnetic studies have shown a great variety of lateral heterogeneities in the conductivity structure of the mantle transition zone. The mantle beneath the Philippine Sea and China, for example, is where descending slabs stagnate at the transition zone and has conductivity higher than that of the mantle beneath central Europe and north America. Such a large variation in electrical conductivity suggests variation in water content, temperature, and other conductive agents such as hydrous or carbonate partial melt in the transition zone.

At shallower levels- N and W Pacific?

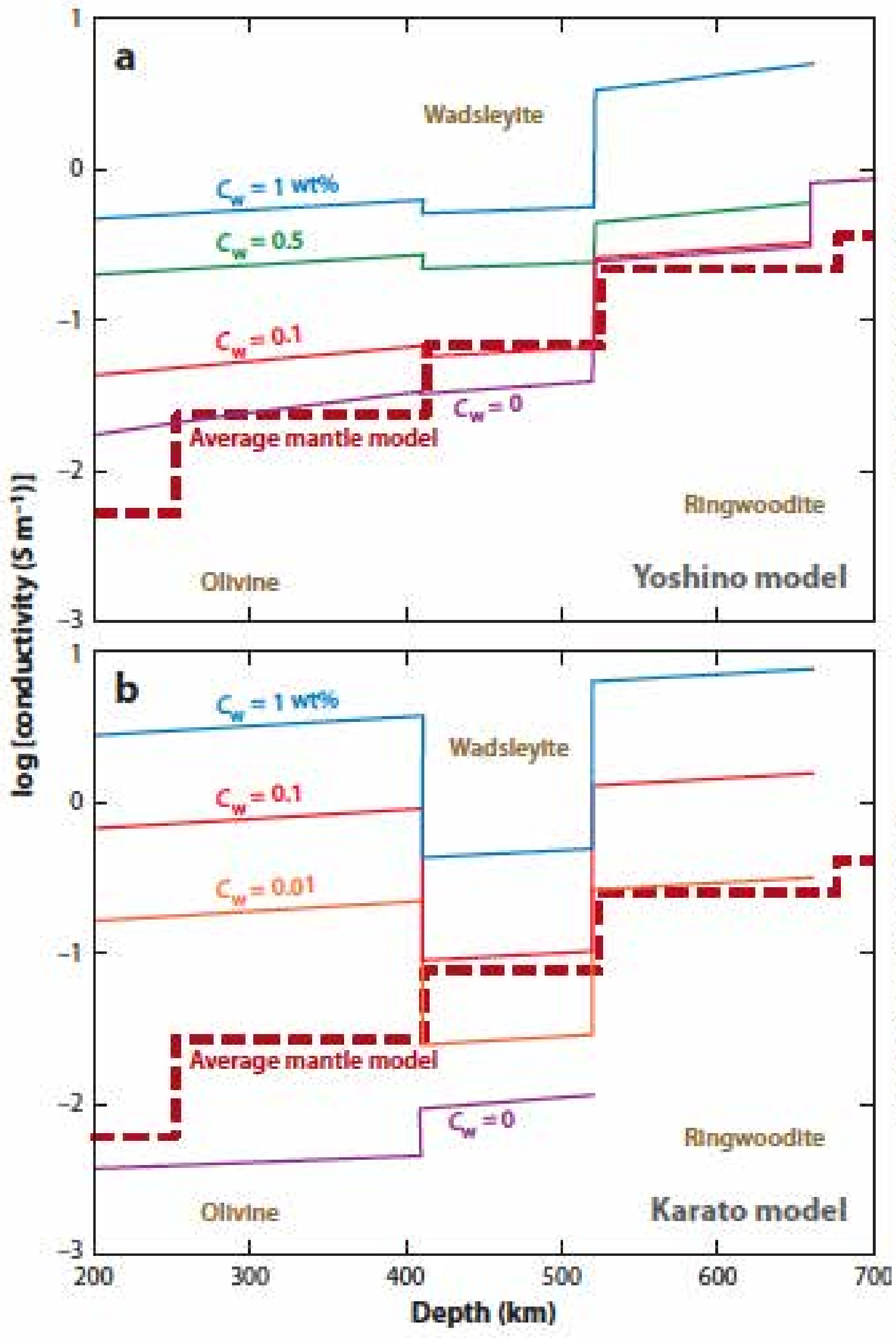
- In most cases, electrical conductivity of a mineral is caused by the hopping of electrons between ferric and ferrous iron (composition, fO_2) but is sensitive to water content. This is why geophysically inferred electrical conductivity of Earth's interior provides important constraints on the distribution of water (hydrogen).

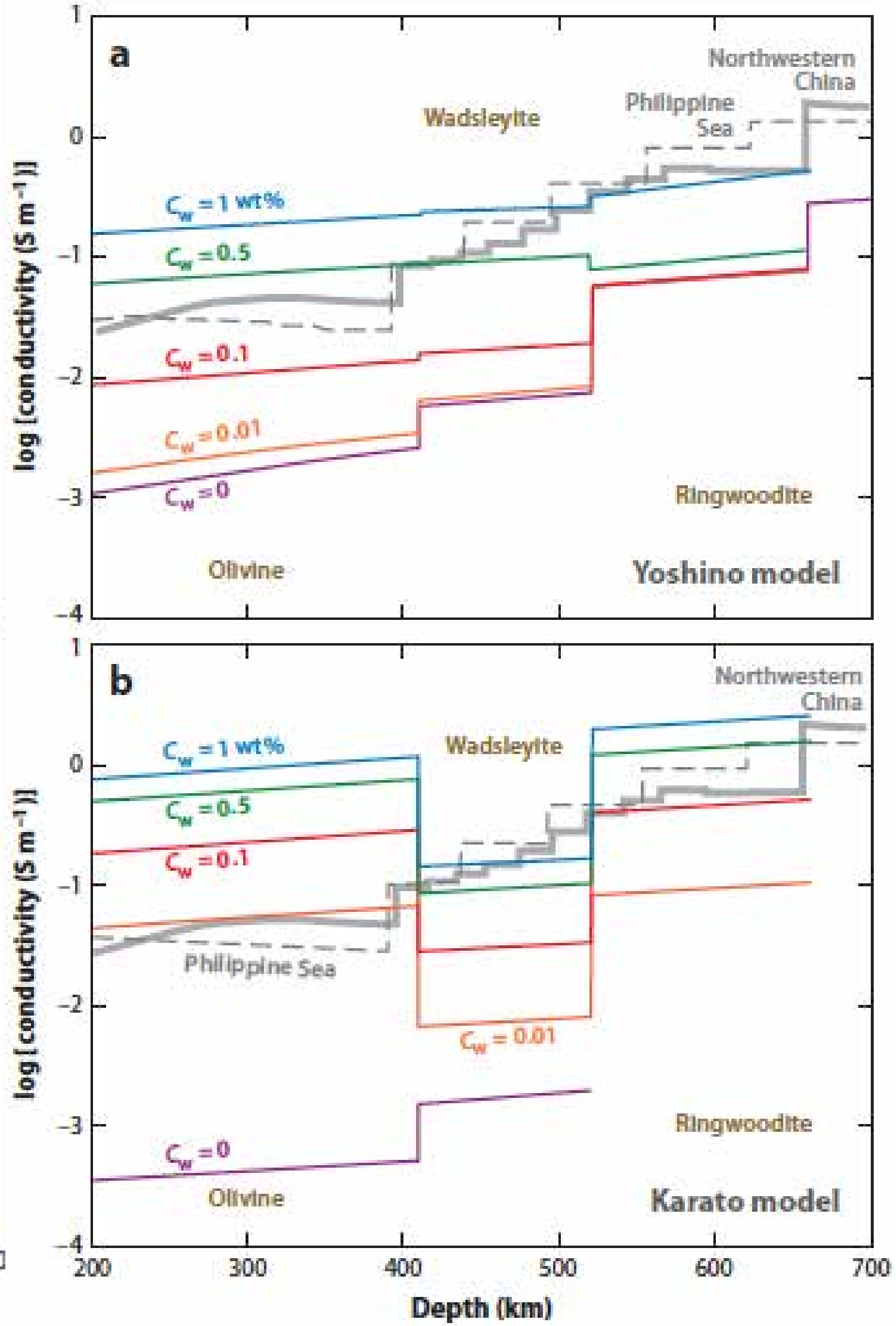
- Several studies have begun to constrain water content in nominally anhydrous minerals stable in the mantle and mantle transition zone to address these observables (and to also explore the reason behind the low velocity zone there). Estimates have been made using available laboratory data, but there are discrepancies.

- Note - it is proposed that extremely water-rich melt compositions (supercritical fluid or melt) might explain some of the transition zone discrepancies but no measurements are available to date (Manthilake et al., 2009).



From Karato (2011). experimental measurements of upper mantle and transition zone minerals as a function of water content (Cw).The bars show the influence of the other major factors.

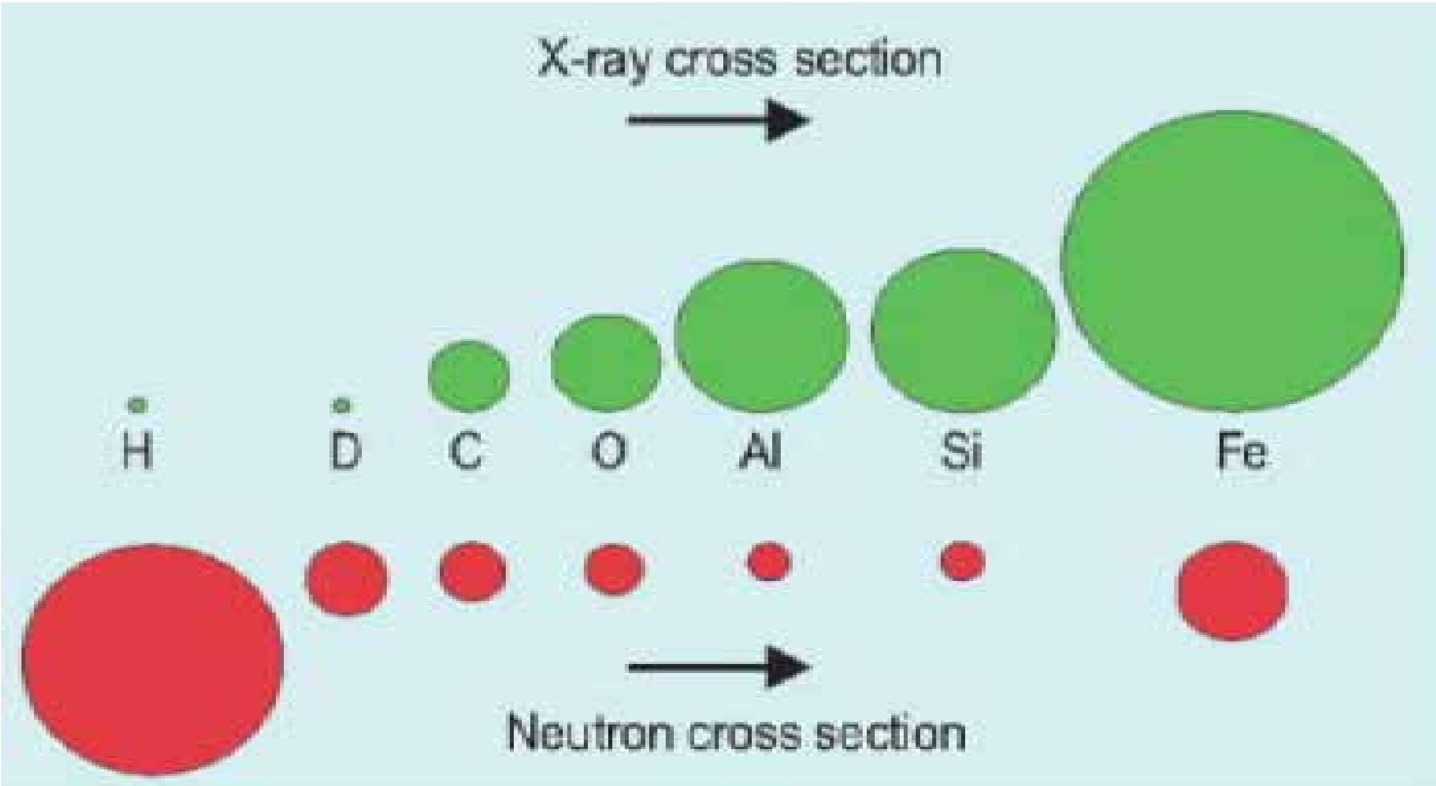




300°C lower than mantle geotherm

4) How do aqueous and carbon-rich fluids behave at depth, and how do fluids and rocks interact, particularly in subduction-zone environments?

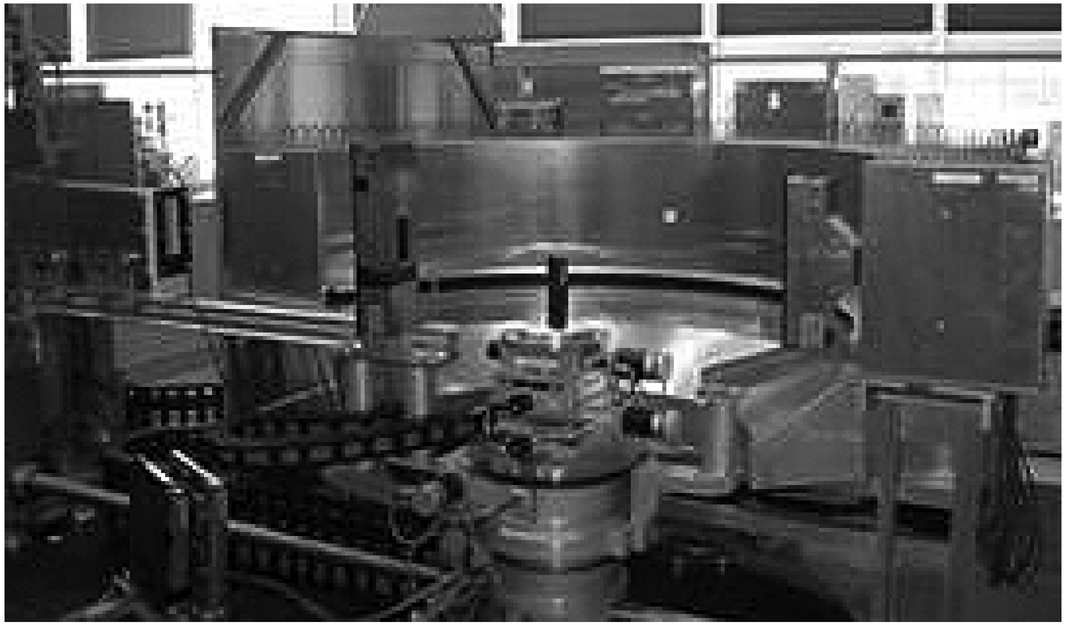
Ah - a new technique is needed….H is the key



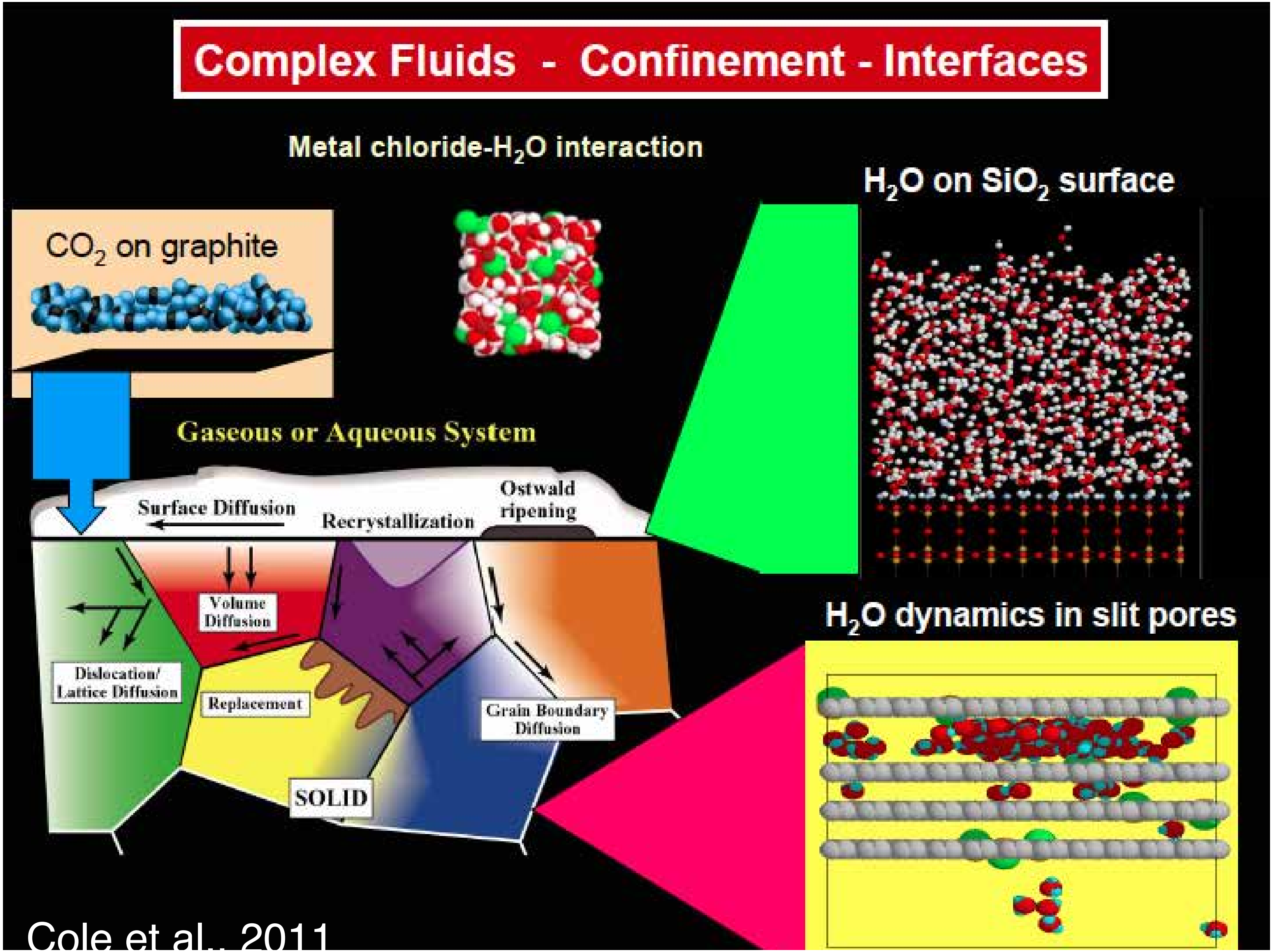
Neutron scattering:

- Strong scattering by H and low atomic number (Z) atoms
- Have a high penetration depth so can enter high pressure and temperature environments

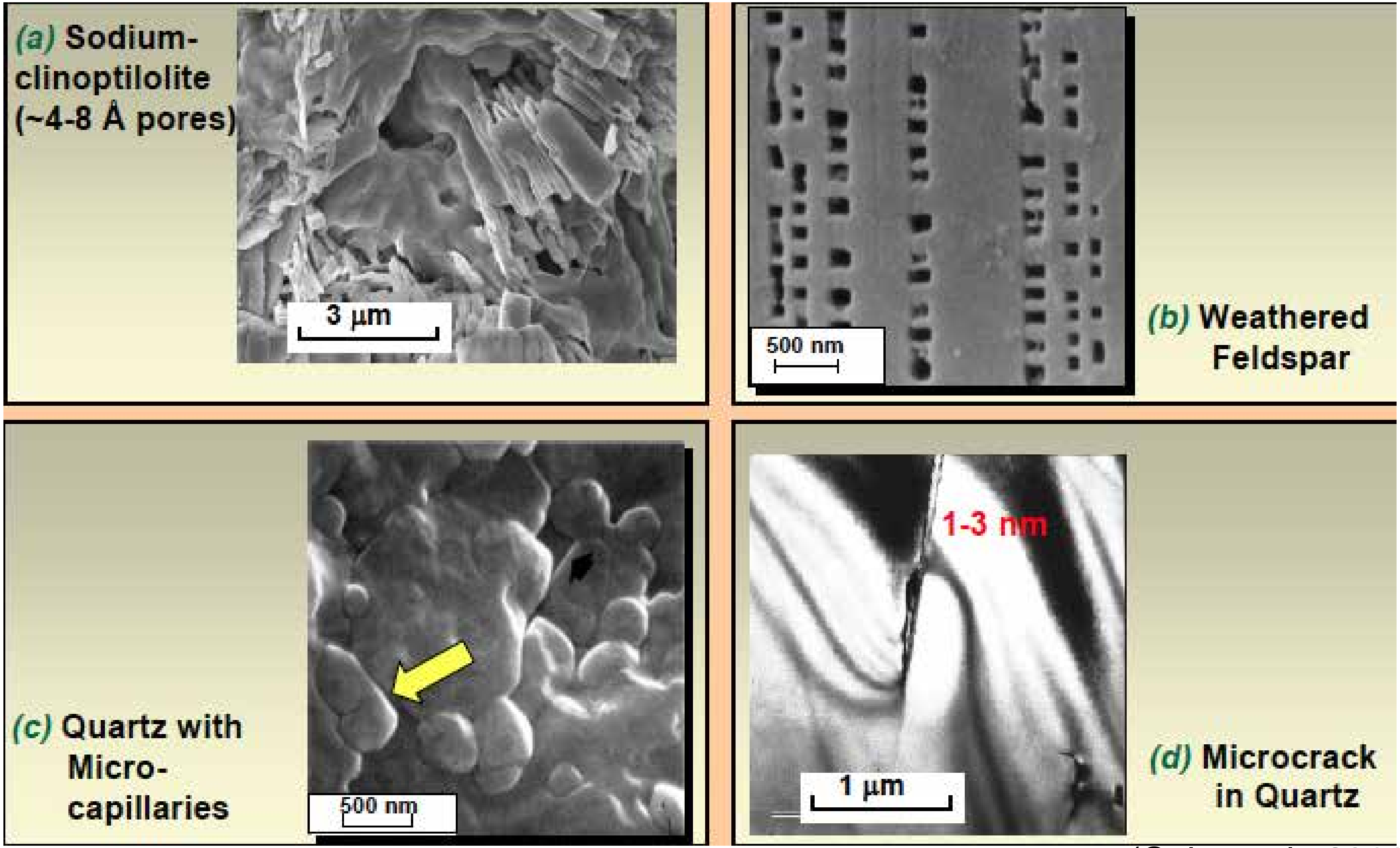
ANSTO (OPAL) and Bragg Institute



WOMBAT - high intensity neutron diffractometer


Complex Fluids - Confinement - Interfaces
Metal chloride-H2O interaction
H2O on SiO2 surface
CO2 on graphite
Gaseous or Aqueous System
Surface Diffusion
Recrystallization
Ostwald ripening
Volume Diffusion
Dislocation/ Lattice Diffusion
Replacement
Grain Boundary Diffusion
SOLID
H2O dynamics in slit pores
Cole et al., 2011

Mainly used now to investigate surface fluid-solid relationships (pore size, distribution, connvectivity) And relevant to oil and gas



(Cole et al., 2011)

OH and fluid-bearing experiments during in-situ, high pressure experimentation

- Early days, but clear areas of research will be determining the water-bearing phases at different depths in the lithosphere and the impact of deformation on melt distribution.

Solid-solution of important mantle phases

- For example, Al-Si ordering in garnet solid solution. The developments of large volume synthesis for neutron studies will begin to make studies like these feasible, as only neutron scattering can tell if there is ordering.

Simon is a mineral "dynamicist" based at Cambridge University, UK

Simon Redfern

- Simon has developed new experimental methods (eg. RoPEC) for investigating role that microstructure has on the properties of minerals in the Earth and probing acoustic attenuation in minerals to uncover (experimentally) the mesoscopic controls on seismic properties.
- RoPEC is now at the Bragg Institute - ANSTO

Rotational (modified) Paris-Edinburgh Cell - portable and can do deformation experiments

Summary

- New techniques in high pressure geoscience have revolutionized our ability to explore the deep Earth and address major questions and take on new challenges.
- The Australian Synchrotron high pressure facility is now under development so we can begin these state-of-the-art experiments in Australia.
- Developing the high pressure experimental program at ANSTO for complimentary experiments that are OH and fluid-bearing. In addition, we plan solid-solution studies on major mantle phases that will help understand their chemical changes at high pressure and temperature.

Future Directions

- Important links between strong geophysical programs in Australia and new models (eg. AuSREM) with targeted high pressure experimental studies.

- Data input into state-of-the-art numerical models (eg. LitMod) of difficult to access material properties. Targeted experiments for non-unique solutions from the models?

Acknowledgements

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