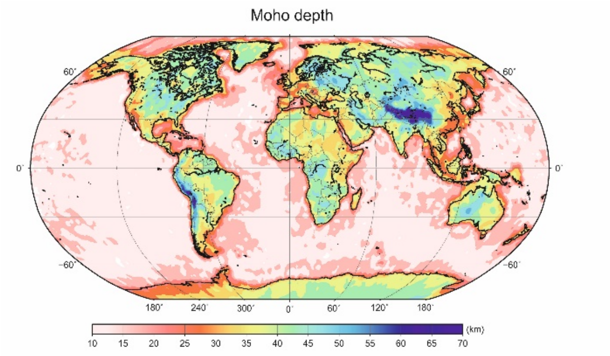
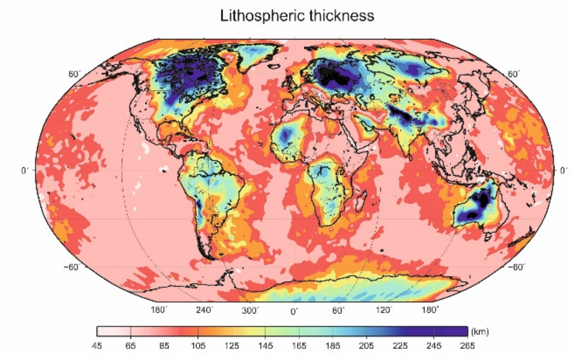
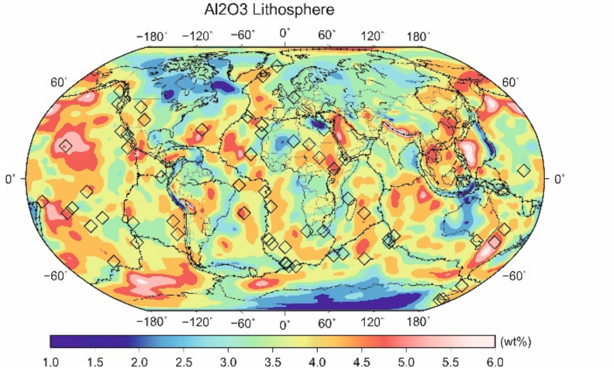
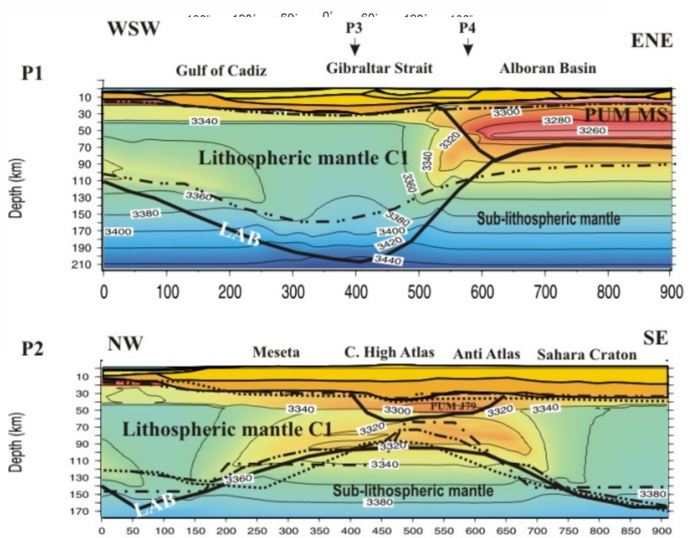
Lithosphere-upper mantle thermochemical modelling at global and regional scale

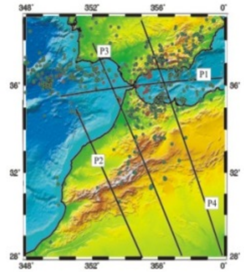






Al2O3 sub-lithosphere



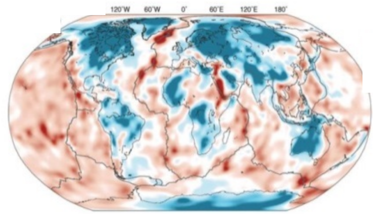


Lithosphere-upper mantle thermochemical structure: why bother?

- ✓ Mantle flow informing plate tectonics: density+ viscosity
- ✓ What supports the Earth's surface topography?
- ✓ Cooling of oceanic lithosphere: half-space vs plate model?
- ✓ Mid Oceanic Ridges: composition, temperature, spreading rate
- ✓ Mantle plumes: temperature and composition
- ✓ Stability of cratonic continental lithosphere

➢ ***Many techniques/observations, just ONE Earth...***

Seismic Velocity models



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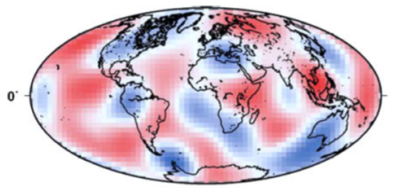
Electrical Conductivity models



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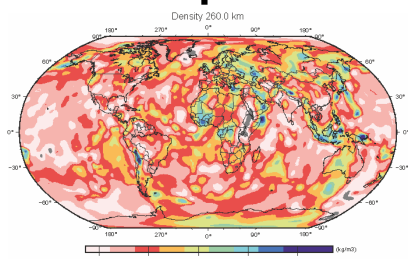
Density models



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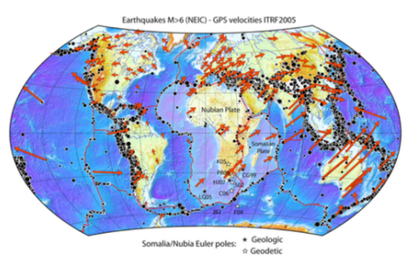
Deformation models



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...

- Rock properties → non linear functions of thermochemical structure...!

=

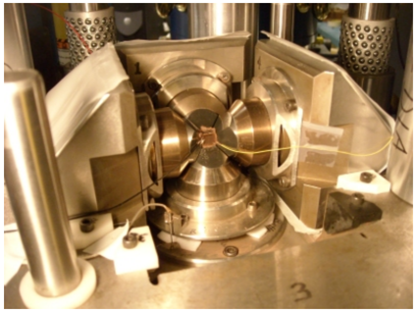
$$dG = V\,dP - S\,dT + \Sigma_i \mu_i\,dX_i$$

Thermodynamics

+

Petrology

+

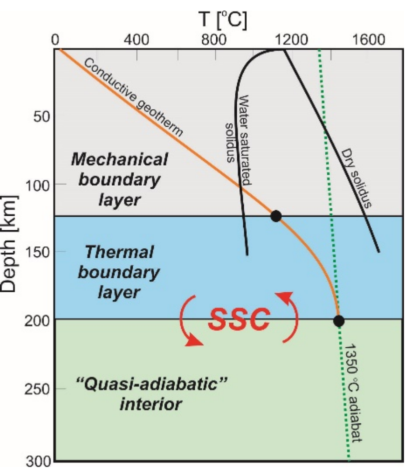


Mineral physics

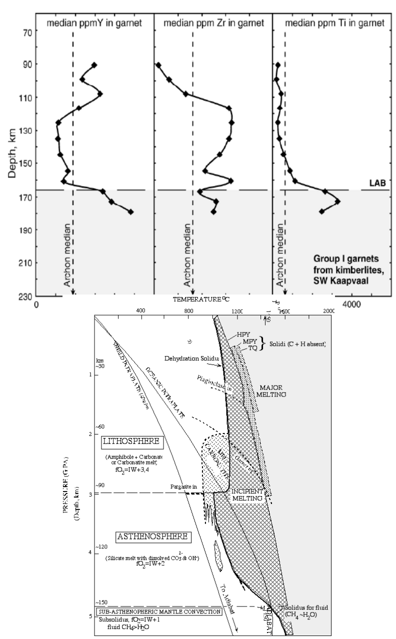
Why integrated modelling...?

A fundamental upper mantle discontinuity for plate tectonics: the lithosphere-asthenosphere boundary (LAB) can be defined as **thermal, mechanical and chemical boundary.**

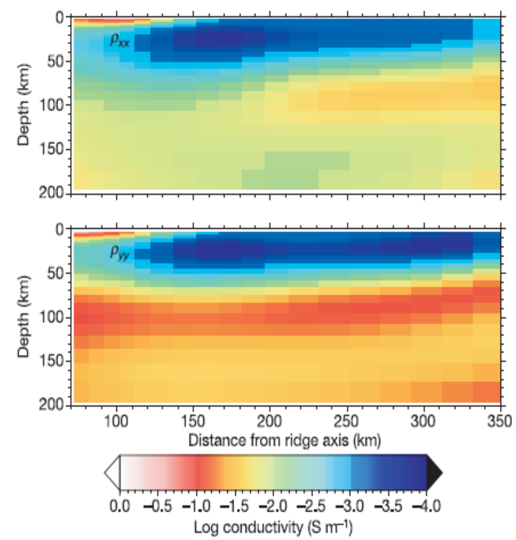
According to the property we focus on (e.g., **temperature, composition, Vs, Vp, anisotropy, electrical conductivity…**) there are many possible "**LABs**" (e.g. Eaton 2009):



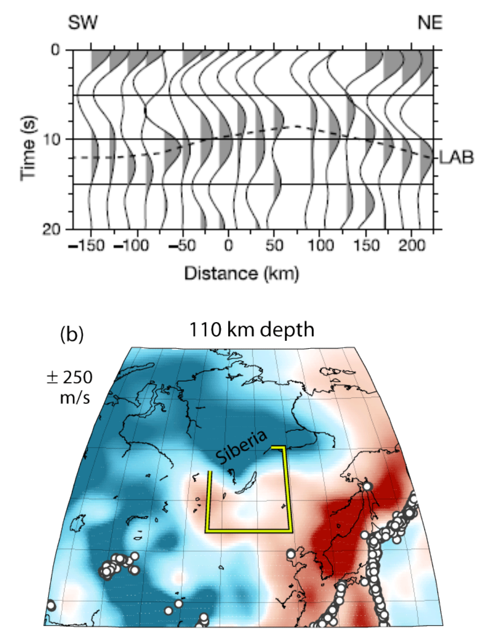
Thermal LAB



Geochemical/ petrological LAB

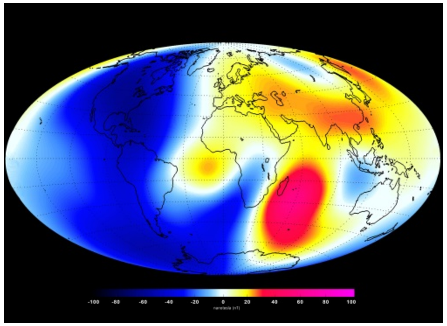


Electric LAB



Seismic LAB

➢ Earth structure: what can we know?

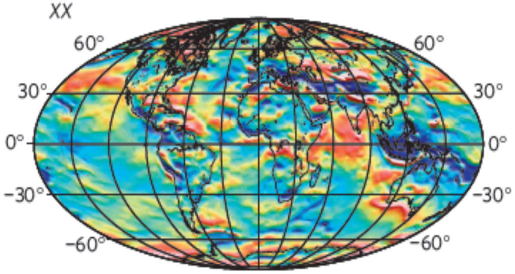


Swarm magnetic data
(+ airborne surveys
+observatories and MT)

→ ***Electrical Conductivity, Curie isotherm, susceptibility***
(global models
Regional models)

→ ***Temperature***
→ ***H_2O***
→ ***melt***

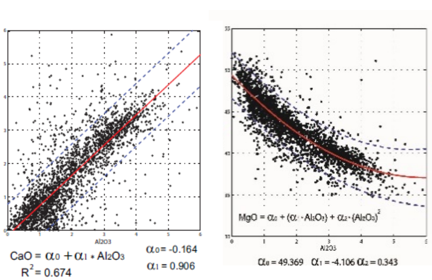
XX



GOCE gravity data
(+ land gravimetry)

→ ***Density, Elastic thickness***
(global and
regional models)

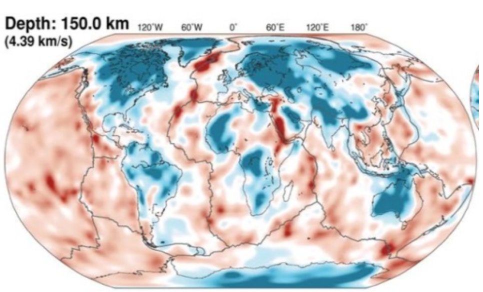
→ ***Temperature***
→ ***Composition***



World petrological
Data sets

→ ***Thermo-barometers, Major oxides chemistry***

→ ***Temperature***
→ ***Composition***



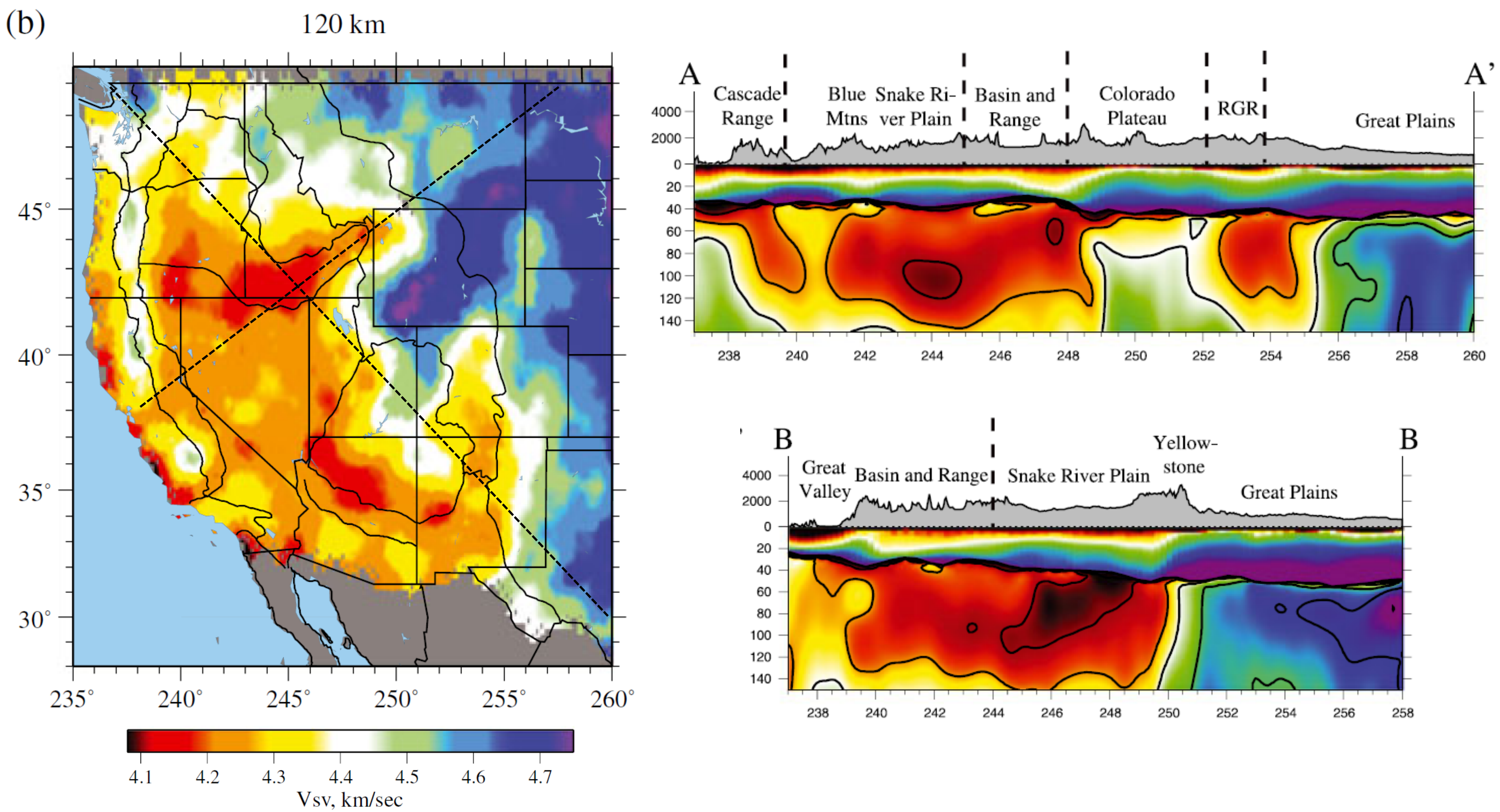
Seismic tomography
(surface, body waves,
normal modes)

→ ***Seismic velocities anisotropy***
(global and
regional models)

→ ***Temperature***
→ ***Composition***
→ ***melt***

What is the nature of the heterogeneity "observed" in the mantle?

Geophysical point of view



Shen et al., 2013, JGR

What is the nature of the heterogeneity "observed" in the mantle?

Petrological point of view

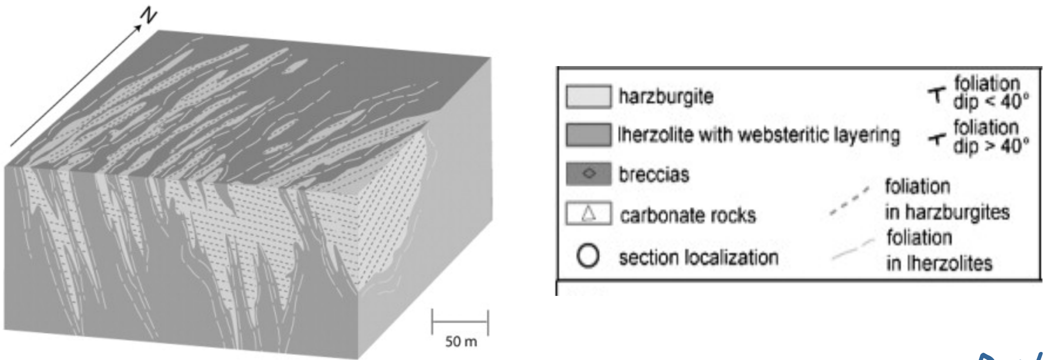
In mantle xenoliths

In outcrops

Courtesy of GEMOC

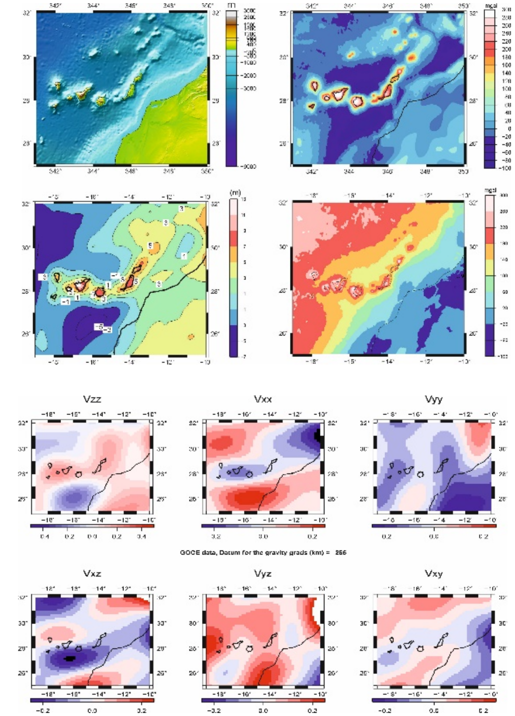
What is the nature of the heterogeneity "observed" in the mantle?

Representativeness of observed mantle samples (xenoliths, peridotite massifs etc..) on the lithospheric scale



Forward modeling

Geophysical data



Depleted (columns 1–3)

Depleted +metasomatised (column 4)

	1) Av. Harz. Lanzarote (wt%)[a]	2) Av. HEXO Tenerife (wt%)[b]	3) Av. Harz. La Palma av. (wt%)[c]	4) Av. HLCO Tenerife (wt%)[b]	5) Av. Ocean floor peridot. (wt%)[d]	6) Av. Middle Atlas (wt%)[e]
SiO_2	43.78	43.32	43.07	42.14	45.09	43.48
Al_2O_3	0.7	0.61	0.53	0.73	2.33	2.38
FeO	7.79	8.04	8.43	8.8	8.4	8
MgO	46.1	45.31	45.19	44.14	41.23	42.6
CaO	0.6	0.81	0.68	1.68	1.32	2.83
Na_2O	0.1	0.14	0.17	0.18	0.23	0.24
Mg#	91.34	90.96	90.53	89.94	89.7	90.47

← *Mantle Depletion (partial melting)*

Mantle metasomatism (refertilization) →

Mantle Geotherm: thermal lithosphere-asthenosphere boundary

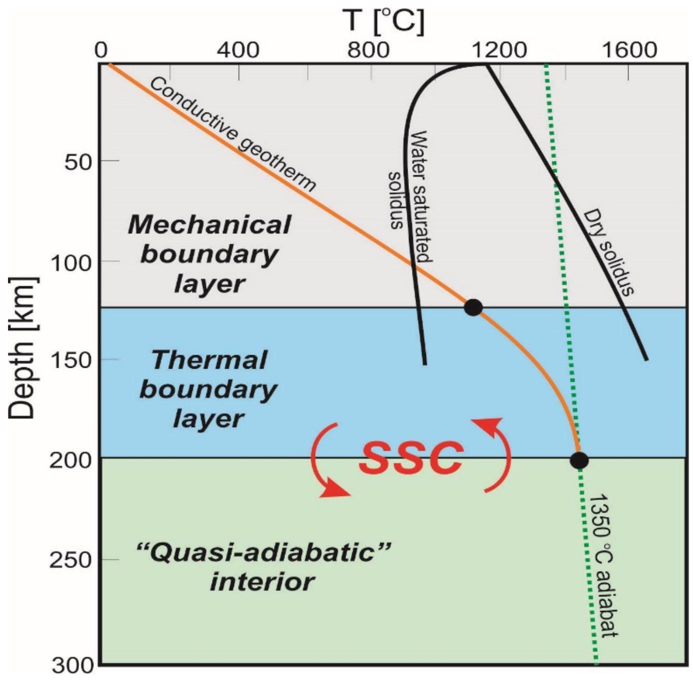
Heat transport equation:

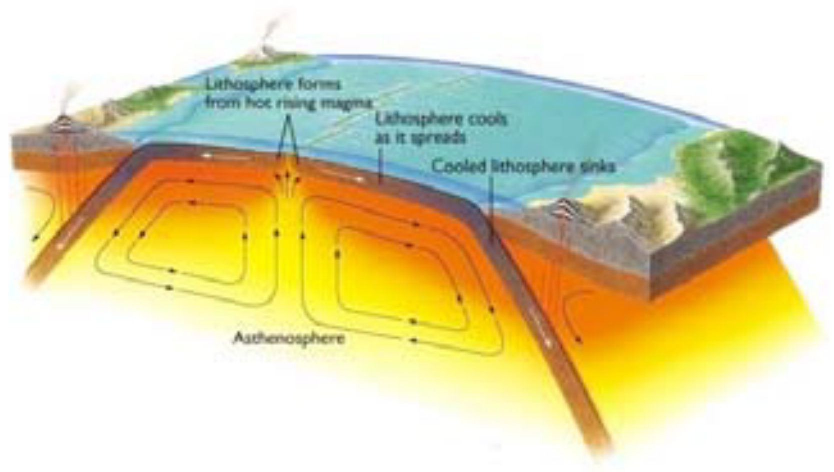
$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + H - \rho c_p \vec{u} \cdot \nabla T$$

Lithosphere: conductive mantle

Steady-state conduction equation: dT/dt=0 and U=0→Diffusion PDE

$$\nabla \cdot [k(\vec{x}, T, P) \nabla T(\vec{x})] = -H(\vec{x})$$





Sub-Lithosphere: mantle convection

Convection in the mantle (i.e. no heat interexchange with the surroundings). Fast heat transport mechanism compared to conduction

$$\left(\frac{\partial T}{\partial r}\right)_S = \frac{T\alpha g}{c_P}$$

Adiabatic gradient: typically 0.4-0.5 K/km in the uppermost mantle

Thermal field

- ✓ Mantle thermal conductivity dependent on T, P and C (numerical iteration)

$$k_{(T,P)} = k^{\circ}\left(\frac{298}{T}\right)^{a} \exp\left[-(4\gamma + 1/3)\int_{298}^{T} \alpha(T)dt\right] \times \left(1 + \frac{K_0' P}{K_T}\right) + k_{rad}(T)$$

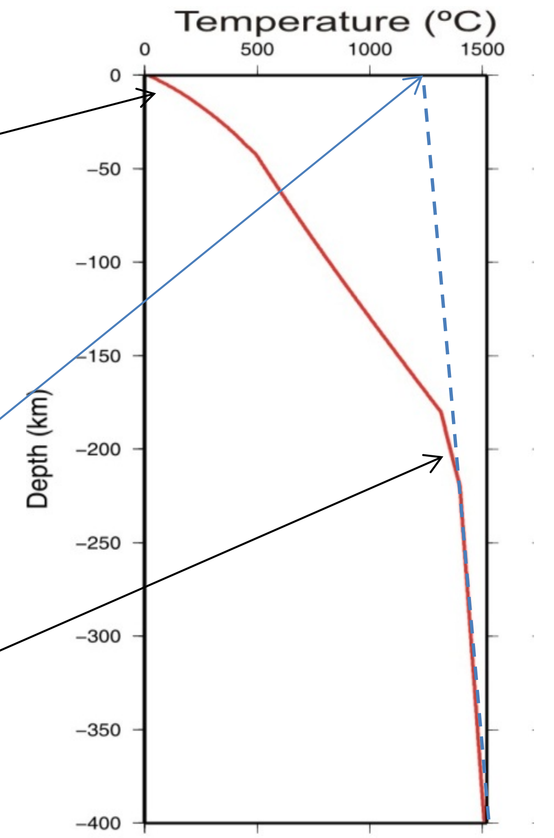
- ✓ Surface Heat flow (SHF)= Kc*dT/dz

- ✓ Crustal heat production accounts for 20-40% of SHF in continents

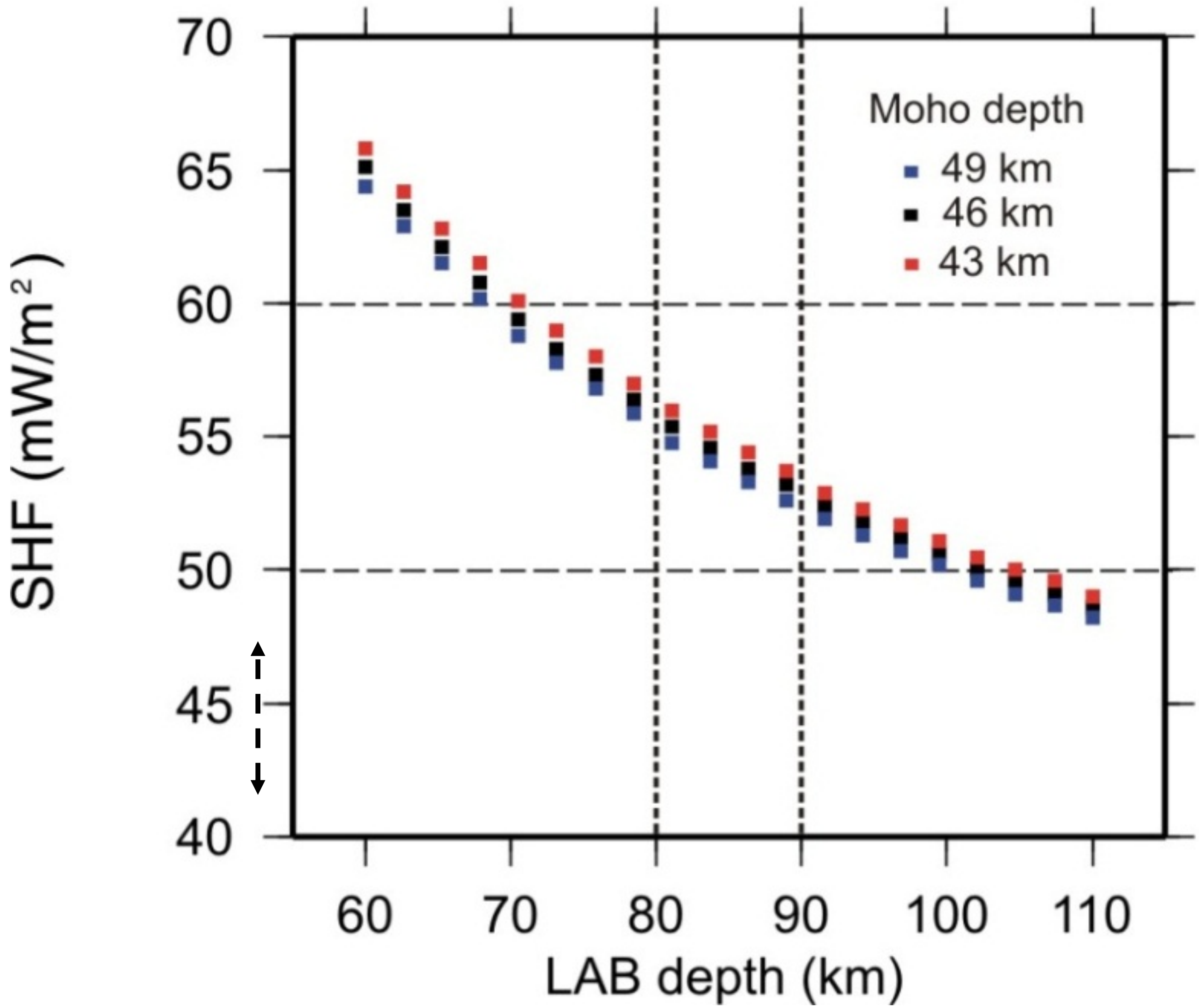
- ✓ Thermal buffer connecting the conductive lithosphere with the adiabatic sublithosphere. Tbuffer=1420 ºC (mantle potential temperature of 1350 ºC)

- ✓ Sublithospheric geotherm: adiabatic gradient (usually 0.4-0.5 K/km) and potential temperature

- ✓ T@410 km =1520 -1600 ºC (Katsura 2022)

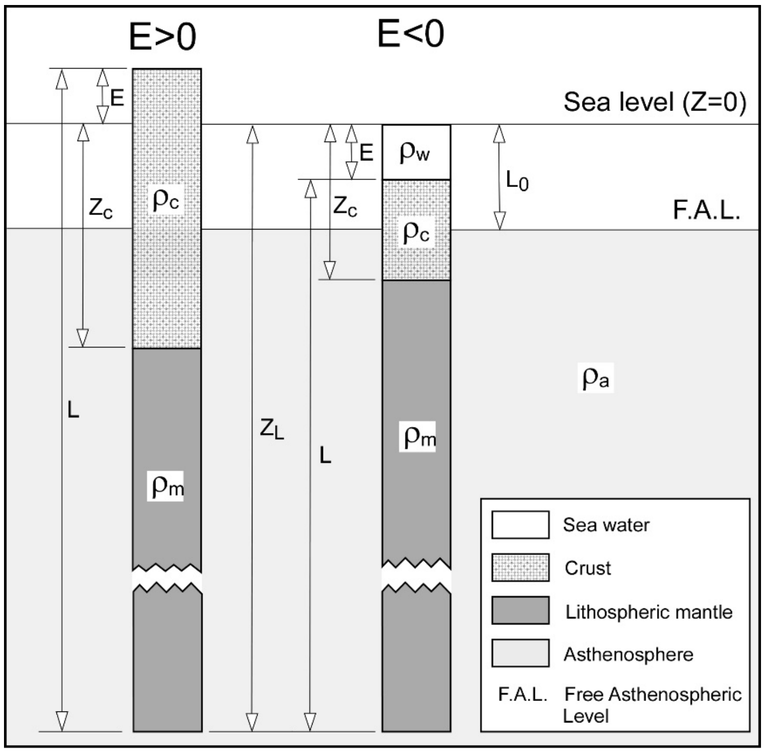


Surface heat Flow and lithospheric thickness



Isostasy

✓ ***Lithospheric isostasy: (absolute) elevation as a measure of the bouyancy of the lithosphere***



$$\int_{LC} \Delta\rho(z)\,dz = 0$$

$$E = \frac{\rho_a - \rho_L}{\rho_a} \cdot L - L_0 \quad (E > 0)$$

$$E = \frac{\rho_a}{\rho_a - \rho_w} \cdot \left(\frac{\rho_a - \rho_L}{\rho_a} \cdot L - L_0 \right) \quad (E < 0)$$

$$\rho_L = \frac{(E + z_c)\rho_c + (z_L - z_c)\rho_m}{(E + z_L)}$$

(e.g. Lachenbruch & Morgan 1990)

➢ ***Lithospheric mantle able to hold density contrasts over geological time scales…***

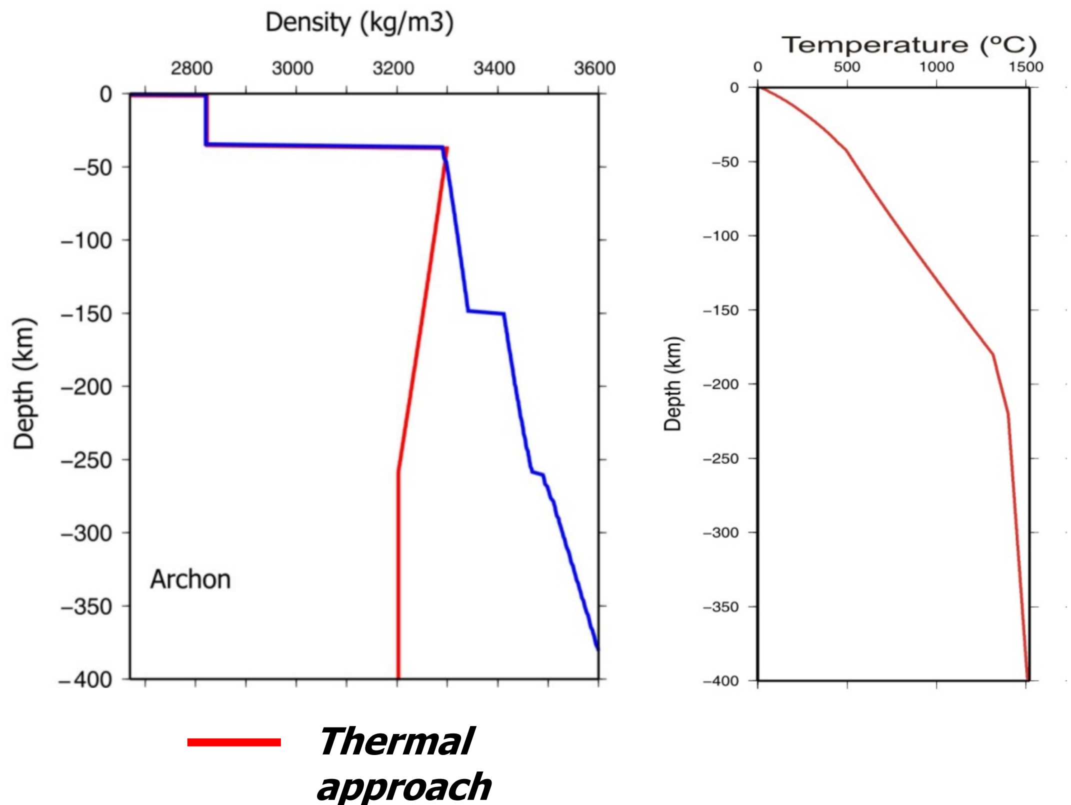
Local isostasy: average density of the lithosphere

Linear mantle density models (pressure effect neglected):

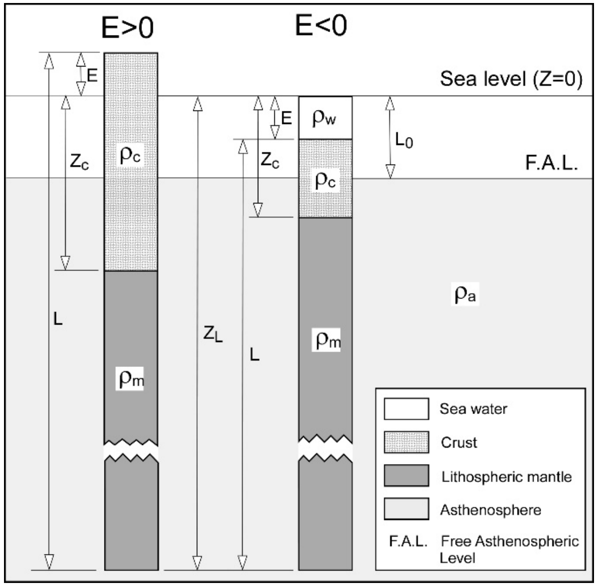
$$\rho_m(z) = \rho_a(1 + \alpha[T_a - T_m(z)])$$

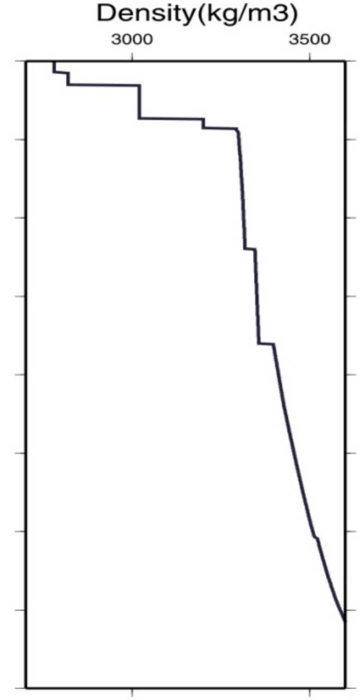
$$\rho_m(z) = \rho_0(1 - \alpha[T_m(z)])$$

Ta Lithosphere-asthenosphere boundary temperature (1200-1315 C typically), α thermal expansion coefficient, ρ_a asthenospheric density (typically 3200 kg/m3), ρ_0 mantle density at the surface (T=0)



Local isostasy: average density of the lithosphere





$$\int_{LC} \Delta\rho(z)\, dz = 0$$

$$E = \frac{\rho_a - \rho_L}{\rho_a} \cdot L - L_0 \quad (E > 0)$$

$$E = \frac{\rho_a}{\rho_a - \rho_w} \cdot \left(\frac{\rho_a - \rho_L}{\rho_a} \cdot L - L_0 \right) \quad (E < 0)$$

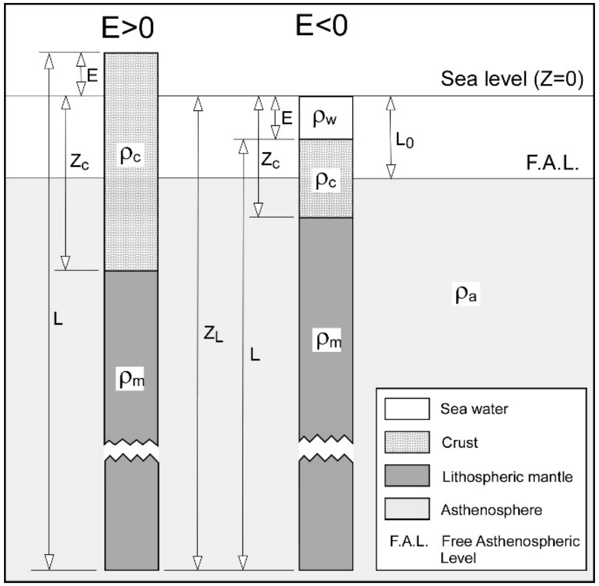
$$\rho_L = \frac{(E + z_c)\rho_c + (z_L - z_c)\rho_m}{(E + z_L)}$$

Classical formulation of lithospheric isostasy (Lachenbruch & Morgan, 1990).

Includes variations in crustal and lithospheric thickness as well as crustal and mantle density.

A Mid Oceanic Ridge (MOR) is taken as the reference column (Lo)

Local isostasy: average density of the lithosphere



In terms of pressure, P, at the compensation level (CL), for an arbitrary reference column with E=0:

$$P_{ref} = \int_0^{z_{cREF}} \rho_c dz + \int_{z_{cREF}}^{z_{LREF}} \rho_m(z) dz + \int_{z_{LREF}}^{CL} \rho_{msub}(z) dz$$

For any other column at the CL the pressure must be the same. If the average lithospheric density is < reference lithospheric density the topography compensates the pressure deficit:

$$P_c = \int_0^{z_c} \rho_c dz + \int_{z_c}^{z_L} \rho_m(z) dz + \int_{z_L}^{CL} \rho_{msub}(z) dz + \int_0^{h_{cont}} \rho_c dz = P_{ref}$$

If the average lithospheric density is > reference lithospheric density the bathymetry compensates the pressure excess:

$$P_c = \int_0^{z_c} \rho_c dz + \int_{z_c}^{z_L} \rho_m(z) dz + \int_{z_L}^{CL} \rho_{msub}(z) dz + \int_0^{h_{bathy}} (\rho_w - \rho_c) dz = P_{ref}$$

Mantle density-pressure coupling

The lithostatic pressure, P, at any depth depends on the weight of the lithospheric column above:

$$P = \rho g z$$

But in general ρ=ρ(P), this coupling is solved numerically in a iterative scheme:

$$P_0(z) = P(z - \Delta z) + \rho(z - \Delta z) g \Delta z$$

$$\rho(z) = F(P_0(z));\ \overline{\rho_1} = \frac{\rho(z) + \rho(z - \Delta z)}{2}$$

$$P_1(z) = P(z - \Delta z) + \overline{\rho_1} g \Delta z$$

$$\rho(z) = F(P_1(z));\ \overline{\rho_2} = \frac{\rho(z) + \rho(z - \Delta z)}{2}$$

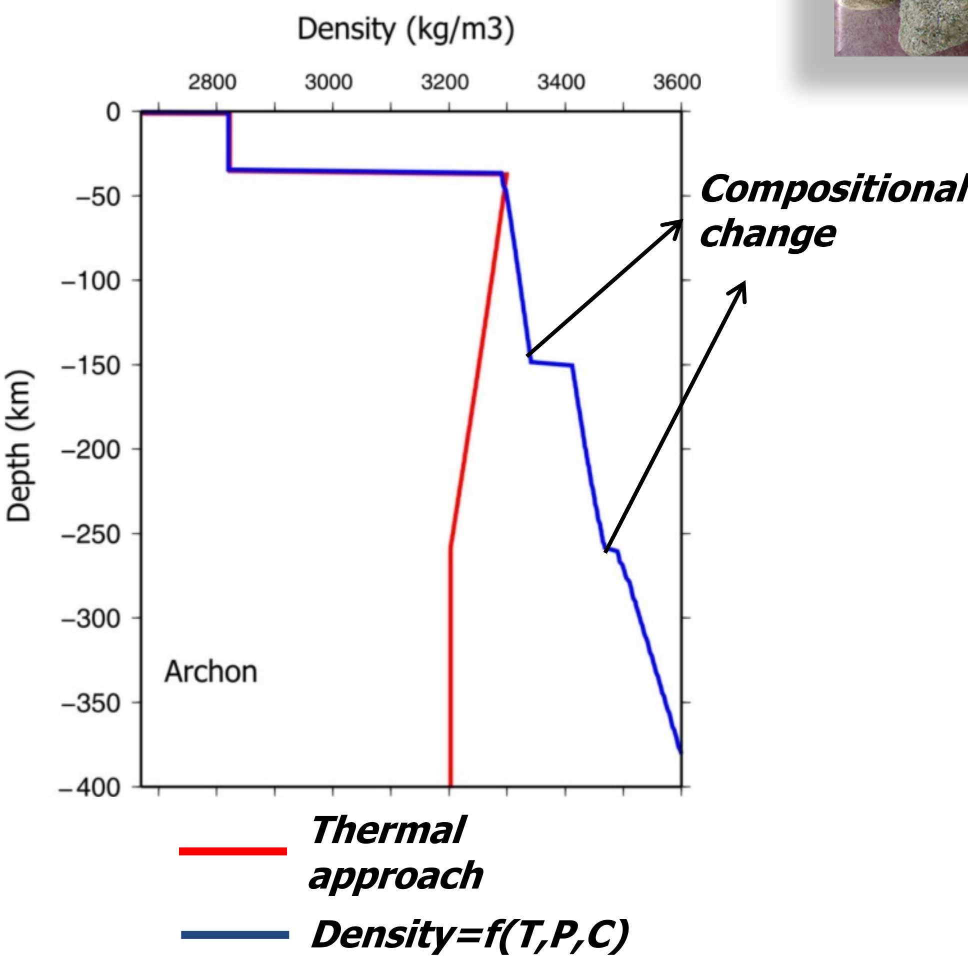
$$P_2(z) = P(z - \Delta z) + \overline{\rho_2} g \Delta z$$

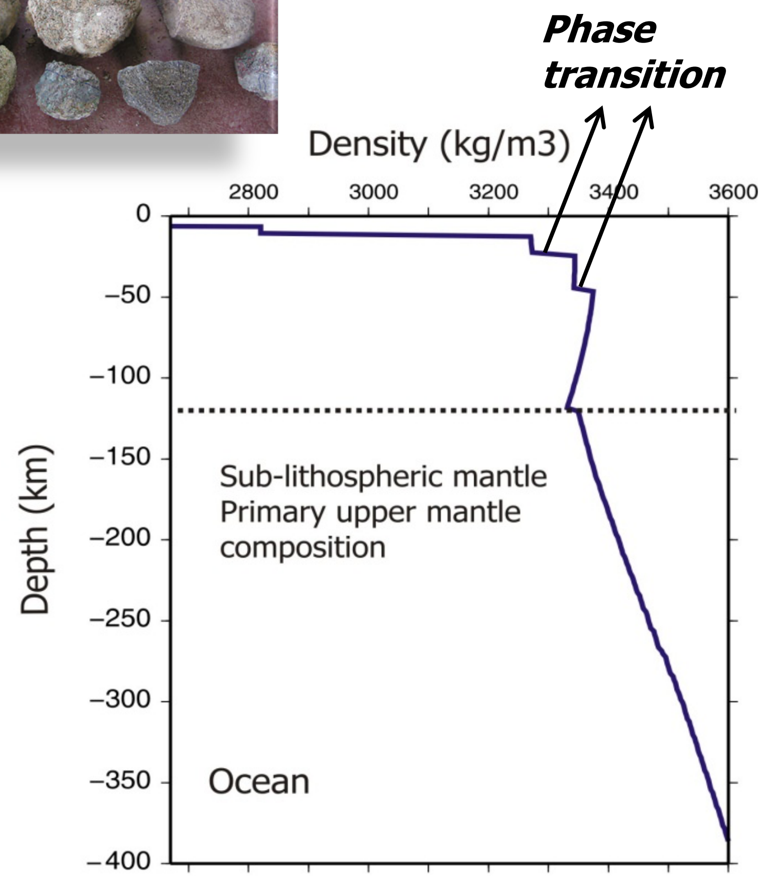
…

✓ **Easy density dependence: Cold = dense = less buoyant**

$$\rho_m(z) = \rho_a\left(1 + \alpha\left[T_a - T_m(z)\right]\right)$$

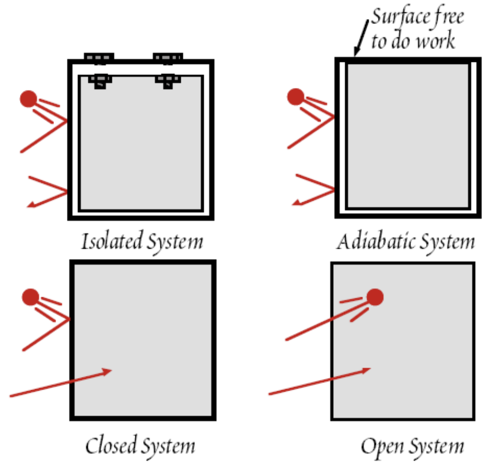
Yes but, let's consider composition…





Summary of basic thermodynamic concepts

System: *the region of interest, of sufficient size that average properties like temperature are well-defined; to be distinguished from the* environment *(i.e. the rest of the universe)*

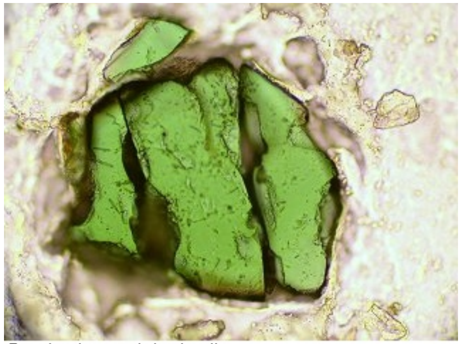


***Isolated system**: exchanges neither matter nor energy across its boundaries*

***Closed system**: may exchange energy across boundaries, but not matter*

***Open system**: may exchange matter and energy across boundaries*

Phase: *a physically homogeneous and mechanically separable part of the system, e.g. a vapor, liquid, or mineral.* A system may be homogeneous (one phase) or heterogeneous (multiple phases). *E.g. solid solution of Forsterite and Fayalite (Olivine end-member minerals).*


Synthetic wadsleyite II

Olivine Forsterite Mg_2SiO_4 → Fayalite Fe_2SiO_4

Plagioclase Albite $NaAlSi_3O_8$ → Anorthite $CaAl_2Si_2O_8$

Component: *a chemical formula; a basis vector for expressing compositional variations in thermodynamic systems; e.g., H_2O, SiO_2, Fe, NaCl . Must be independently variable, but we choose the minimum set to span all phases. Main oxides in the mantle NCFMAS system (sometimes also Cr2O3)*

Phase vs system component (e.g. oxide).

Summary of basic thermodynamic concepts

Gibbs free energy: ***is the energy available for non-PV work (such as chemical work)***

$$G = H - TS \quad (13)$$

$$\boxed{dG = VdP - SdT} \quad (15)$$

Note that $(dG/dT)_p = -S$ $(dG/dP)_T = V$

Since its independent variables are P and T, it is useful for equilibrium studies.
It also contains the entropy term which can be used as an indication of the direction in which spontaneous reactions will occur.

Note that if P and T remain constant through any spontaneous change in state, then dG = 0 !!!!!!!!!

- ***Gibbs free energy is adequate for equilibrium studies because its independent variables are T and P, i.e. the ones we are usually interested in!***
- ***Spontaneous reactions evolve to minimize the Gibbs free energy.***

- ***At equilibrium, dG = 0 and ΔG = 0. in other words, products and reactants are in equilibrium when their G are equal.***

Summary of basic thermodynamic concepts

$$\Delta G_{T',P'} = \Delta G_{T_{ref},P_{ref}} + \int_{P_{ref}}^{P'} \Delta V_r dP - \int_{T_{ref}}^{T'} \Delta S_r dT$$

$$\left(\frac{\partial \Delta G}{\partial T}\right)_P = -\Delta S$$

$$\left(\frac{\partial \Delta G}{\partial P}\right)_T = \Delta V$$

$$\Delta S(T) = \Delta S_{T_{ref}} + \int_{T_{ref}}^{T} \frac{\Delta C_p}{T} dT$$

Solve this system iteratively for discrete ΔT and ΔP and find the point where $\Delta G = 0$

How do we get the fundamental parameters?

Two main categories:

****Analysis of each phase individually (calorimetry, electrochemical)***

****Relate thermodynamic properties of minerals to each other (int. consist. dataset)***

The "solution" is a combination of calorimetric data and additional constraints such as reaction reversal brackets.

A thermodynamic dataset compatible with calorimetry and reaction reversals alike is called an internally consistent thermodynamic dataset (e.g. Holland and Powel 98, Stixrude 05, etc.)

Summary of basic petrological concepts

Ternary compositional plot for peridotites

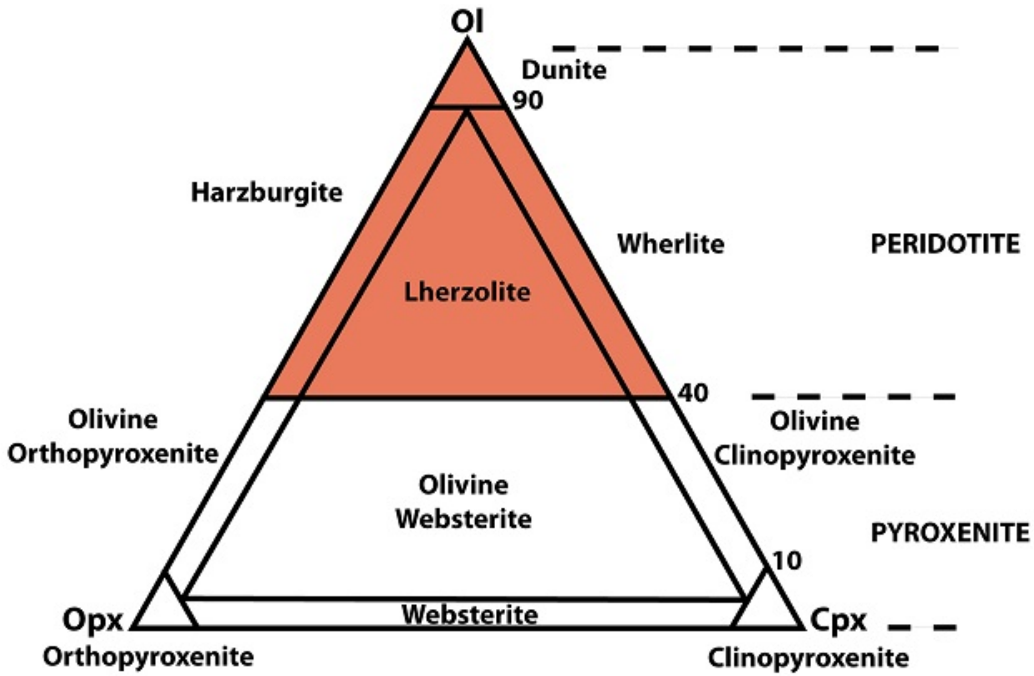


Table 15.2 | Mineralogy of Lherzolites

Mineral	Spinel Lherzolite Average (wt. pct.)	Spinel Lherzolite Range (vol. pct.)	Garnet Lherzolite Average (vol. pct.)	Garnet Lherzolite Range (vol. pct.)
Olivine	66.7	65–90	62.6	60–80
Orthopyroxene	23.7	5–20	30	20–40
Clinopyroxene	7.8	3–14	2	0–5
Spinel	1.7	0.2–3	—	—
Garnet	—	—	5	3–10
Phlogopite	—	—	0.4	0–0.5

Maaløe and Aoki (1977).

Peridotite as function of the stable mineral phases: Olivine (O), pyroxenes (cpx, opx), garnet(gnt) etc.

Summary of basic petrological concepts

Ternary compositional plot for peridotites

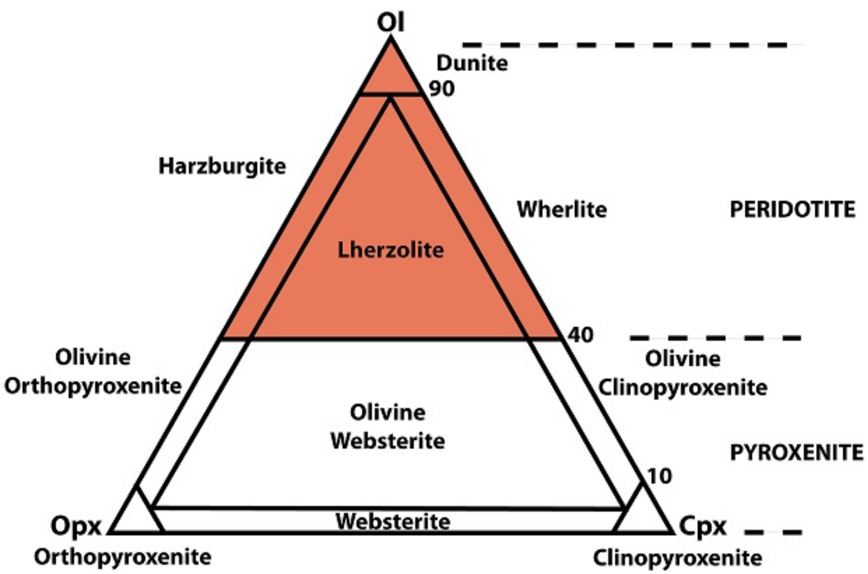


Table 15.3 Compositions of peridotites and pyroxenites

	Lherzolites							
	Spinel		Garnet	Dunite	Pyroxenite	Peridotites		
Oxide	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SiO_2	44.15	44.40	44.90	41.20	48.60	44.14	46.36	42.1
Al_2O_3	1.96	2.38	1.40	1.31	4.30	1.57	0.98	
FeO	8.28	8.31	7.89	11.0	10.0	8.31	6.56	7.10
MgO	42.25	42.06	42.60	43.44	19.10	43.87	44.58	48.3
CaO	2.08	1.34	0.82	0.80	13.60	1.40	0.92	
Na_2O	0.18	0.27	0.11	0.08	0.71	0.15	0.11	
K_2O	0.05	0.09	0.04	0.016	0.28	—	—	
MnO	0.12	0.17	0.11	0.15	0.18	0.11	0.11	
TiO_2	0.07	0.13	0.06	0.06	0.83	0.13	0.05	
P_2O_5	0.02	0.06	—	0.10	0.10	—	—	
NiO	0.27	0.31	0.26	—	—	—	—	
Cr_2O_3	0.44	0.44	0.32	—	—	0.34	0.33	
H_2O	—	—	—	0.50	0.90	—	—	

Peridotite as function of the major oxide composition

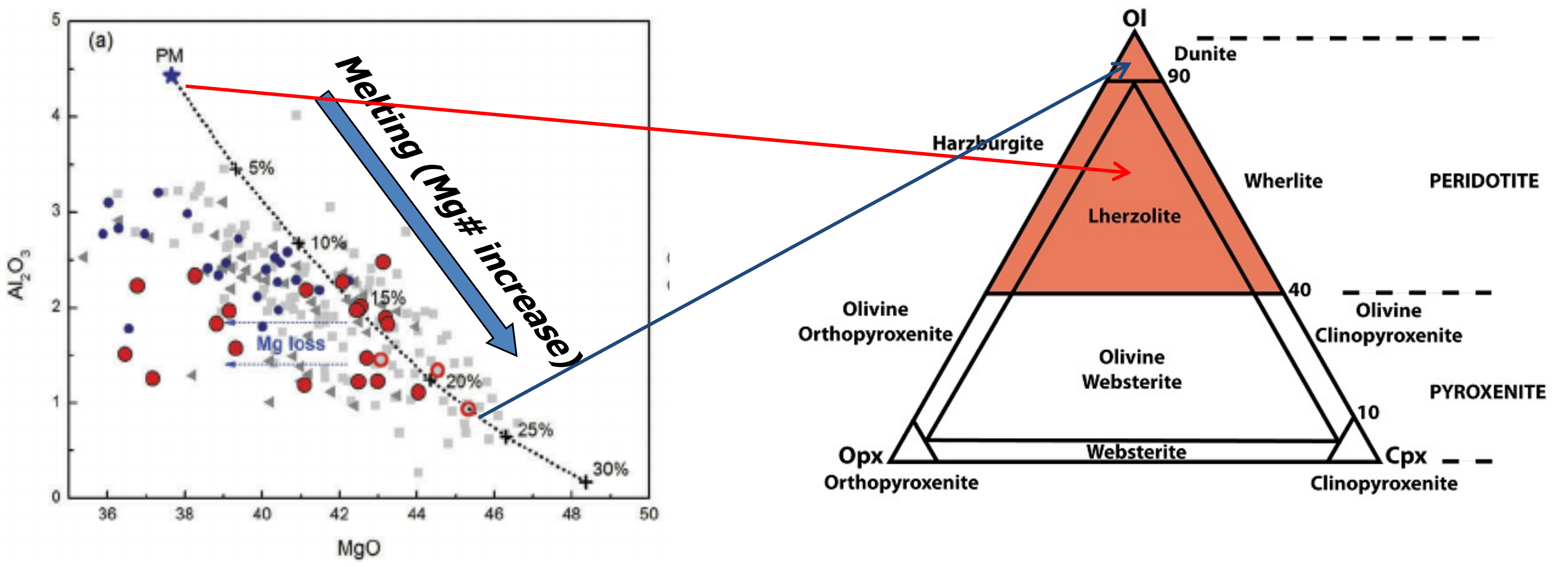
Summary of basic petrological concepts

Magnesium number: Mg#= MgO/(MgO+FeO)

Mg# low→ fertile mantle (enriched in Al2O3 and CaO, depleted in MgO)

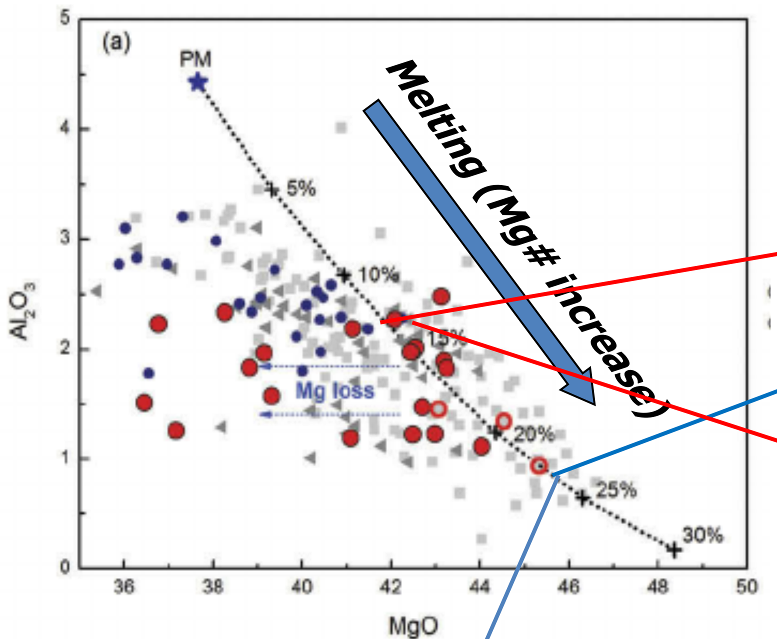
Mg# high→ refractory mantle (enriched in MgO, depleted in Al2O3 and CaO)

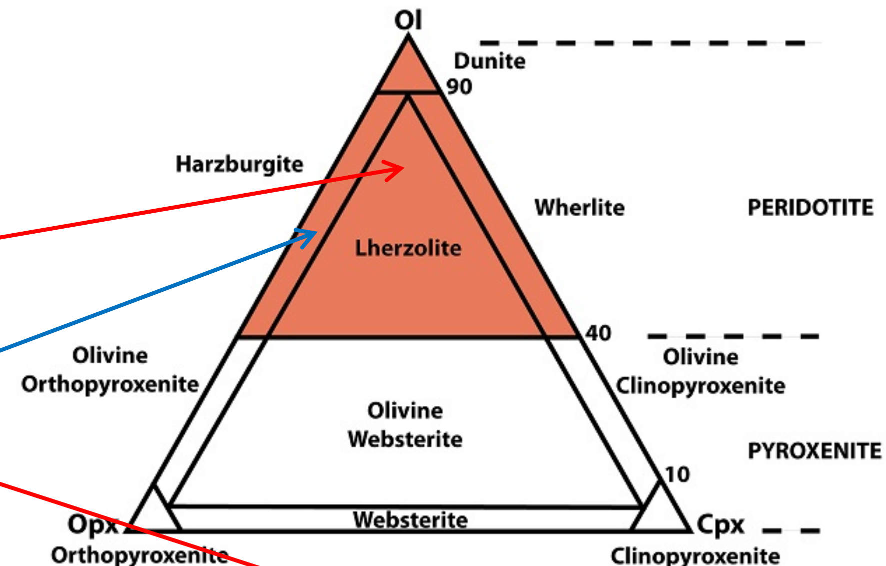
Meting trend



Summary of basic petrological concepts

Meting trend



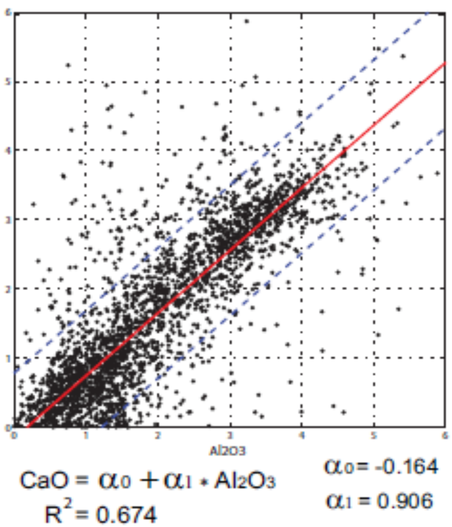


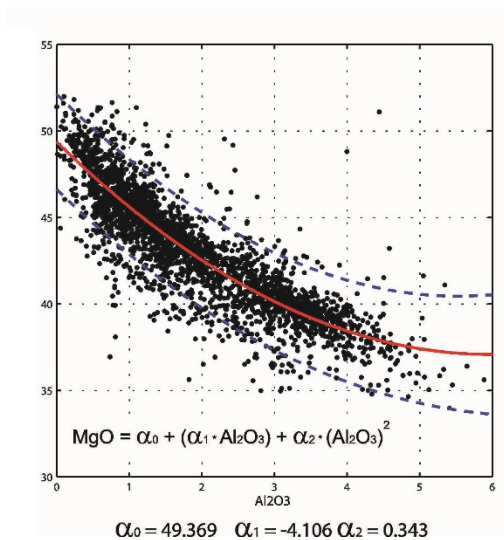
	1) Av. Harz. Lanzarote (wt%)[a]	2) Av. HEXO Tenerife (wt%)[b]	3) Av. Harz. La Palma av. (wt%)[c]	4) Av. HLCO Tenerife (wt%)[b]	5) Av. Ocean floor peridot. (wt%)[d]	6) Av. Middle Atlas (wt%)[e]
SiO_2	43.78	43.32	43.07	42.14	45.09	43.48
Al_2O_3	0.7	0.61	0.53	0.73	2.33	2.38
FeO	7.79	8.04	8.43	8.8	8.4	8
MgO	46.1	45.31	45.19	44.14	41.23	42.6
CaO	0.6	0.81	0.68	1.68	1.32	2.83
Na_2O	0.1	0.14	0.17	0.18	0.23	0.24
Mg#	91.34	90.96	90.53	89.94	89.7	90.47

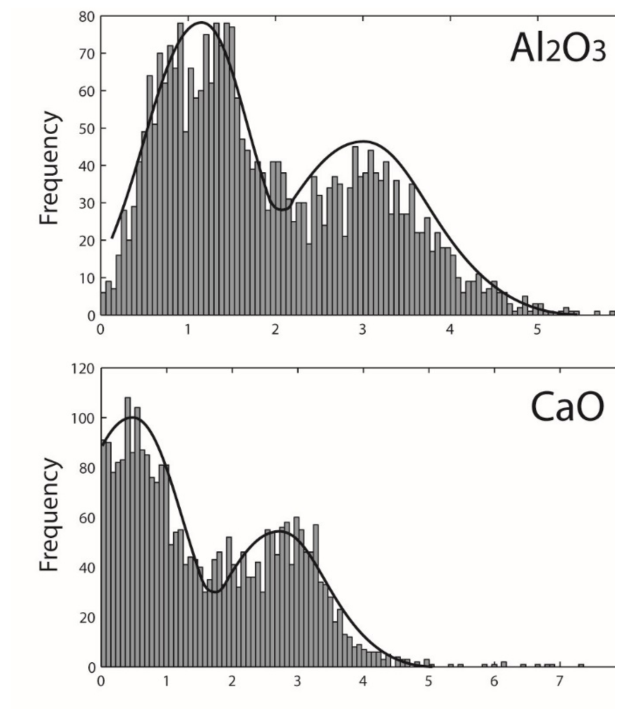
Mantle Depletion (partial melting) | *Mantle metasomatism (refertilization)*

Compositional space: world petrological data bases

*Five major oxides (CFMAS (CaO-FeO-MgO-Al2O3-SiO2).
* A priori petrological data base (>2900 samples from xenoliths, perid. massifs and ophiolites)



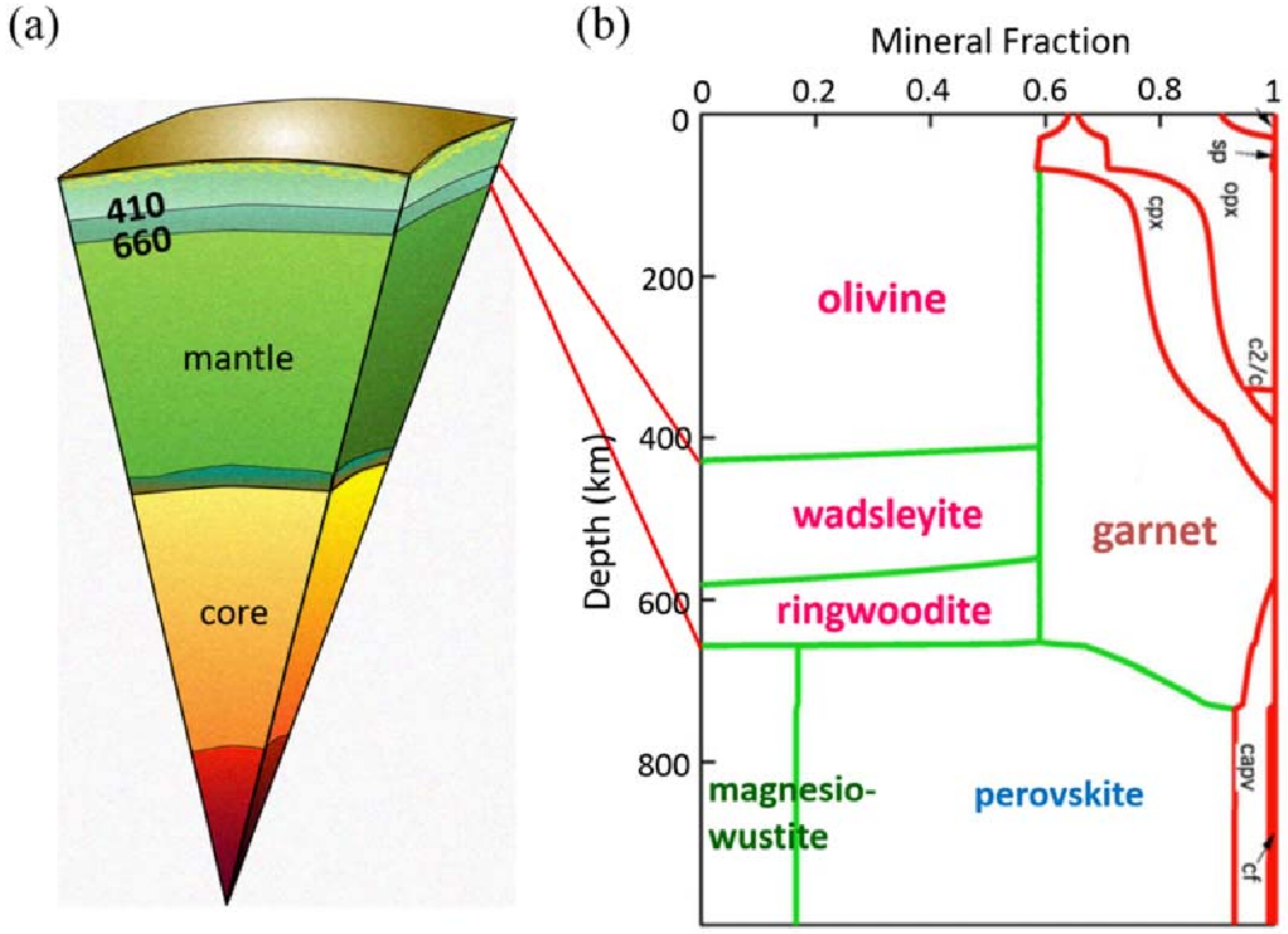




Correlation between oxides regardless of tectonic age or facies.
Al2O3 is strong compositional indicator, mainly through its control of modal garnet.

Possible bias in database (e.g. double peaks) due to sampling

Summary of basic petrological concepts

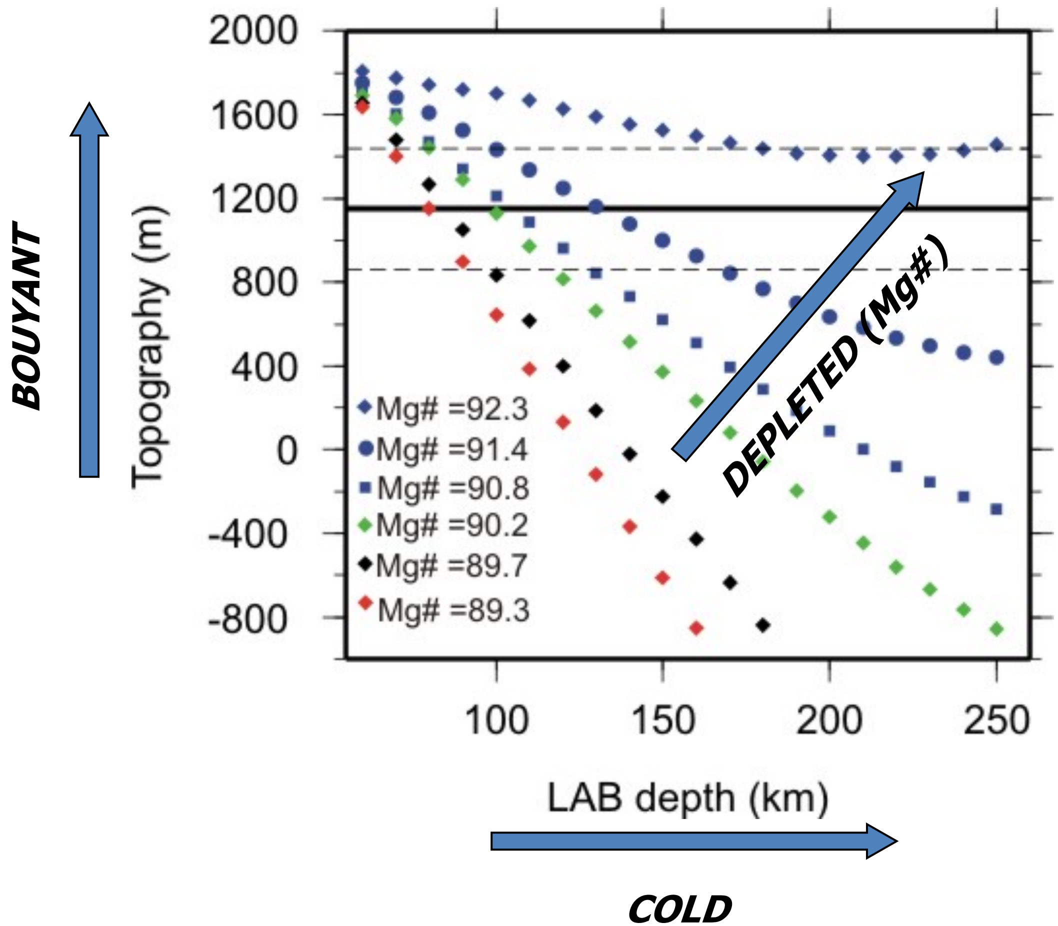


(From Ed Garnero's webpage)

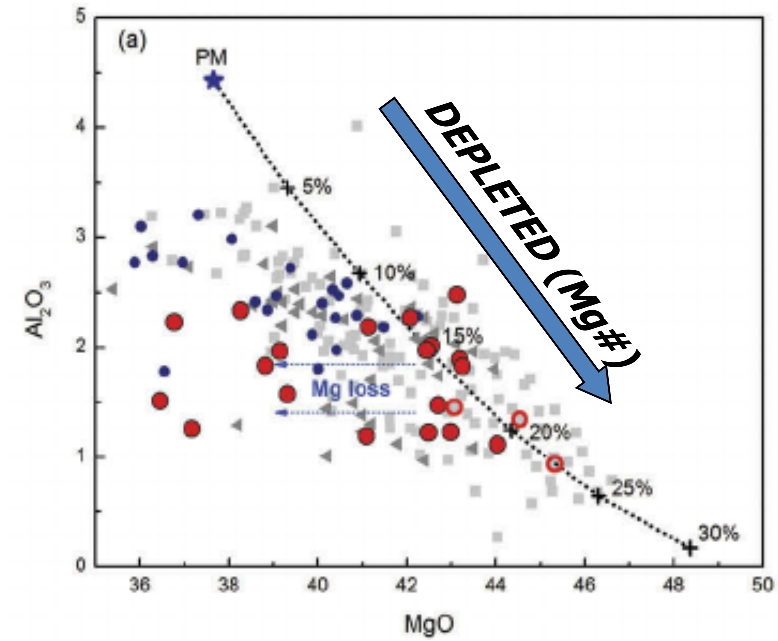
(Modified from Xu et al., 2008)

Summary of basic petrological concepts

Density=f(T,P,C)

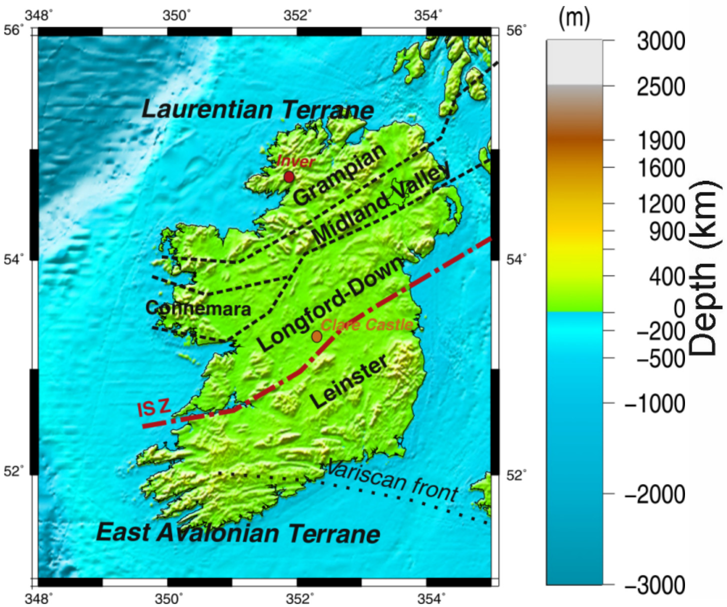


Mg#= MgO/(MgO+FeO)



➢ **Mantle density is anti-correlated with Mg#…**

Summary of basic petrological concepts



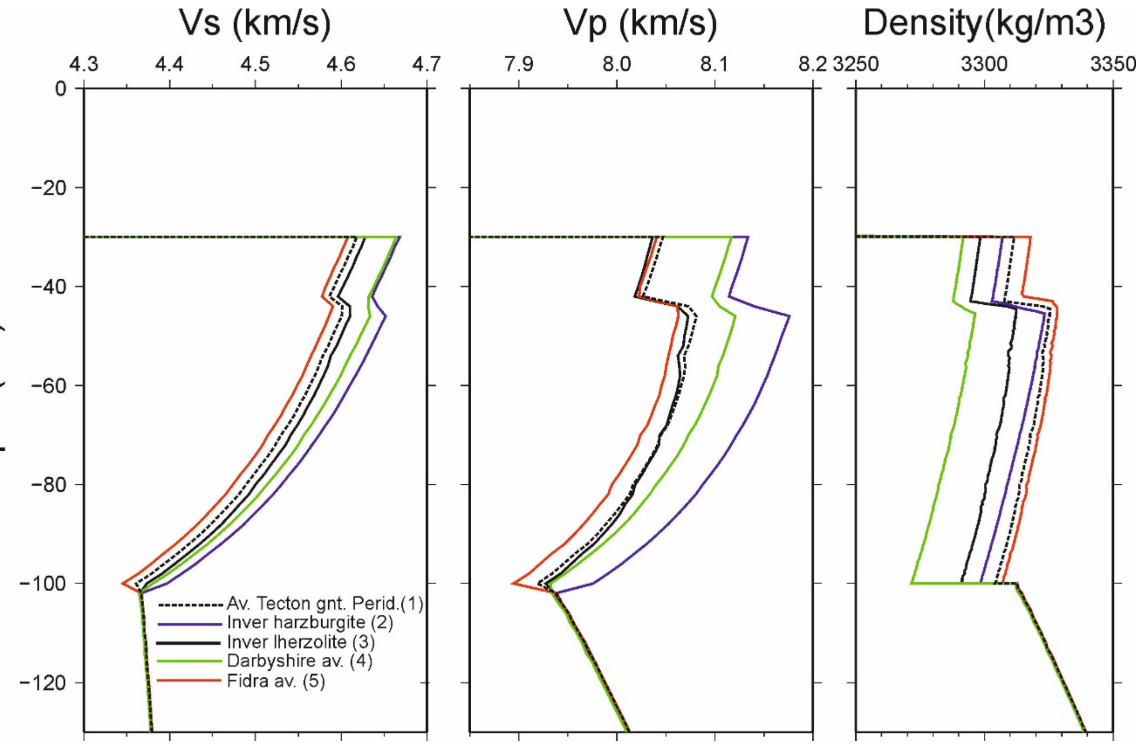


Table 1
Bulk mantle compositions used in this work from xenolith suites and peridotite massifs.

	1) Av. tecton gnt. perid. (wt.%)[a]	2) Harz. inver (wt.%)[b]	3) Lherz. inver (wt.%)[b]	4) Derbyshire av. (wt.%)[c]	5) Fidra av. (wt.%)[d]	6) PUM M&S95 (wt.%)[e]
SiO_2	45	41.7	45.84	43.4	44.31	45
TiO_2	0.16	–	–	0.02	0.15	0.201
Al_2O_3	3.9	2.65	3.92	2	3.5	4.45
Cr_2O_3	0.41	–	–	0.51	–	0.384
FeO	8.1	8.32	7.19	7.4	8.6	8.05
MnO	0.07	–	–	0.22	0.14	0.135
MgO	38.7	44.86	38.05	44.5	38.5	37.8
CaO	3.2	0.77	2.72	1.5	3.3	3.55
Na_2O	0.28	0.05	0.21	0.08	0.3	0.36
NiO	0.24	–	–	0.32	–	–
Total	100.06			99.95	99.8	99.93
Mg#	89.5	90.58	90.42	91.47	87.73	89.3

- ***Mantle density is a complex function of T and C (no shortcuts…)***

Density=f(T,P,C)

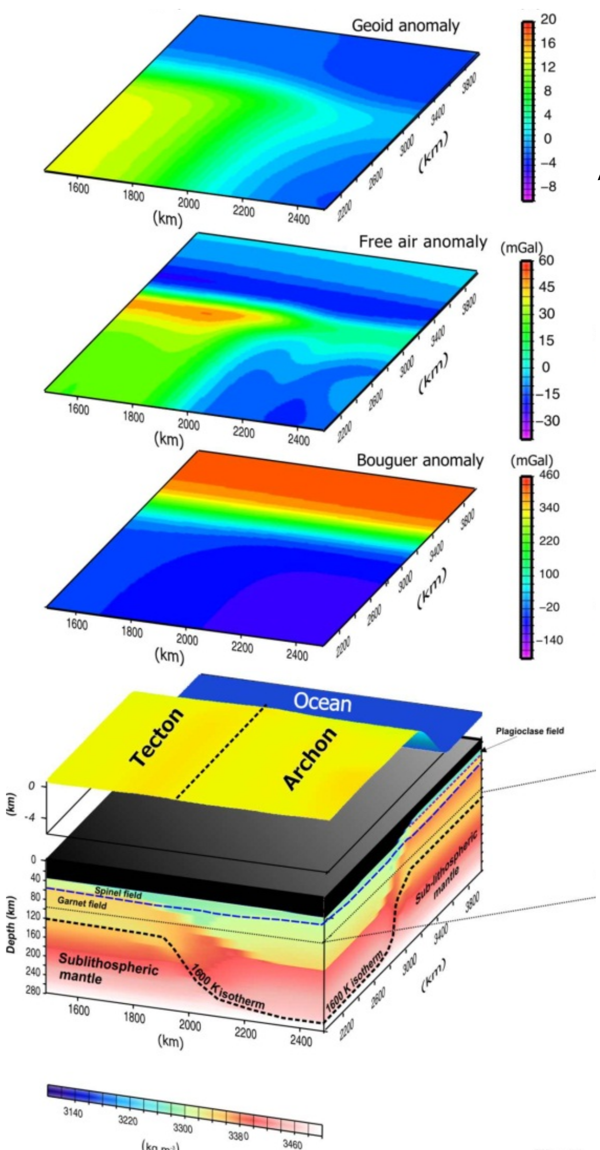
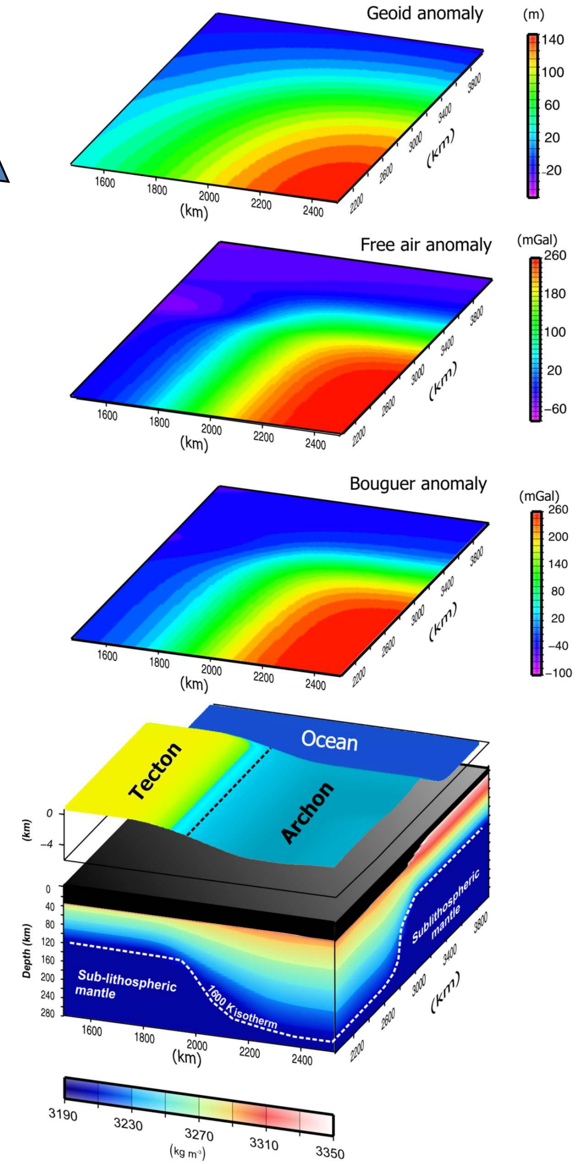


Fig 7

Same geotherm, different chemical layering

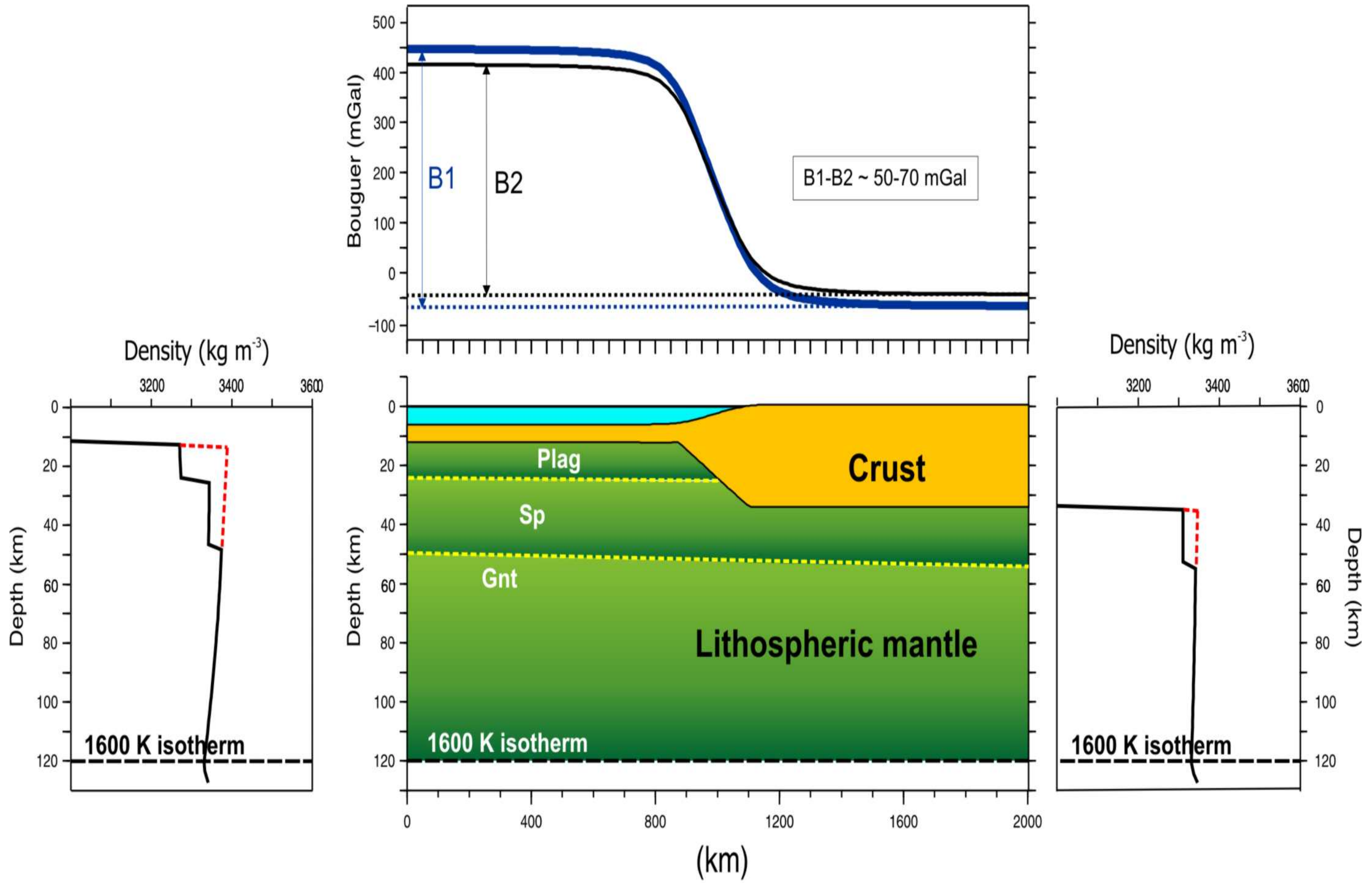
➢ ***Mantle has a strong impact in lithospheric density (buoyancy)!!***

Thermal approach



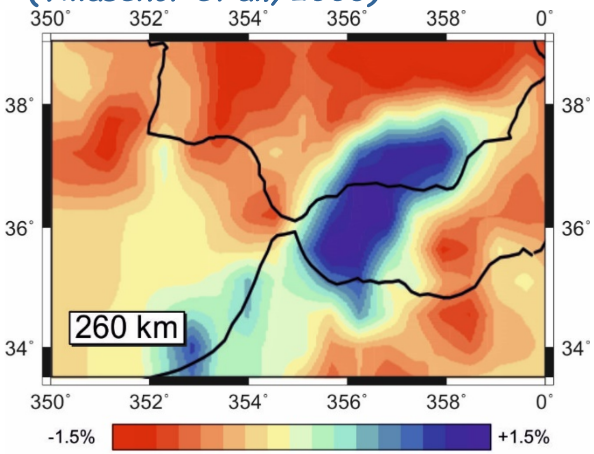
Upper mantle phase transitions

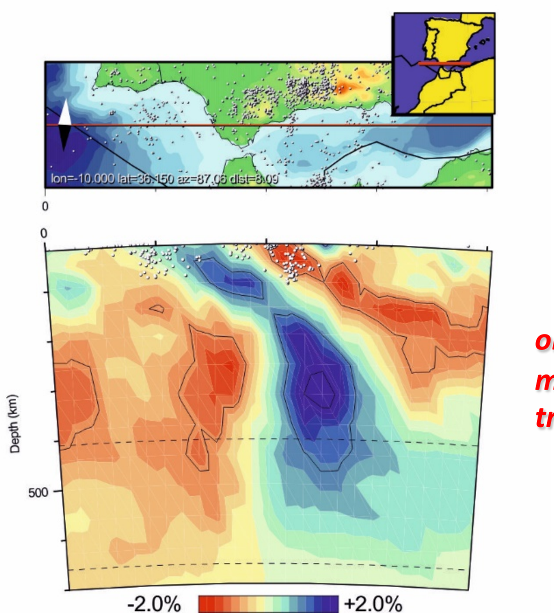
Differences in synthetic Bouguer anomaly due to shallow phase transitions (Al-bearing minerals)

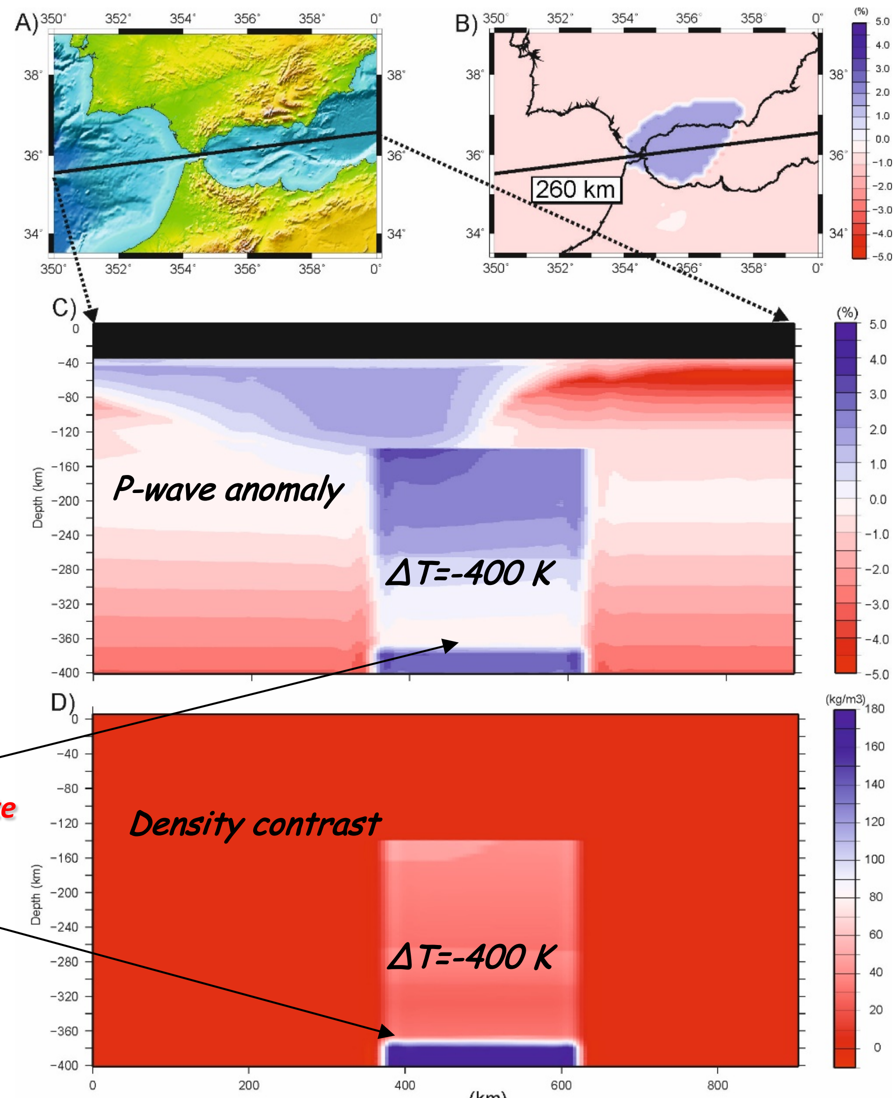


Simplified slab with ΔT=-400 K with respect to ambient mantle based on geodynamic modelling of the Alboran Sea since upper Oligocene (Fullea et al. 2015)

P-wave anomaly seismic tomography model (Villaseñor et al., 2003)

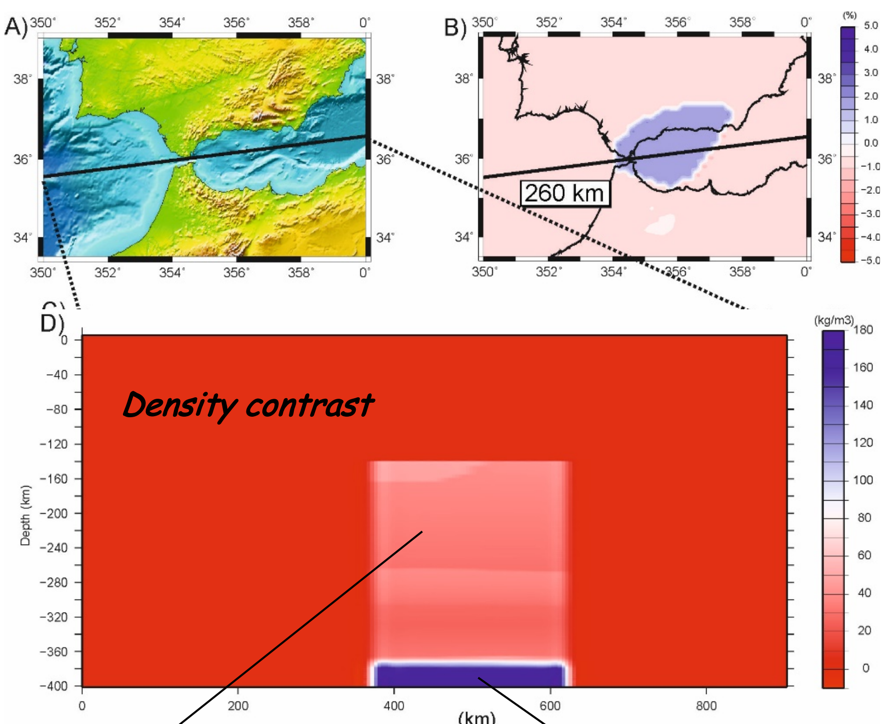






olivine→wadsleyite mineral phase transition

Simplified slab with ΔT=-400 K with respect to ambient mantle based on geodynamic modelling of the Alboran Sea since upper Oligocene (Fullea et al. 2015)



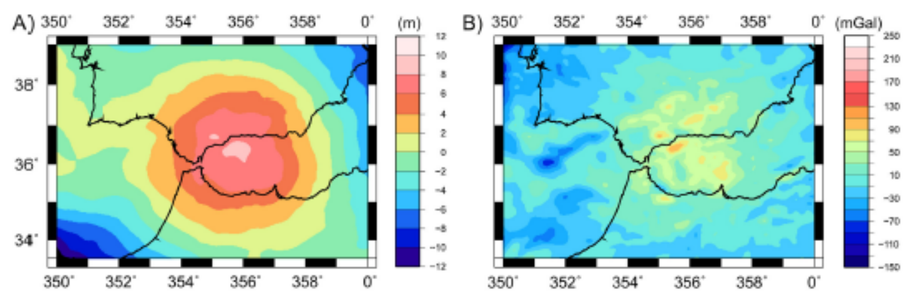
thermal
Δρ=+25-40 kg/m^3

Thermal+phase change
Δρ=+160 kg/m^3

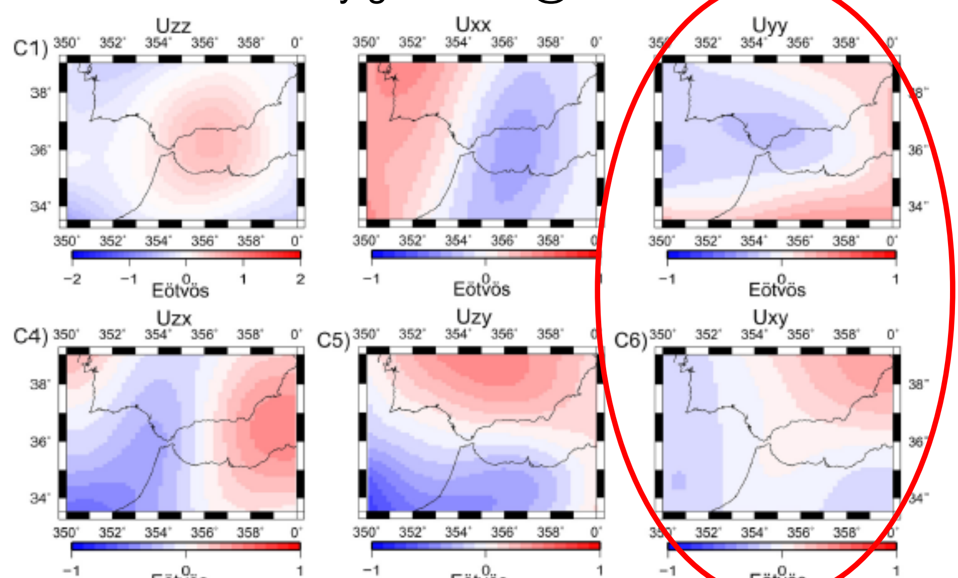
Sublithospheric thermal anomaly effect on gravity field

Geoid anomaly

Bouguer anomaly



Gravity gradients @ 255 km

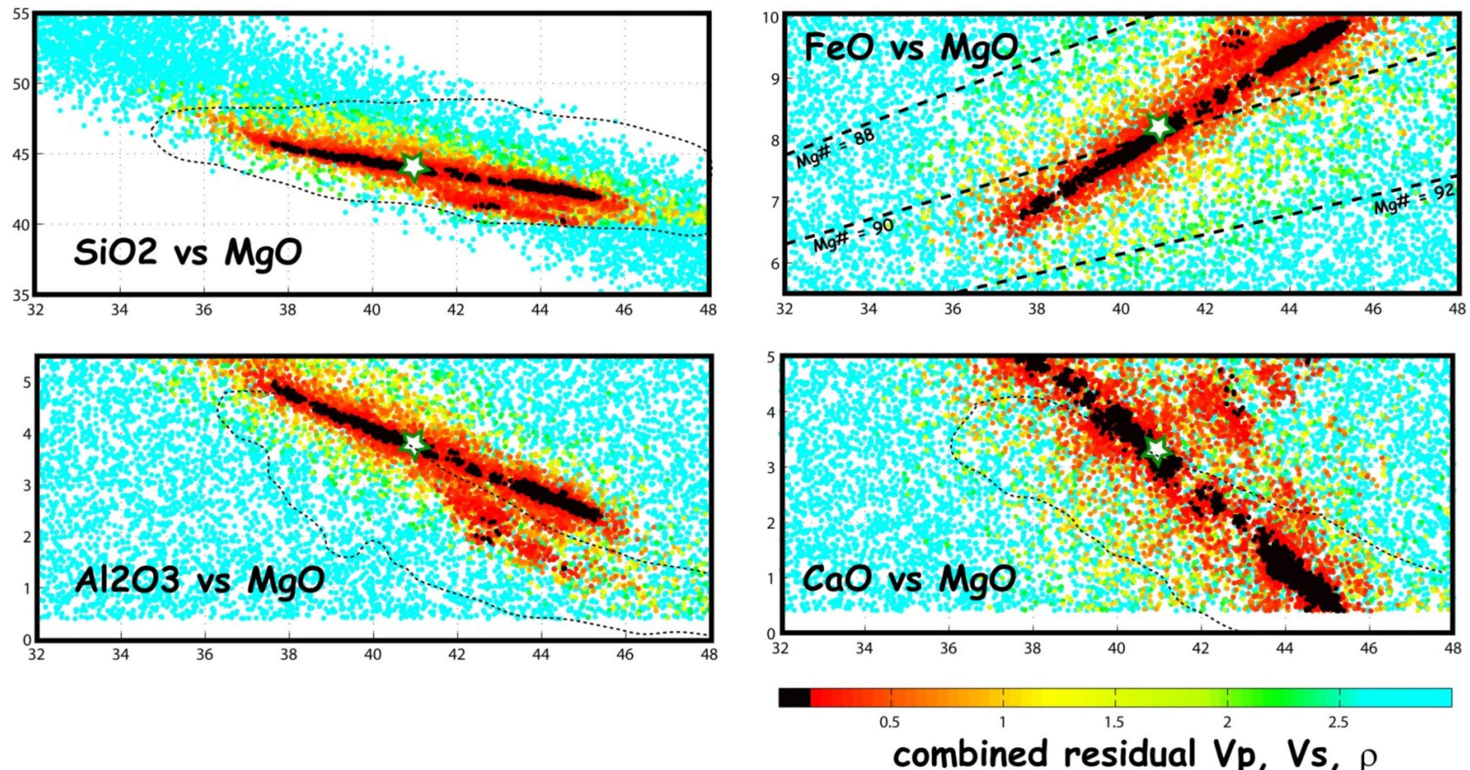


Weaker effect in xy and yy in components

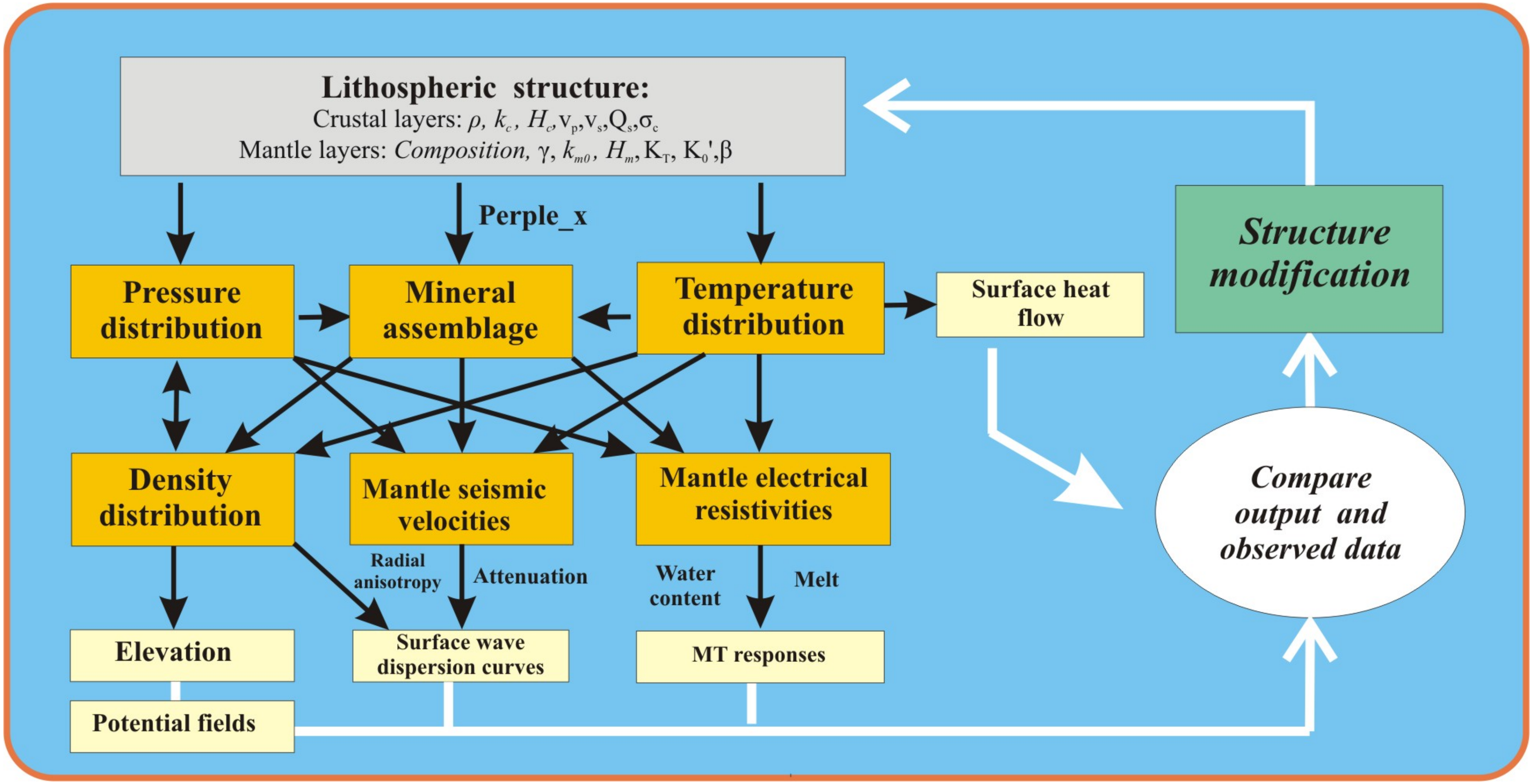
Complex parameter space

* Trade-offs between Temperature and Composition
* T has a greater effect than C in most of the observables
* Non uniqueness of compositional field (worse in the lithosphere than in the sublithosphere)

$$\sigma(\mathbf{m}) = k\rho(\mathbf{m})L(\mathbf{m}) \qquad L(\mathbf{m}) \propto \exp\left\{-\frac{1}{2}[g(\mathbf{m})-\mathbf{d}_{\text{obs}}]^T C_D^{-1}[g(\mathbf{m})-\mathbf{d}_{\text{obs}}]\right\}$$



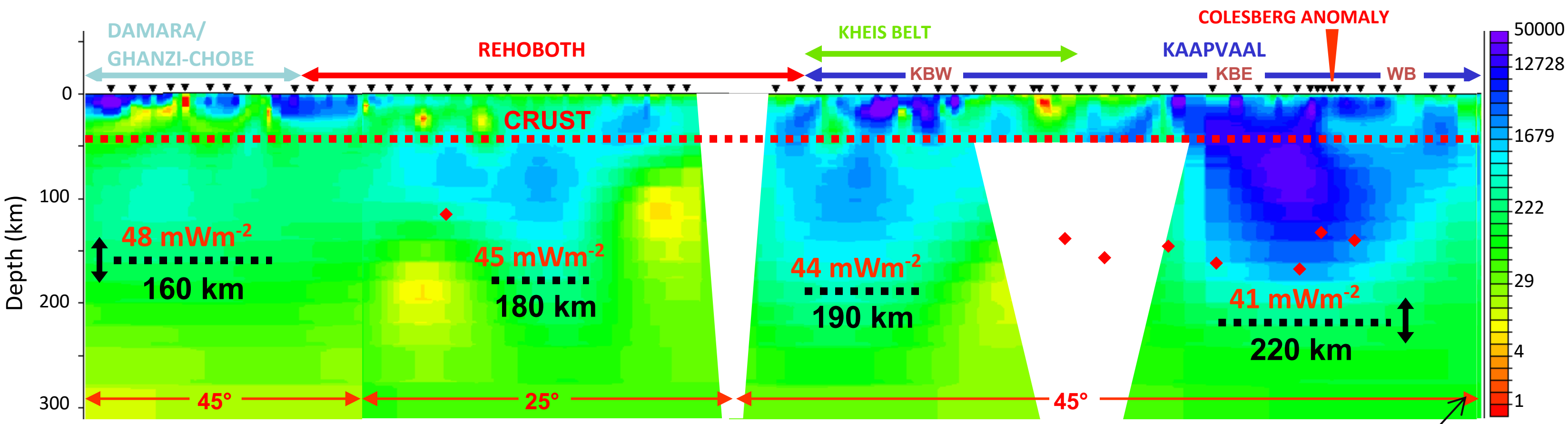
Integrated forward modelling: work flow

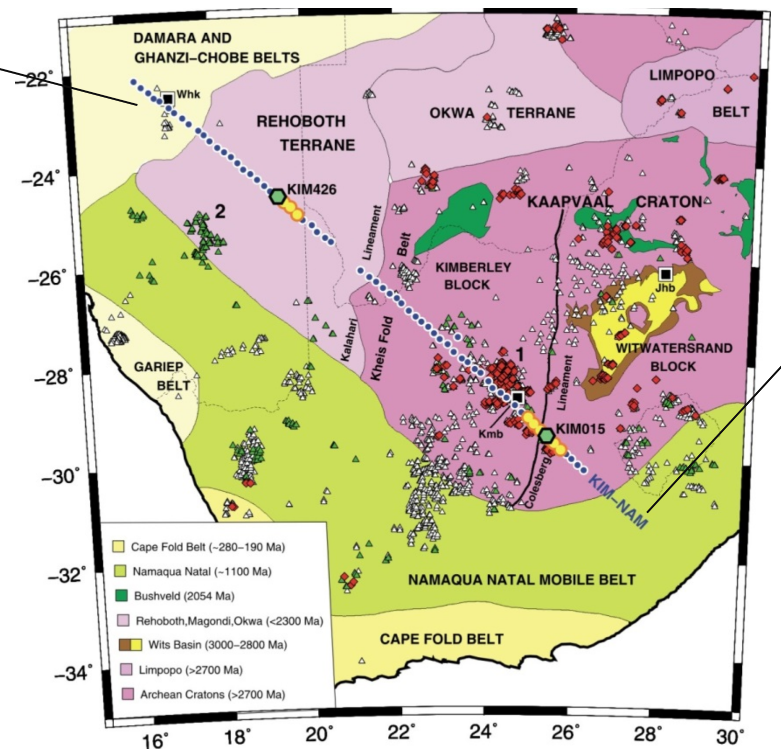


Integrated modelling Magnetotelluric data

(Kaapvaal craton)

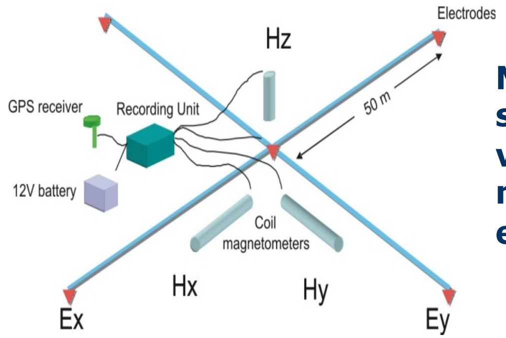
Kaapvaal craton (S. Africa): 2D magnetotelluric (MT) model





SAMTEX (e.g., Muller et al., 2009, Evans et al., 2011)

Magnetotellurics (MT)



MT site: simultaneous variations of magnetic and electric fields

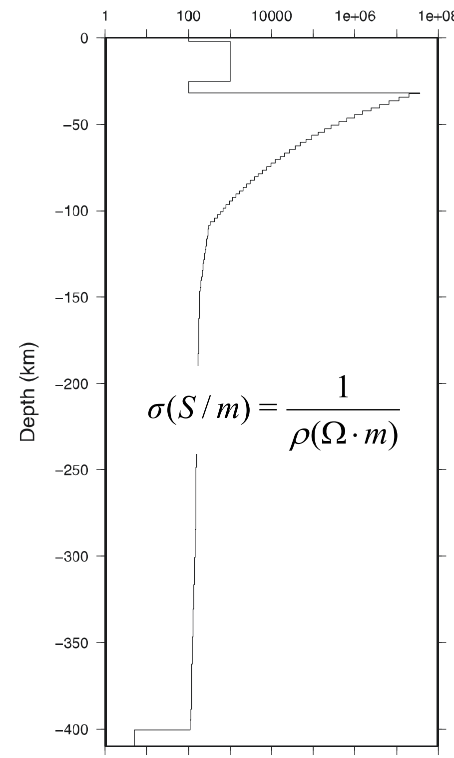
Apparent resistivity

$$\rho_{a,xy}(\omega) = \frac{1}{\omega\mu}\left|\frac{E_x(\omega)}{H_y(\omega)}\right|^2$$

Phase

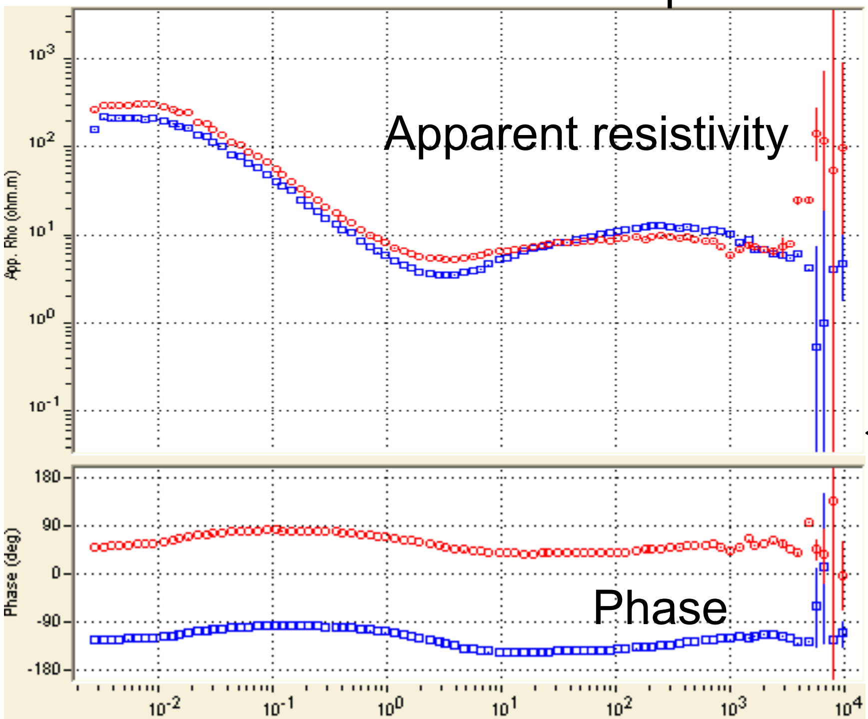
$$\varphi_{xy}(\omega) = \tan^{-1}(E_x(\omega)/H_y(\omega))$$

Resistivity (1/Conductivity)



$$\sigma(S/m) = \frac{1}{\rho(\Omega \cdot m)}$$

Processed MT station response



MT inversion

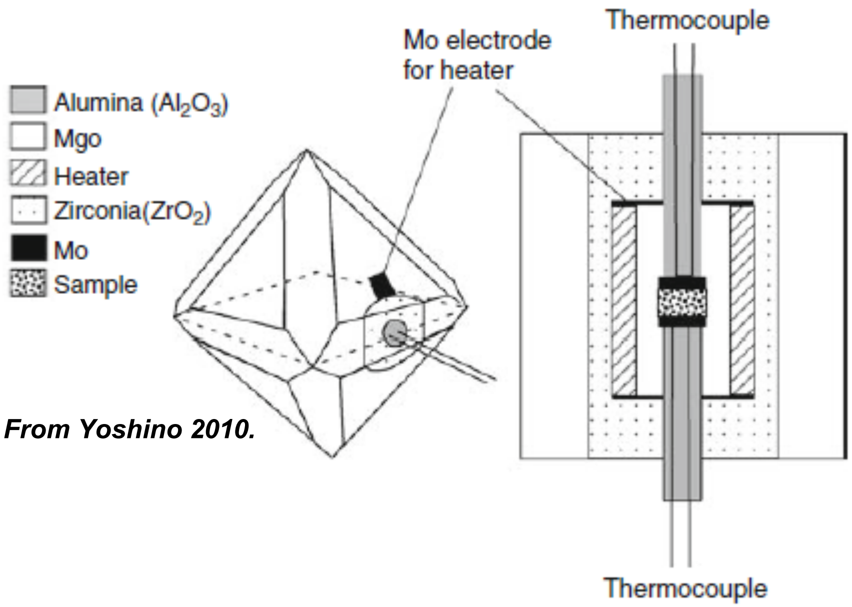
Forward modeling

Mineral physics+lab experiments

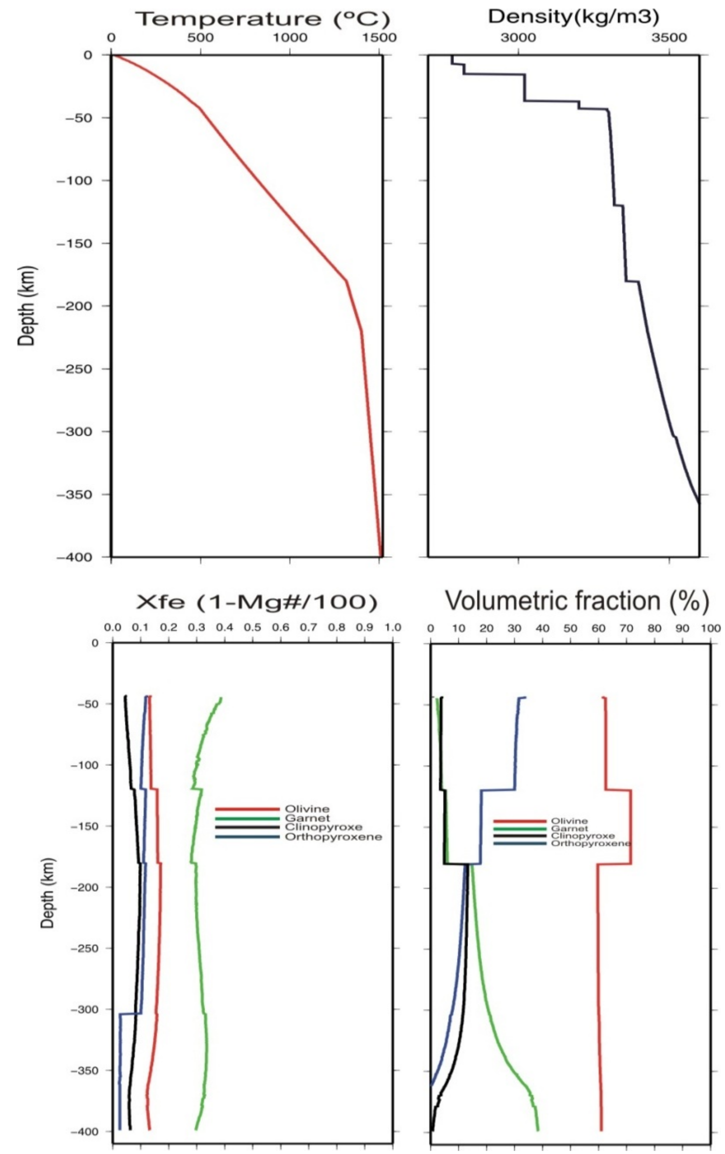
Temperature, pressure and composition

Electrical conductivity: lab experiments and mineral physics

Experimental measurements of conductivity in single crystals or mineral aggregates



From Yoshino 2010.



The electrical conductivity of the mantle minerals is typically of the form:

$$\sigma = \sigma_0 \exp\left(\frac{-\Delta H(X_{Fe},P)}{k_B T}\right) + f(C_w)\exp\left(\frac{-\Delta H_{wet}(C_w)}{k_B T}\right) + \sigma_{0i}\exp\left(\frac{-\Delta H_i}{k_B T}\right)$$

small polaron (electron hopping between ferric Fe3+ and ferrous Fe2+ ions) at T<1300 ºC

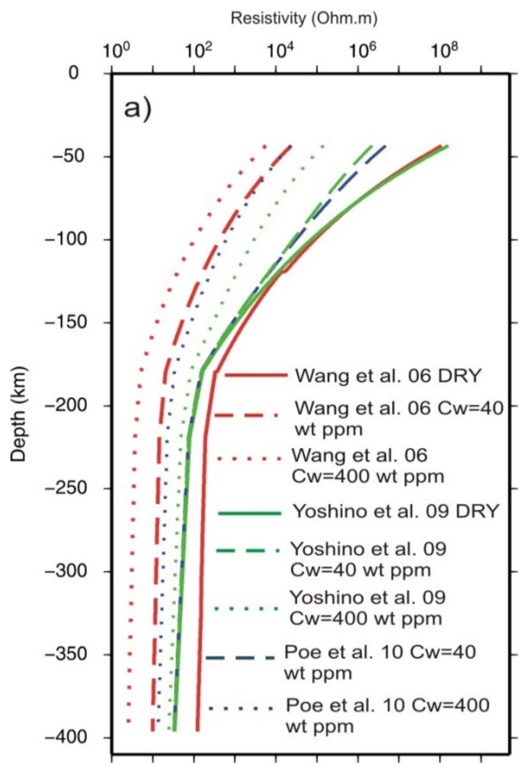
Proton conduction (H+ bound to structural O atoms)

Ionic conduction (Mg vacancies) T>1300 ºC

Electrical conductivity: the water problem

Laboratory uncertainties/discrepancies

olivine



For olivine there are two models for proton conduction based on lab studies:

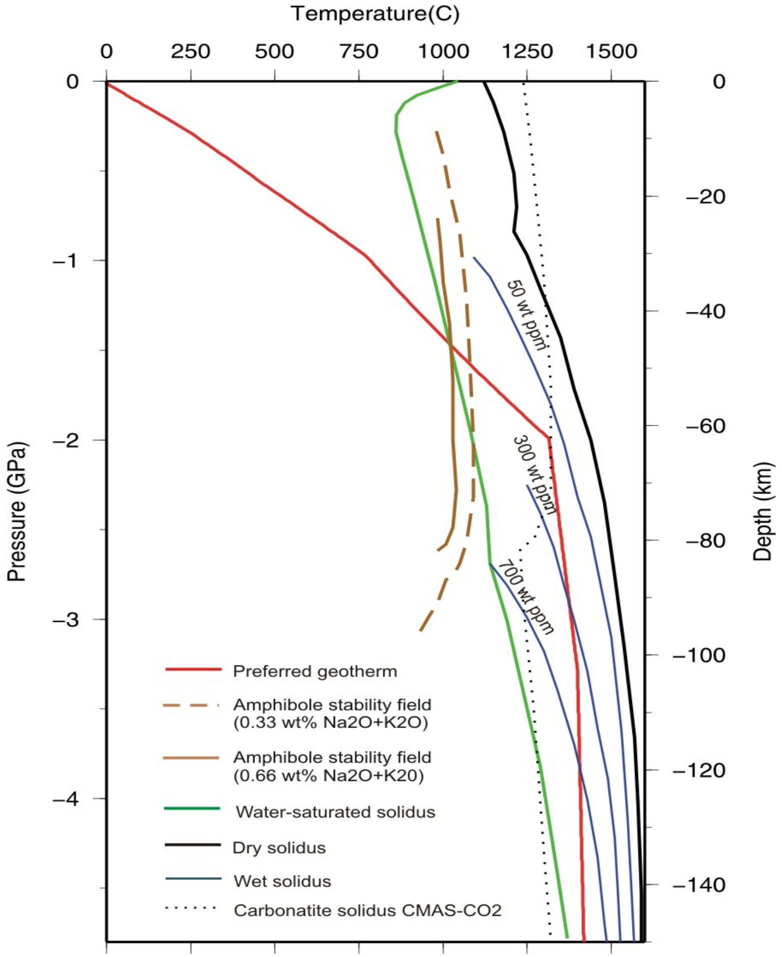
$$\sigma_P = \sigma_{0p} C_w \exp\left(\frac{-\left(\Delta H_0 - \alpha C_w^{1/3}\right)}{k_B T}\right)$$

e.g. Yoshino et al., 09; Manthilake et al., 09 ; Poe et al., 10

$$\sigma_P = A C_w^r \exp\left(\frac{-\Delta H_{wet}}{k_B T}\right)$$

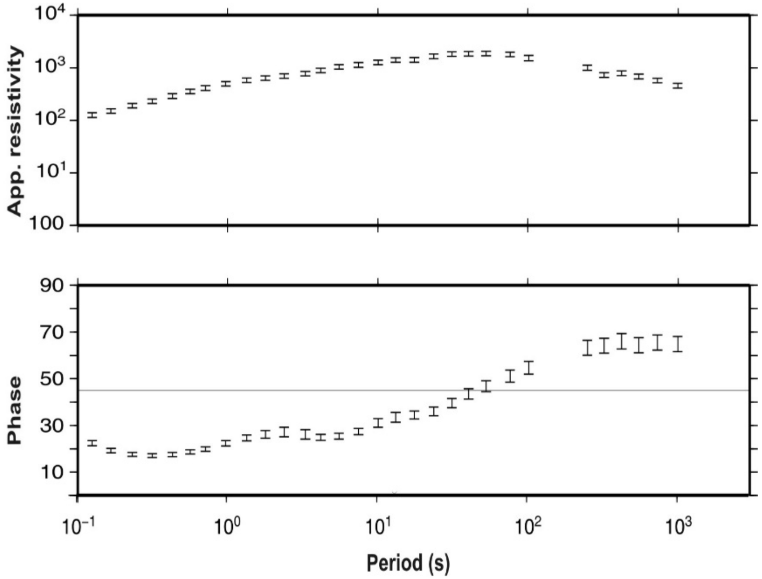
e.g. Wang et al., 06; Dai and Karato 09

Peridotite solidus

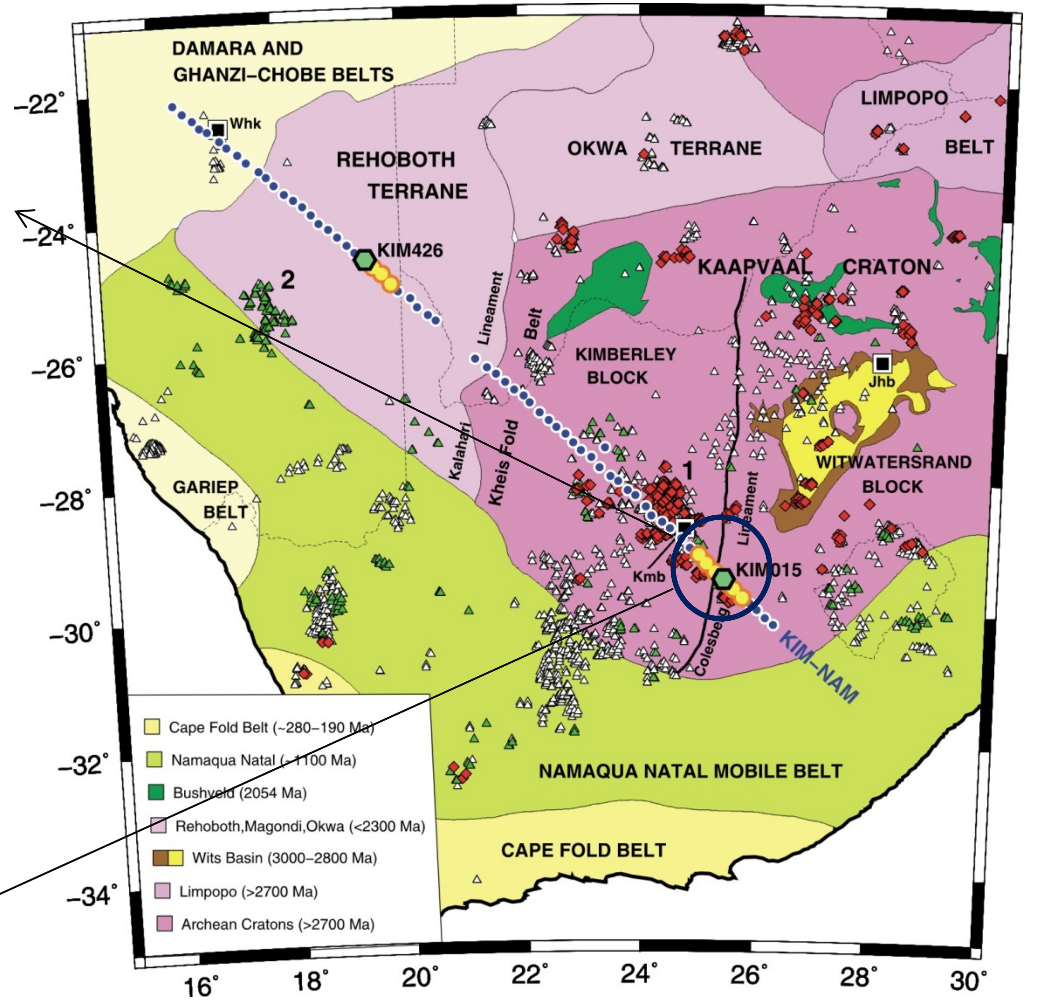


From Asimow et al. (2004)

observed MT responses



SAMTEX (e. g., Jones et al., 2009; Muller et al., 2009, Evans et al., 2011, Miensopust et al., 2001)



The error bars reflect: the maximum of the data processing errors + Groom and Bailey decomposition model errors + departure from a 1D (differences between the TM and TE modes)

Elevation=1.34 km

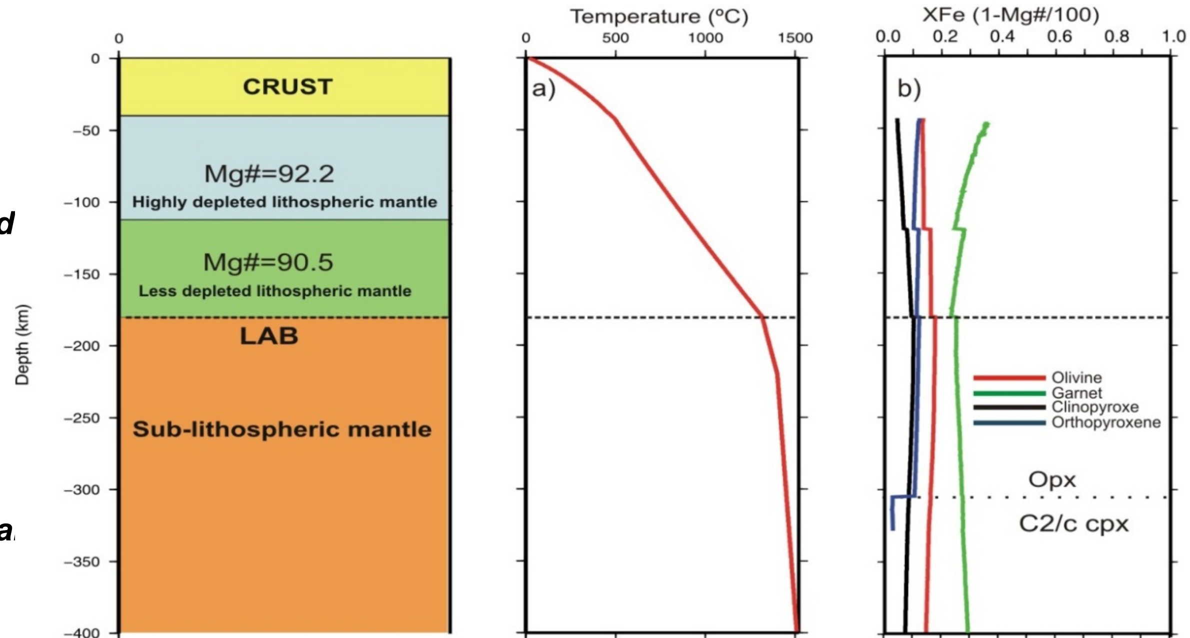
S. Heat flow=38-45 mW/m2

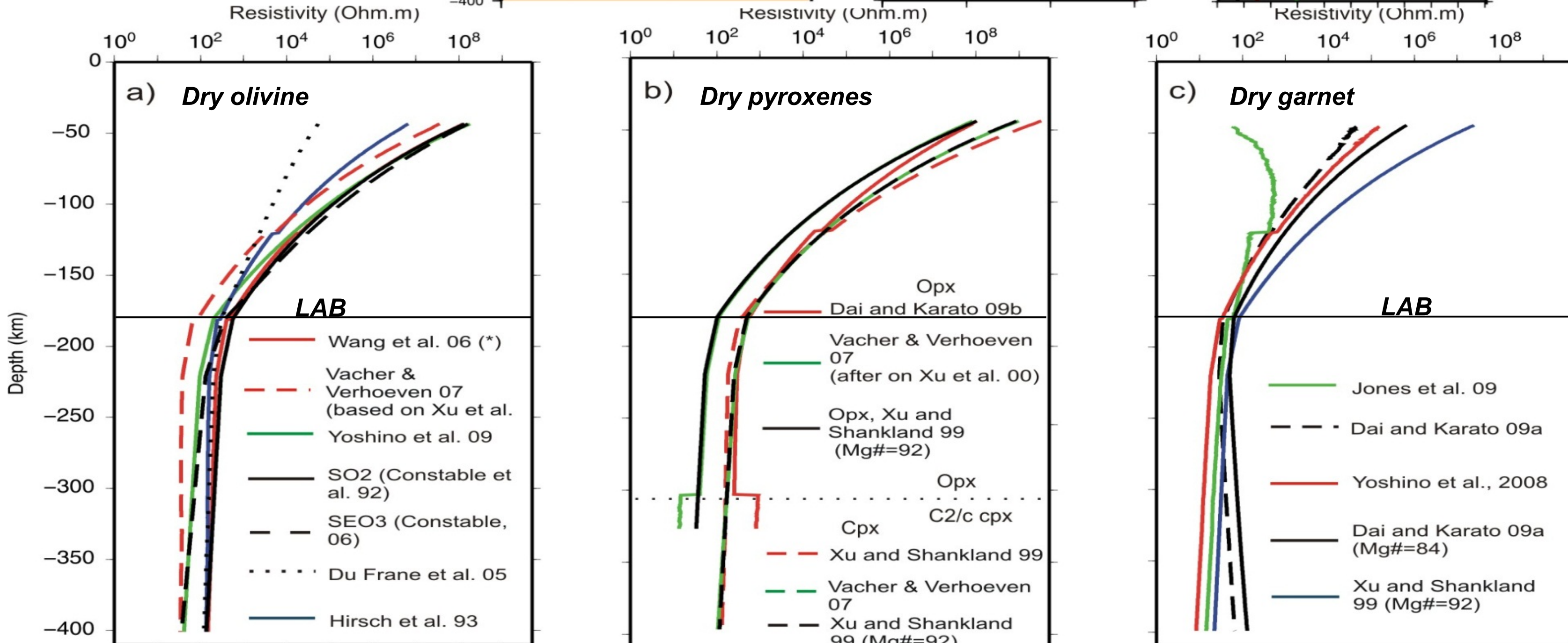
Electrical condutivity of the upper mantle: lab mineral studies (dry)

The electrical conductivity of upper mantle minerals accord to lab experiments:

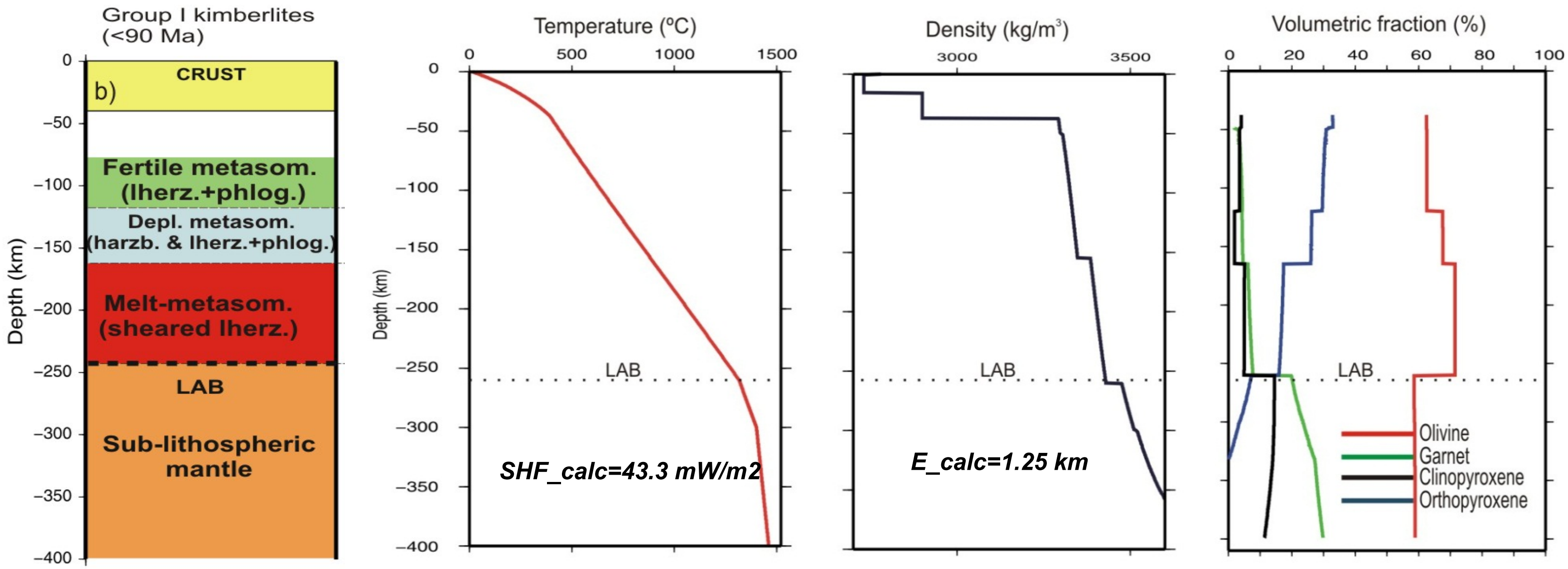
** Depends strongly on temperature*

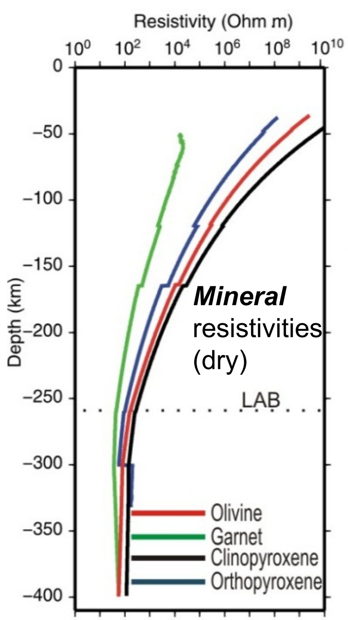
** Compostion and pressure a second order effects*





Electrical conductivity of the upper mantle: Kaapvaal (dry)





Hashin Shtrikman bounds

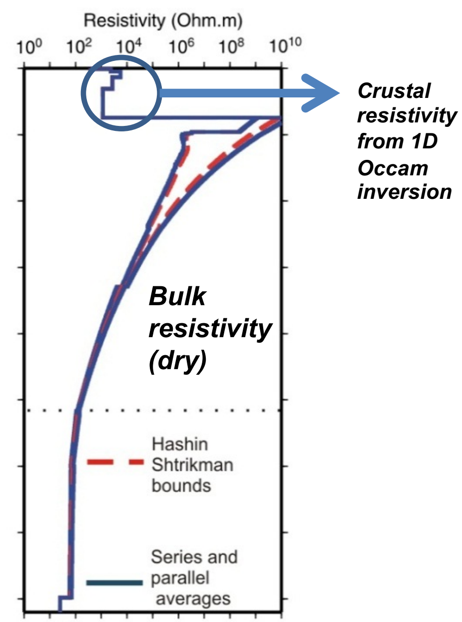
$$\sigma_{HS}^{-} = \left(\sum_{i=1}^{N} \frac{v_i}{\sigma_i + 2\sigma_{min}} \right)^{-1} - 2\sigma_{min}$$

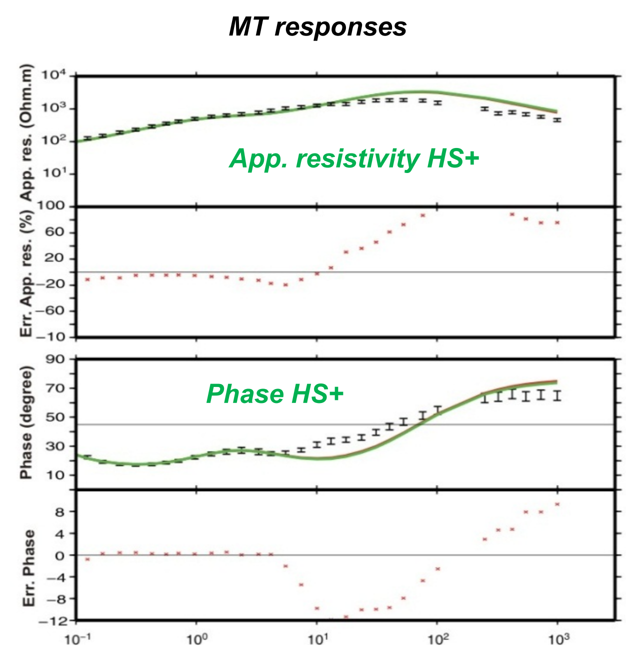
$$\sigma_{HS}^{+} = \left(\sum_{i=1}^{N} \frac{v_i}{\sigma_i + 2\sigma_{max}} \right)^{-1} - 2\sigma_{max}$$

Series and parallel averages

$$\sigma_S = \left(\sum_{i=1}^{N} \frac{v_i}{\sigma_i} \right)^{-1}$$

$$\sigma_P = \left(\sum_{i=1}^{N} \sigma_i v_i \right)$$

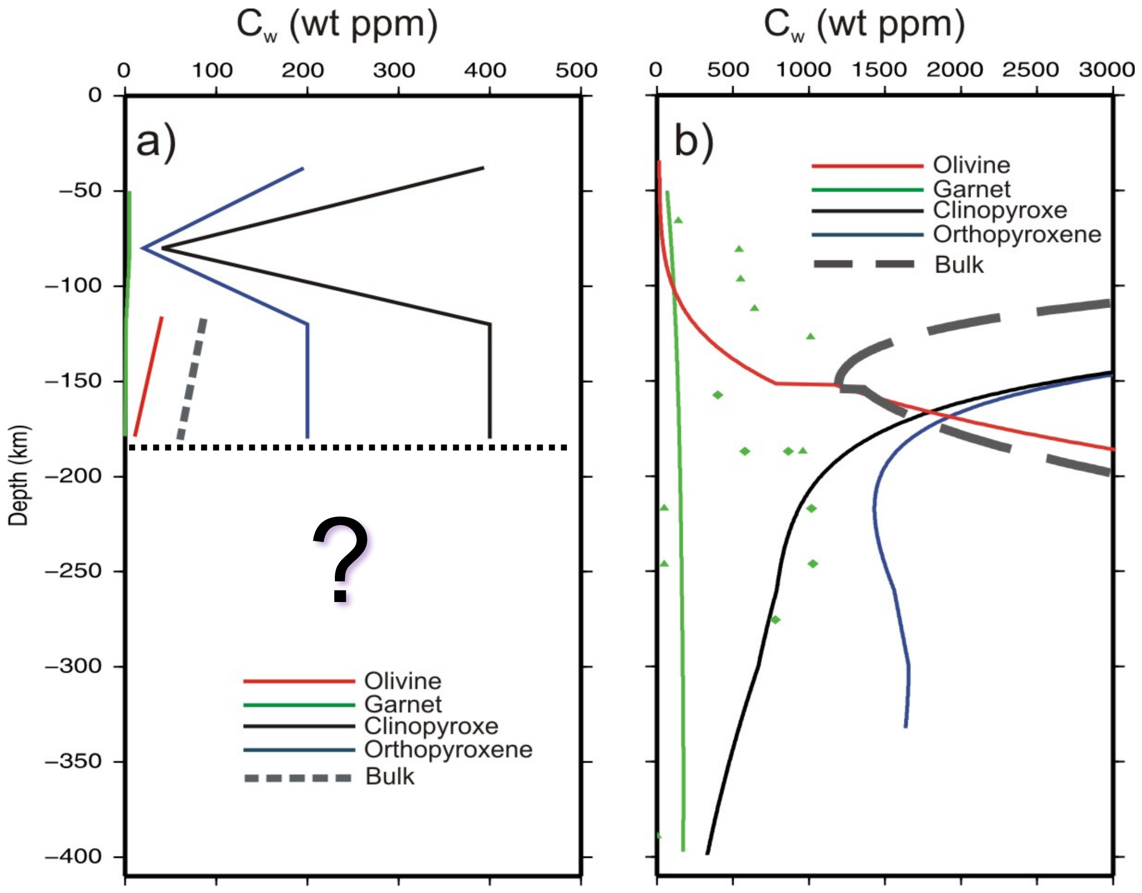




Electrical conductivity of the upper mantle: water content

Water content measurements from xenoliths, Kaapvaal craton

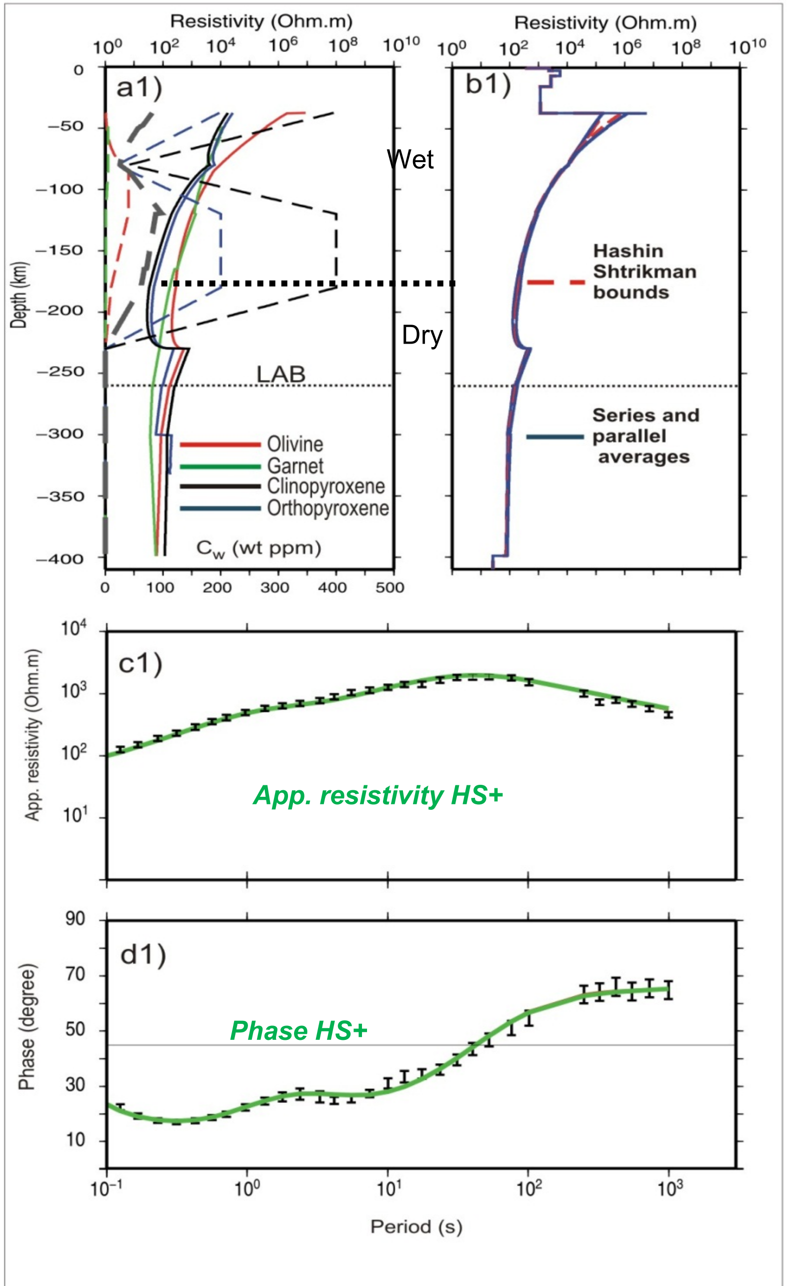
Water solubility from lab studies

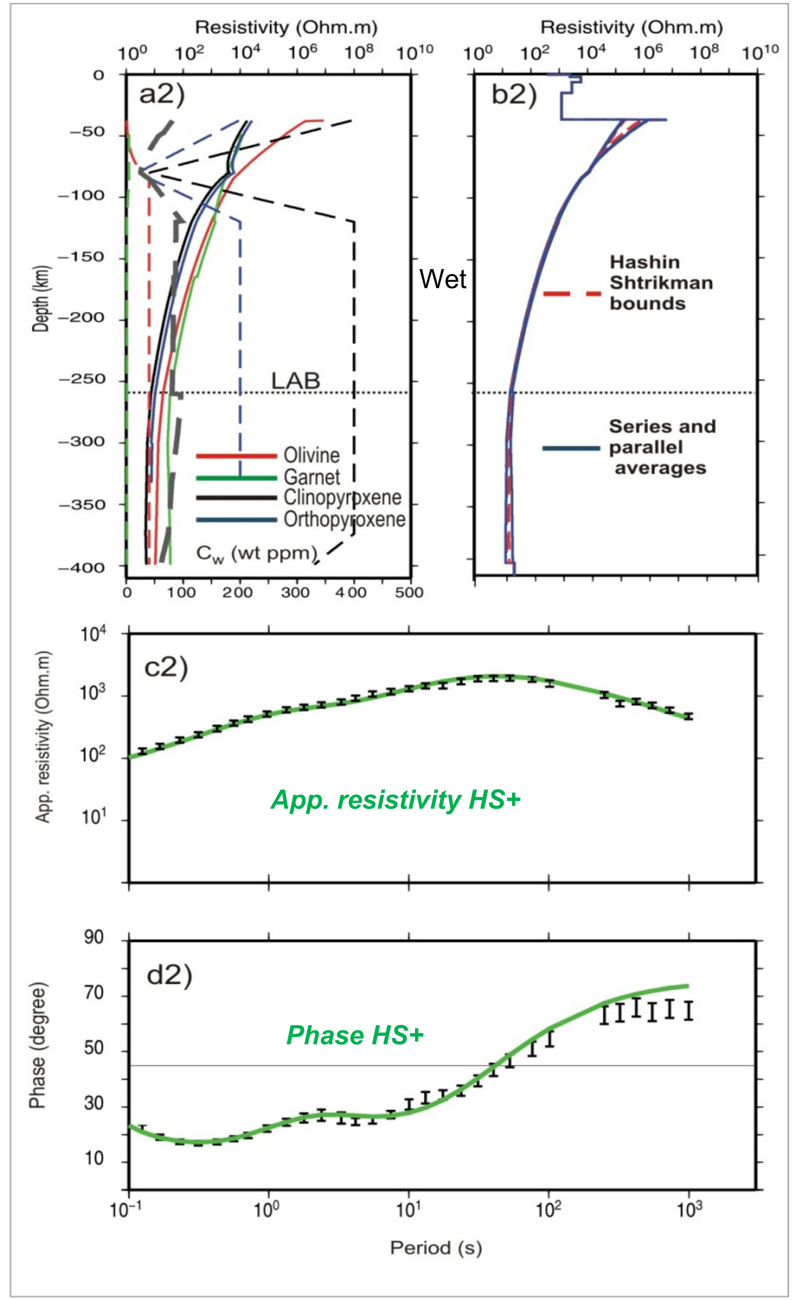


(Peslier, 2009; Grant et al., 2007)

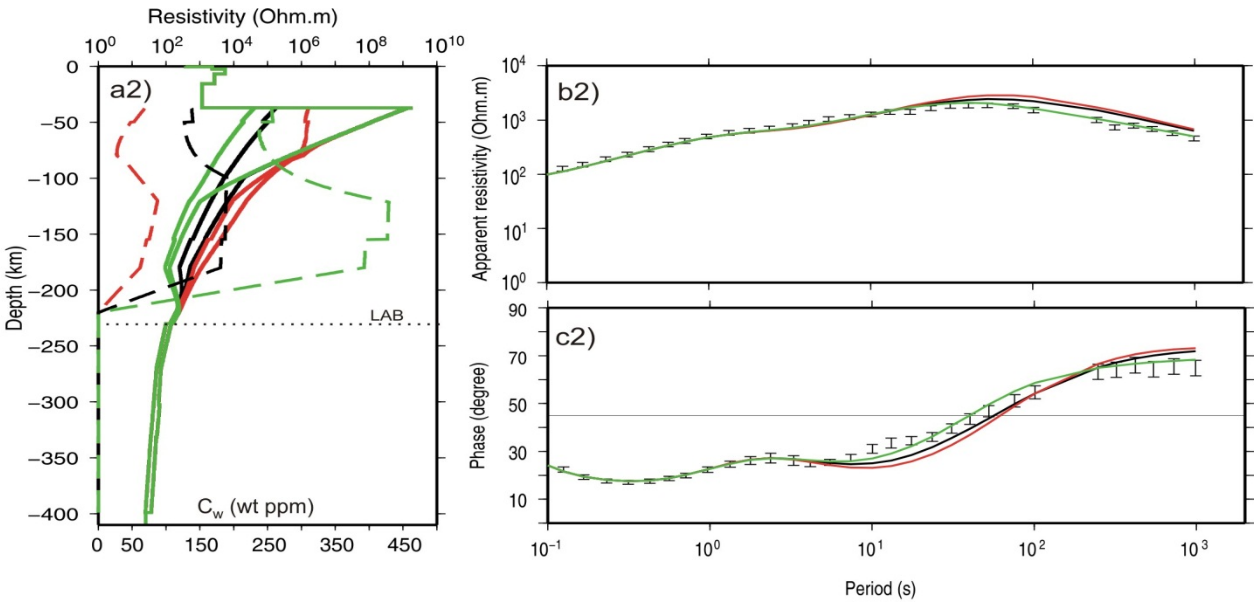
(Zhao et al., 2004; Mierdel et al., 2007; Gavrilenko, 2008; Lu and Keppler, 1997)

Electrical conductivity of the upper mantle: Kaapvaal (wet)

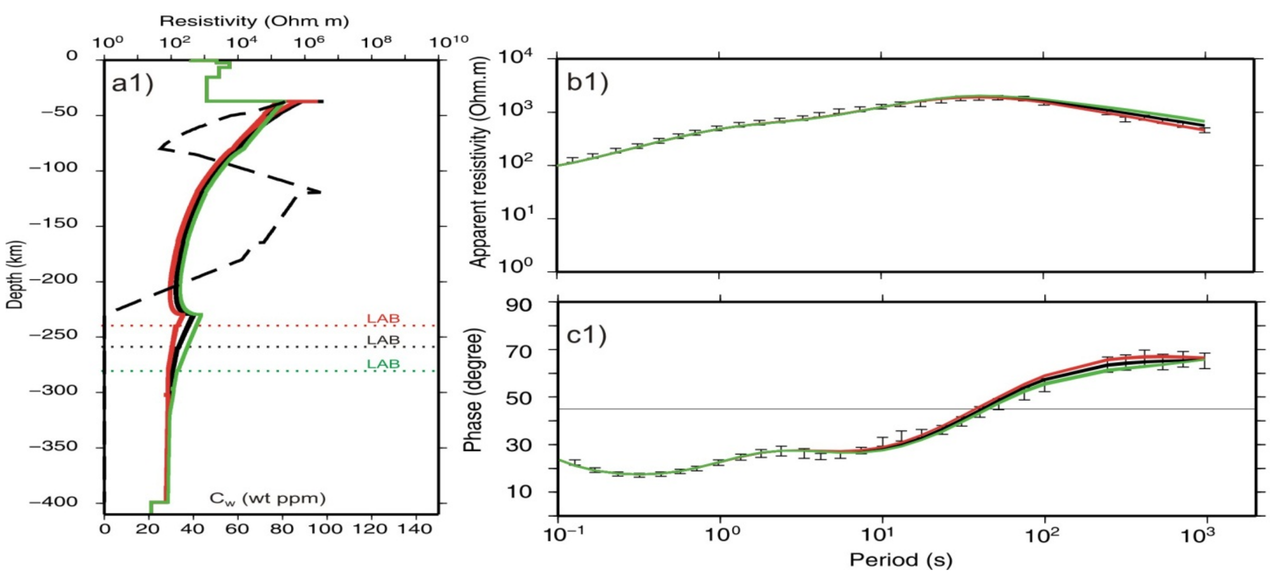




Electrical conductivity of the upper mantle: Sensitivity tests

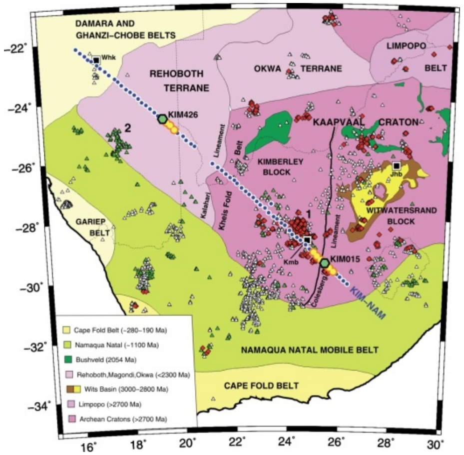


Water content upper most lithospheric mantle: 60-450 ppm



Lithosphere-asthenosphere boundary depth (thermal): 230-260 km

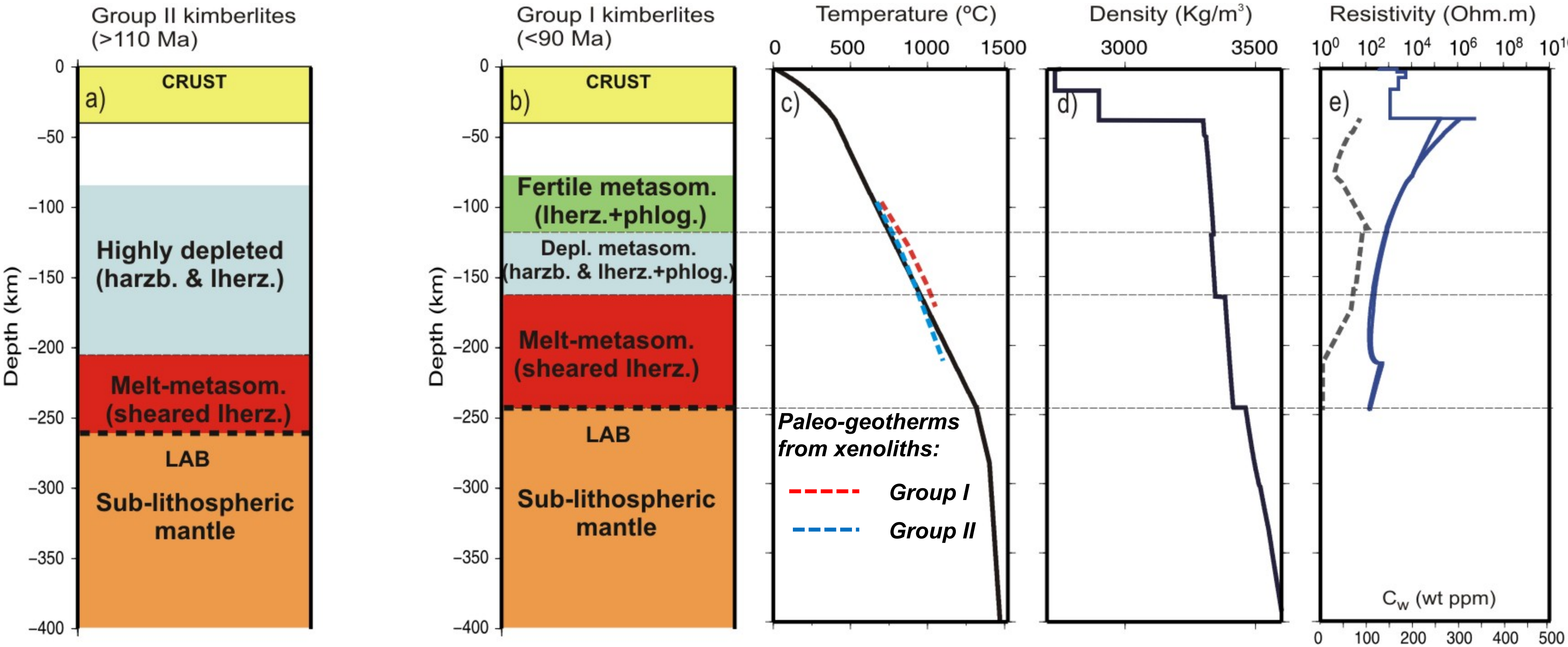
Kimberley block, Kaapvaal craton



Concluding remarks:

** Thermal LAB (230-260 km) consistent with previous seismic and 2D MT studies.*

** Map water content in the lithosphere: wet upper most metasomatized and harburgitic layers, dry melt-metasomatized sheared lherzolites in the lower lithosphere.*

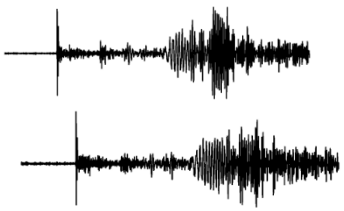


(Griffin et al., 2003; O'Reilly et al. 2010 ; Fullea et al., 2011)

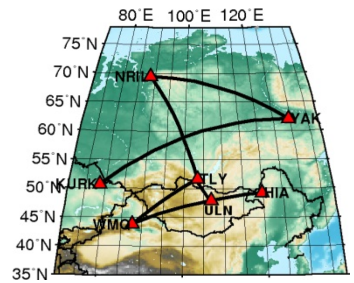
Integrated modelling surface wave data

(Central Mongolia)

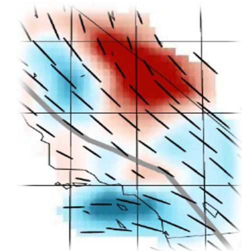
LitMod1D : Surface waves



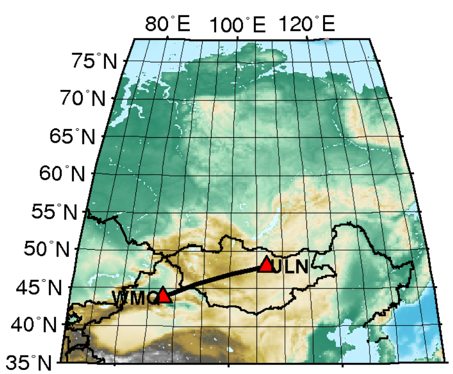
seismograms

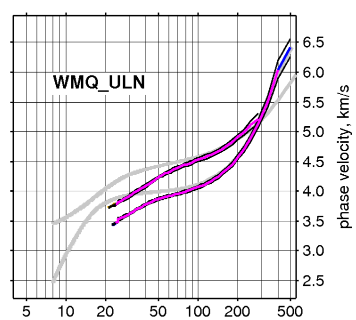


inter-station, array measurements

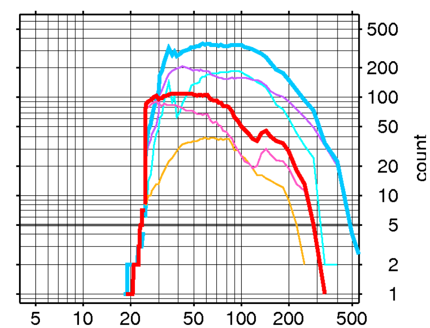


high-resolution regional tomography





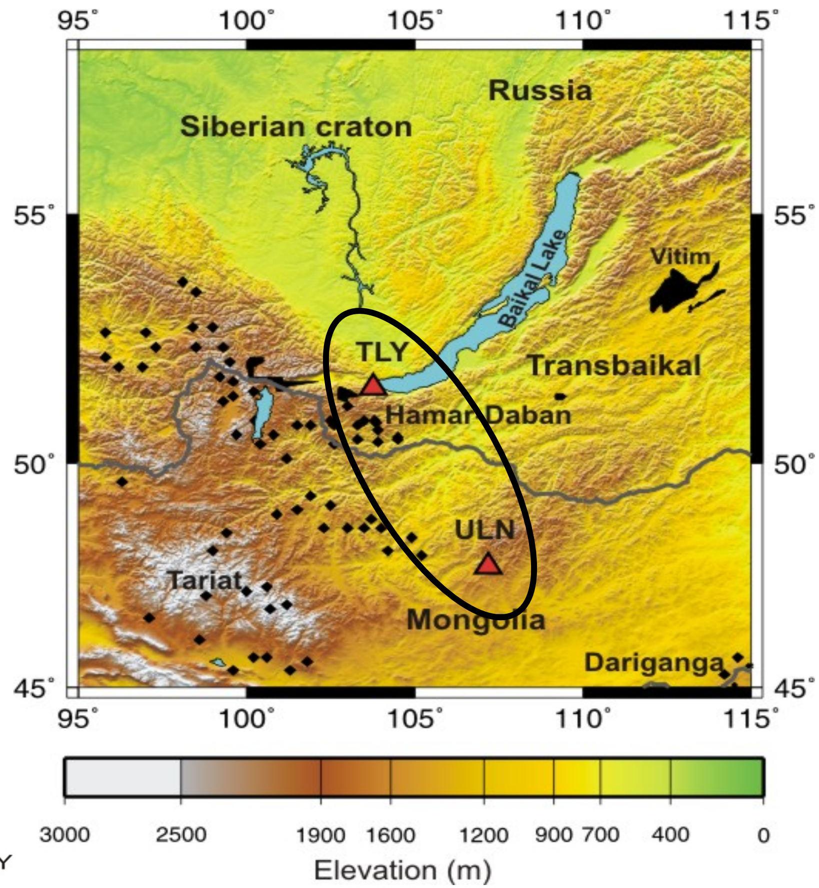
Period (s)

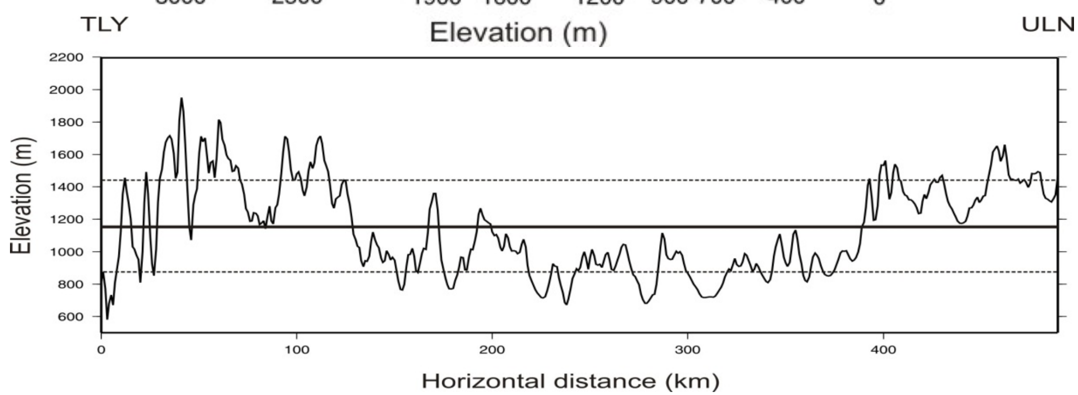


Period (s)

Pairs of stations, detailed dispersion curves

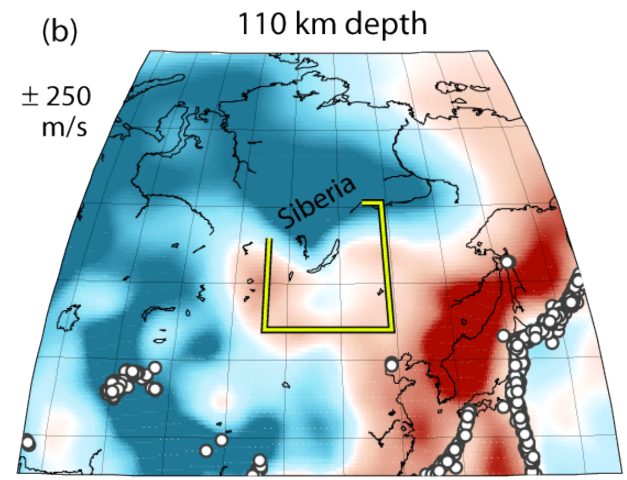
North Central Mongolia





Mantle composition

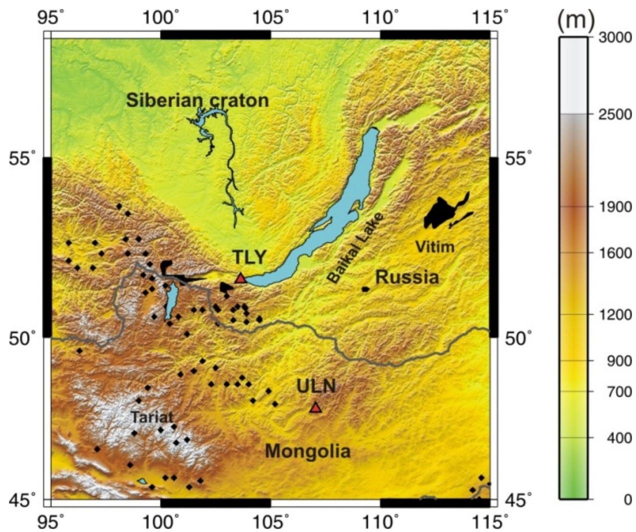
	a) Aver. Central Mongolia and Baikal	b) PUM M&S95
SiO_2	44.59	45
TiO_2	0.14	0.2
Al_2O_3	3.48	4.5
Cr_2O_3	0.4	0.38
FeO	8.25	8.1
MnO	0.14	0.14
MgO	39.56	37.8
CaO	2.85	3.6
Na_2O	0.31	0.36
Mg#	89.7	89.3

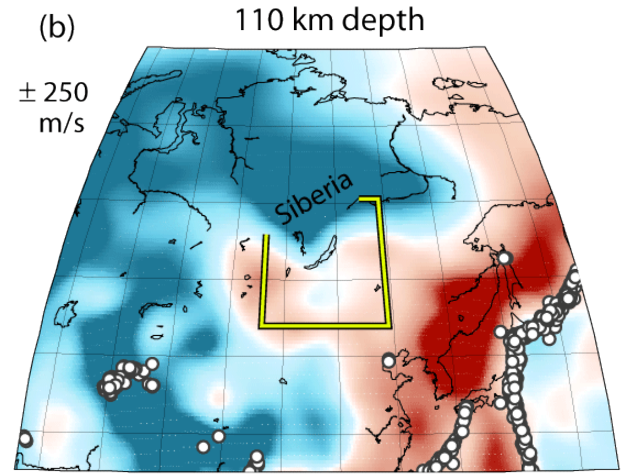


Lebedev et al. EPSL 2006

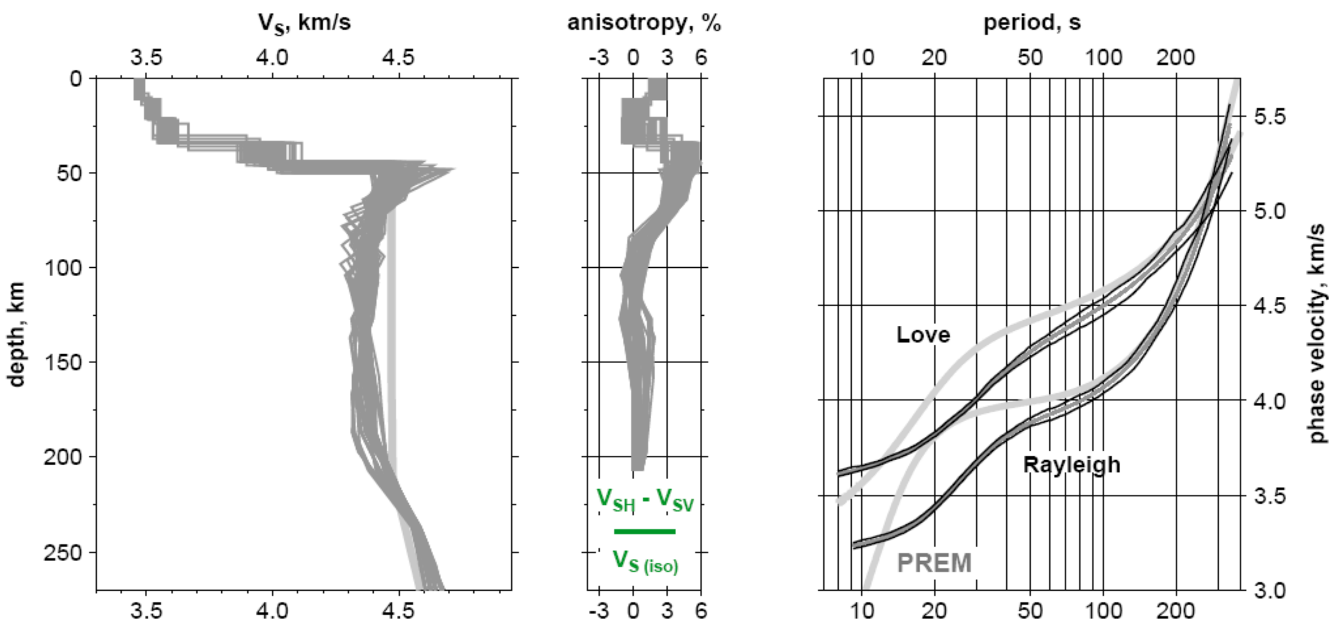
Surface wave seismic tomography

(Purely) Seismic models



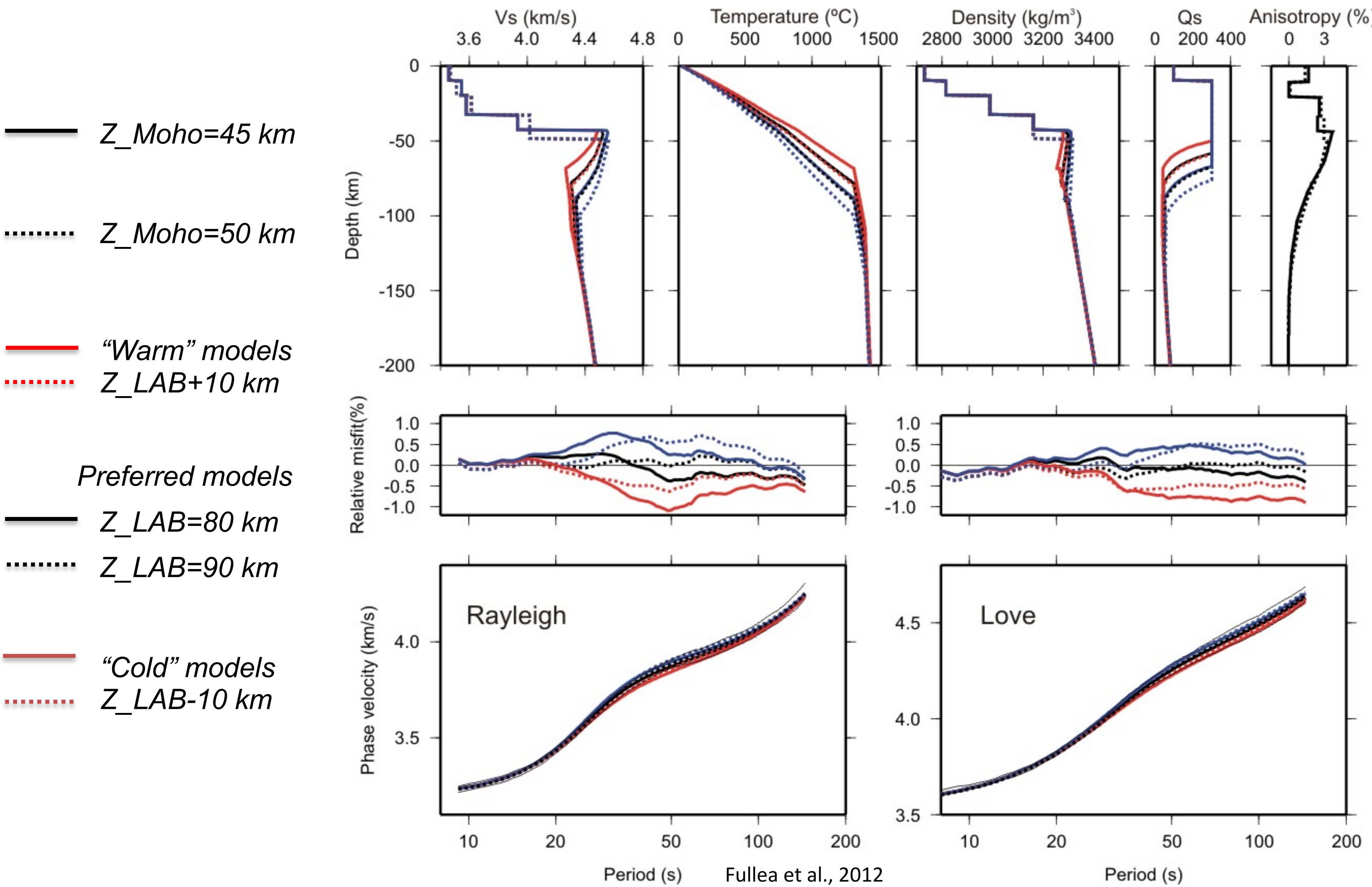


Range of plausible seismic models fitting surface wave data with relative error < 0.1%



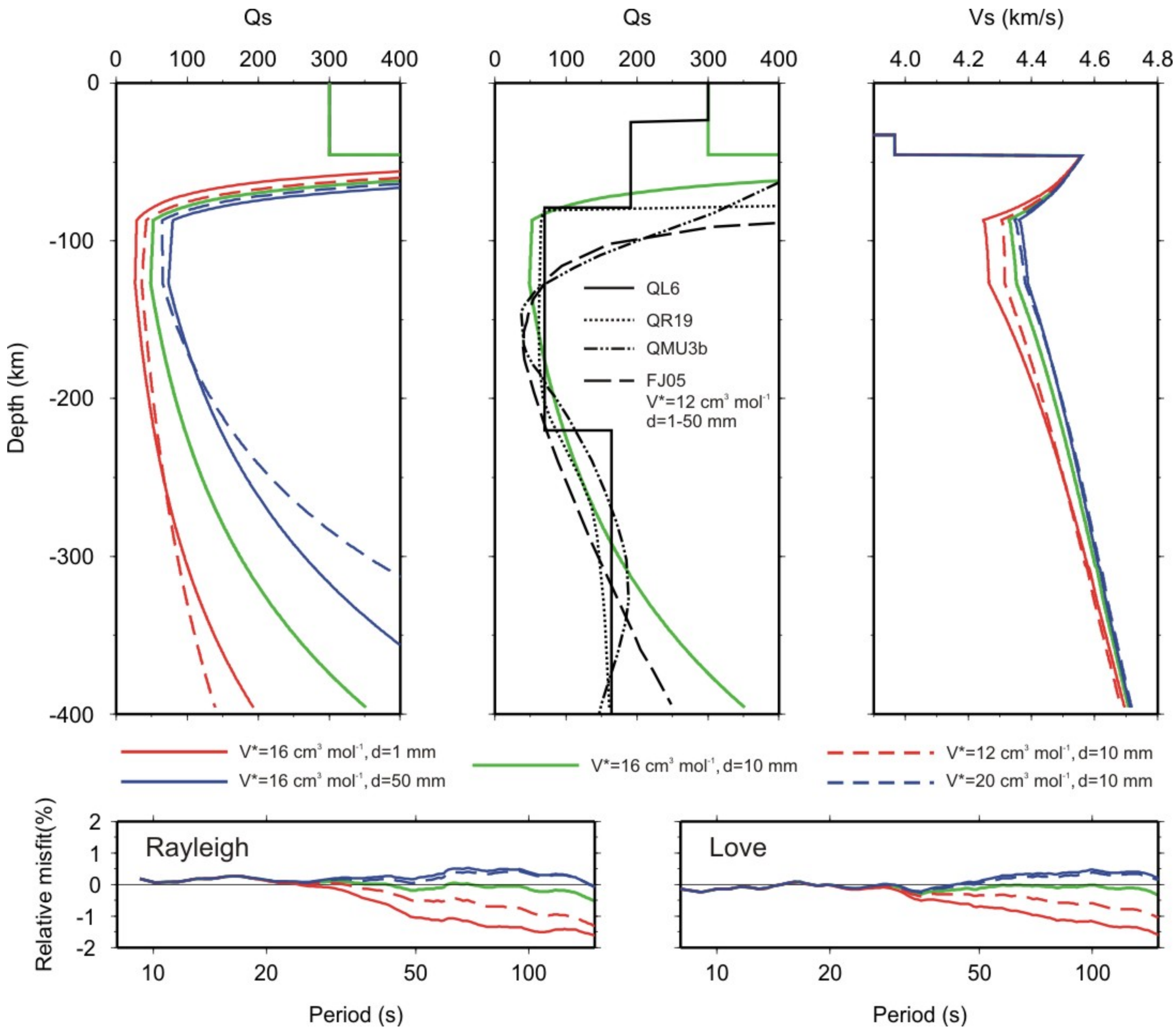
Lebedev et al. EPSL 2006

Range of preferred models fitting surface wave data. Seismic velocities and densities computed as function of T, P and composition (LitMod)

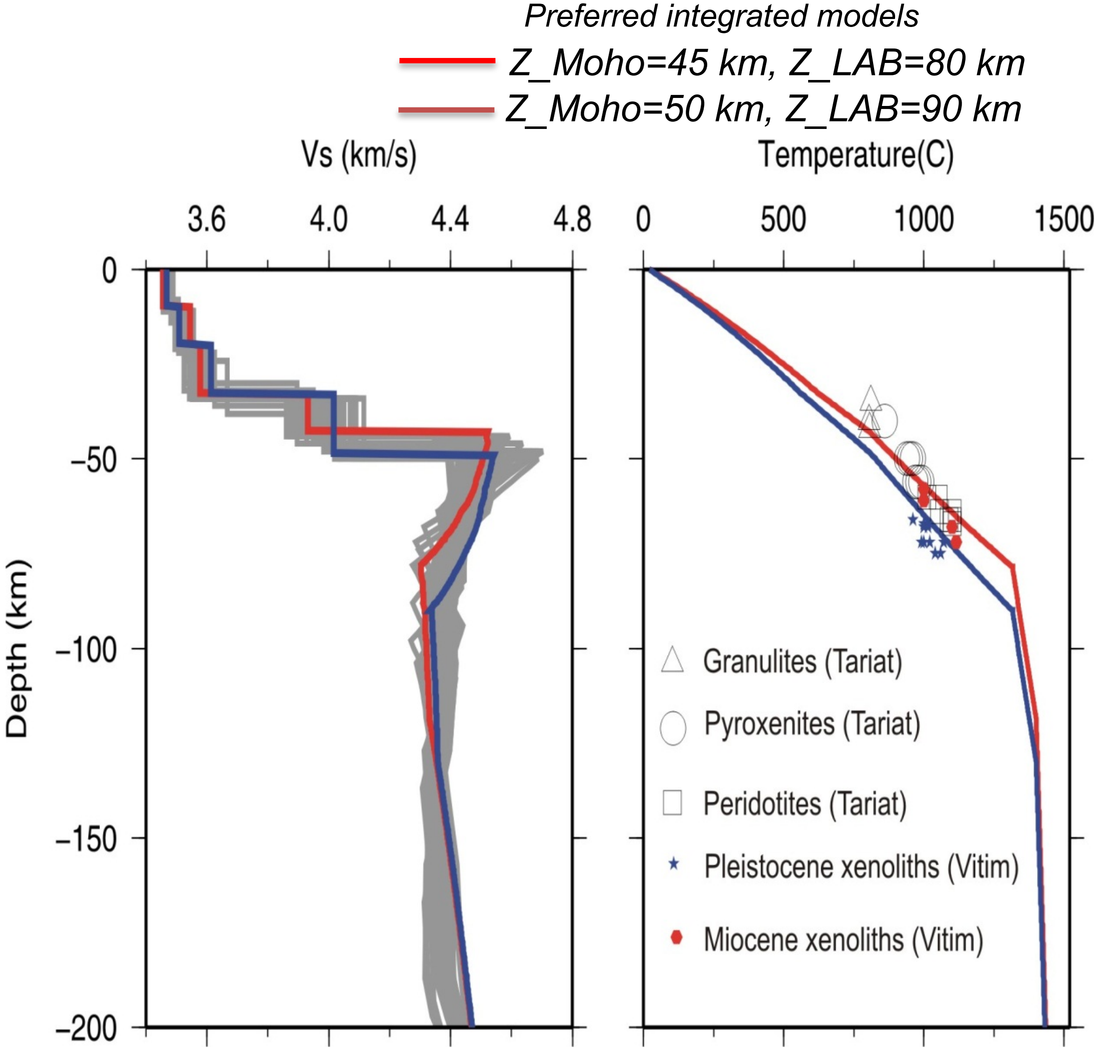


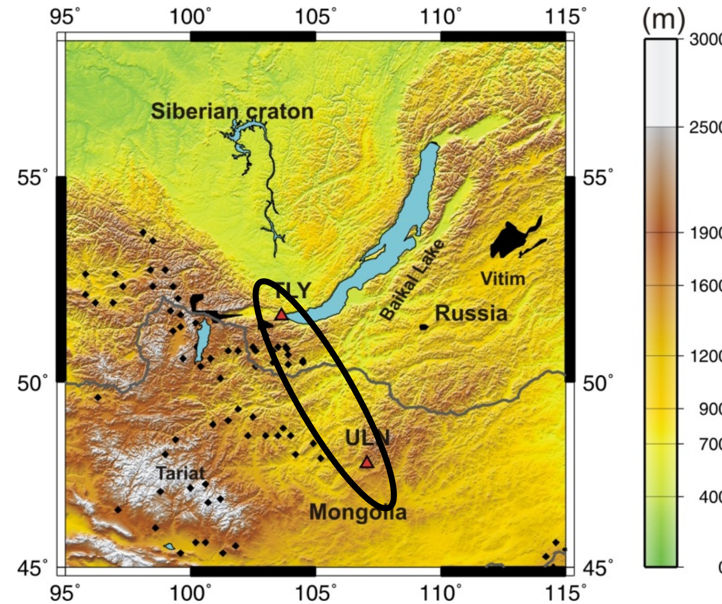
Fullea et al., 2012

Seismic attenuation



Integrated inversion: Xenolith data





→Integrated modelling effectively reduce the uncertainties of purely seismic inversions

→Thermobarometric estimates from Cenozoic mantle xenoliths in central Mongolia confirm estimated geotherms

Summary of results

- 80-90 km LAB
- dense and mafic lower crust
- fertile-moderately depleted lithospheric mantle
- isostatically compensated topography

Fullea et al., 2012

➢ *Surface-wave sensitivity kernels*