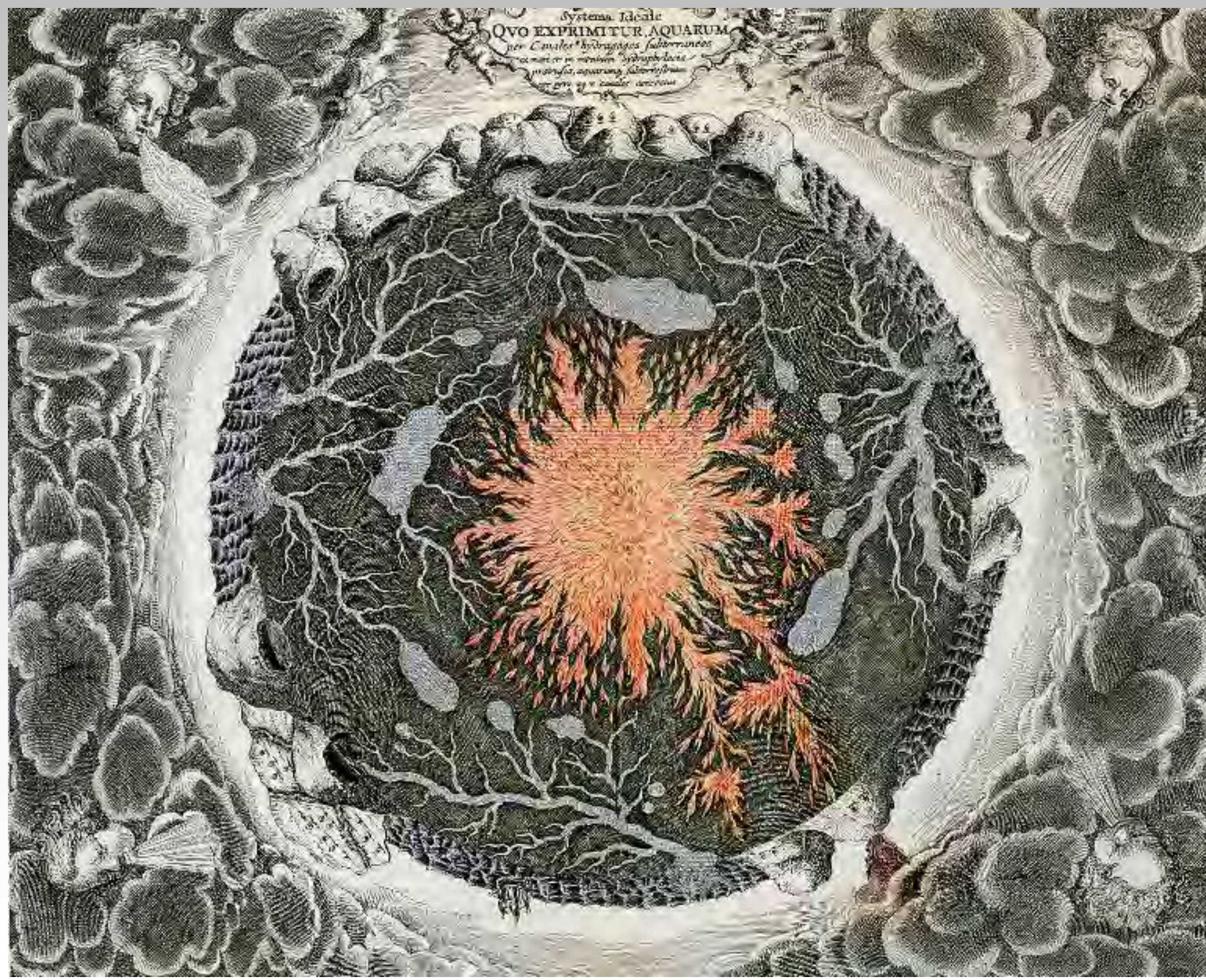
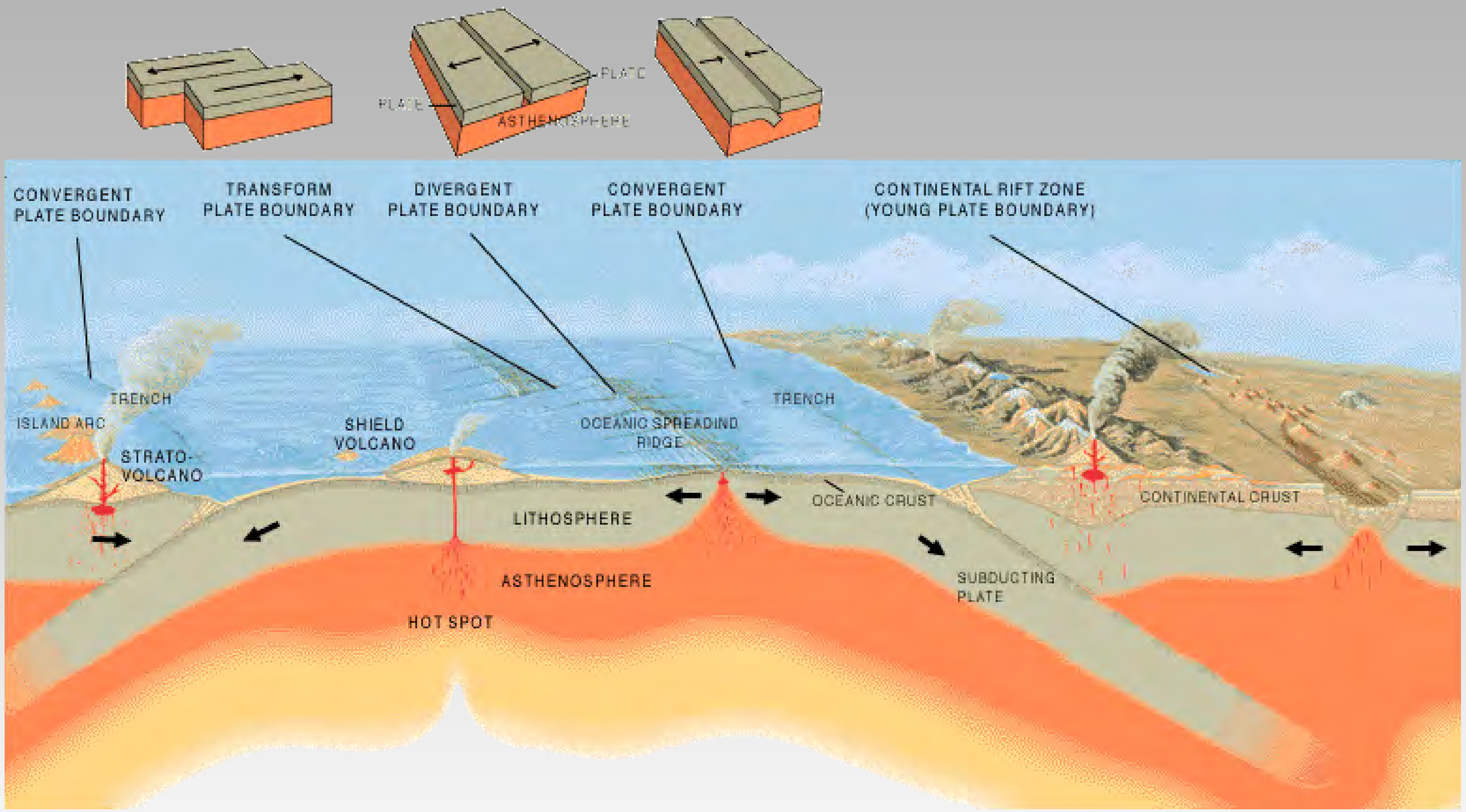
Mapping the distribution of fluids in the crust and lithospheric mantle utilizing geophysical methods

Martyn Unsworth, University of Alberta, CANADA
Stéphane Rondenay, University of Bergen, NORWAY



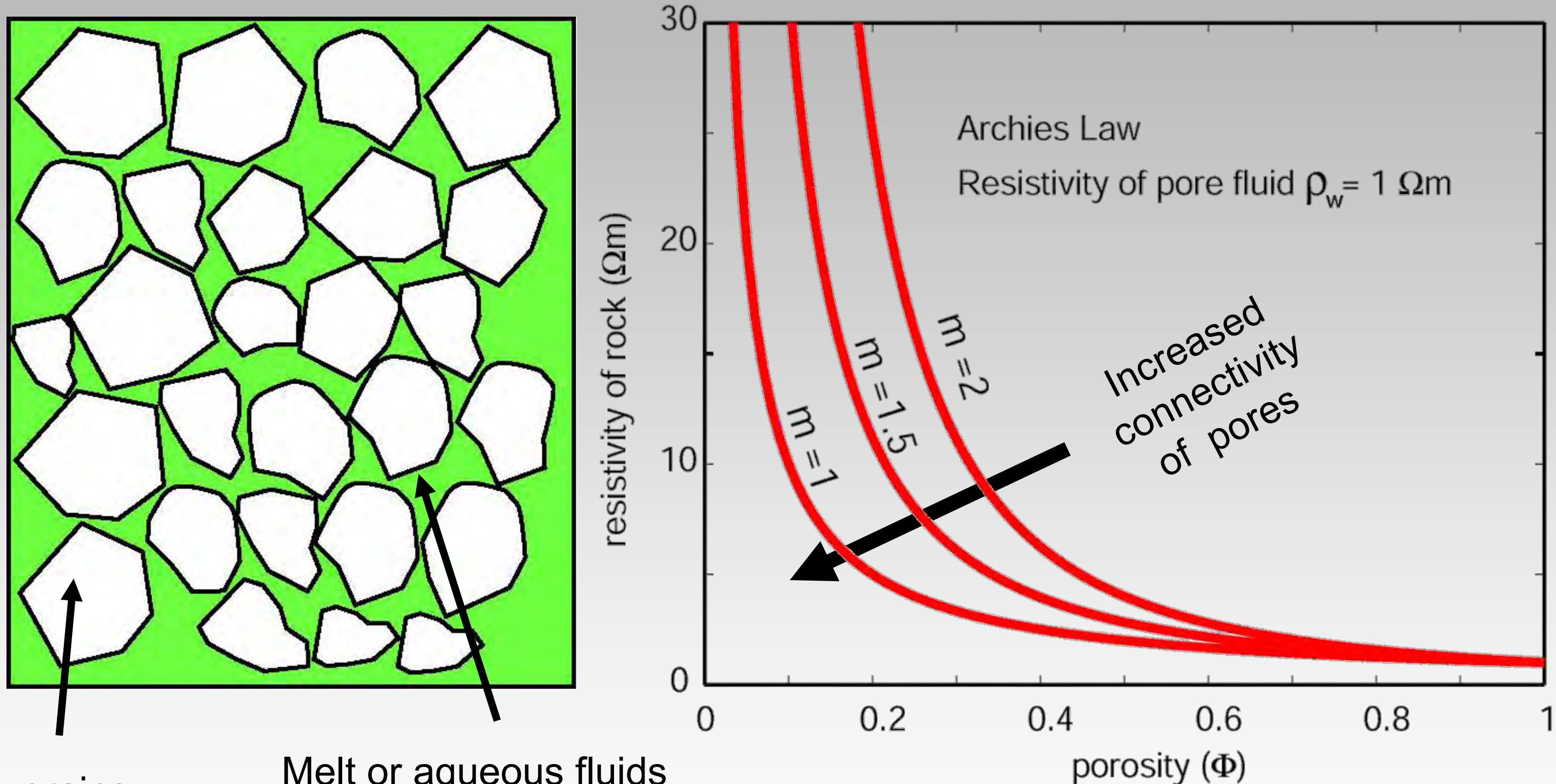


Fluid distribution at depth is important

- changes composition of crust and mantle through metasomatism
- controls rheology, mode of deformation

13.1 : Introduction - effect of fluids on rock properties

	Resistivity	Seismic properties
Free water	Decreases Sensitive to salinity	Lowers velocity Changes Poisson's ratio
Hydrous minerals Source of fluids Result of metasomatism	Decreases?	Lower velocity Increased anisotropy
Anhydrous minerals H+ in olivine	Decreases Anisotropy	Lower velocity Increased anisotropy
Partial melt	Decrease	Lower velocity Attenuation Anisotropy if deformed



rock grains
high resistivity

Melt or aqueous fluids
low resistivity

$$\rho_o = \rho_w \Phi^{-m}$$

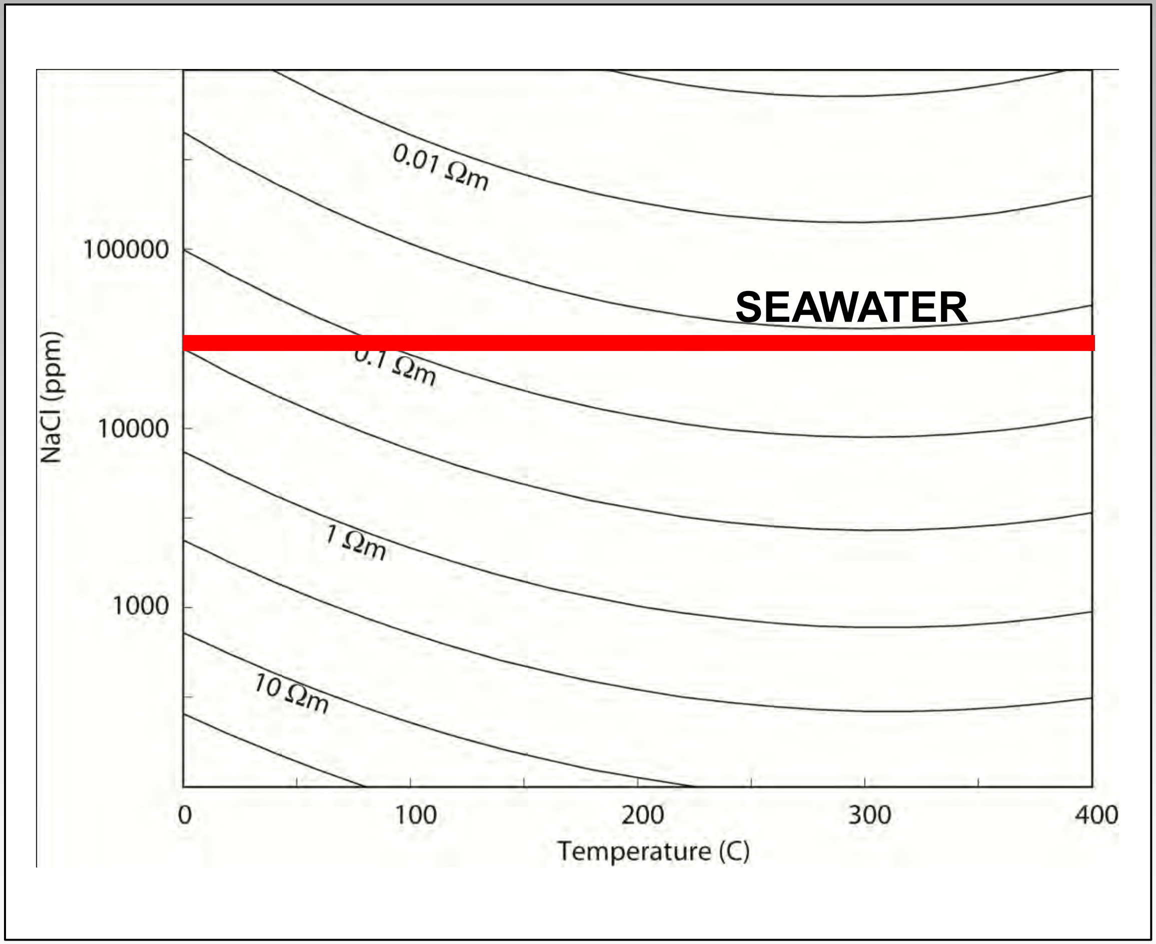

0.01 Ωm
SEAWATER
0.1 Ωm
1 Ωm
10 Ωm
100000
10000
1000
NaCl (ppm)
0
100
200
300
400
Temperature (C)

Figure 13.1

13.2 : Electromagnetic methods – resistivity of aqueous fluids – free water

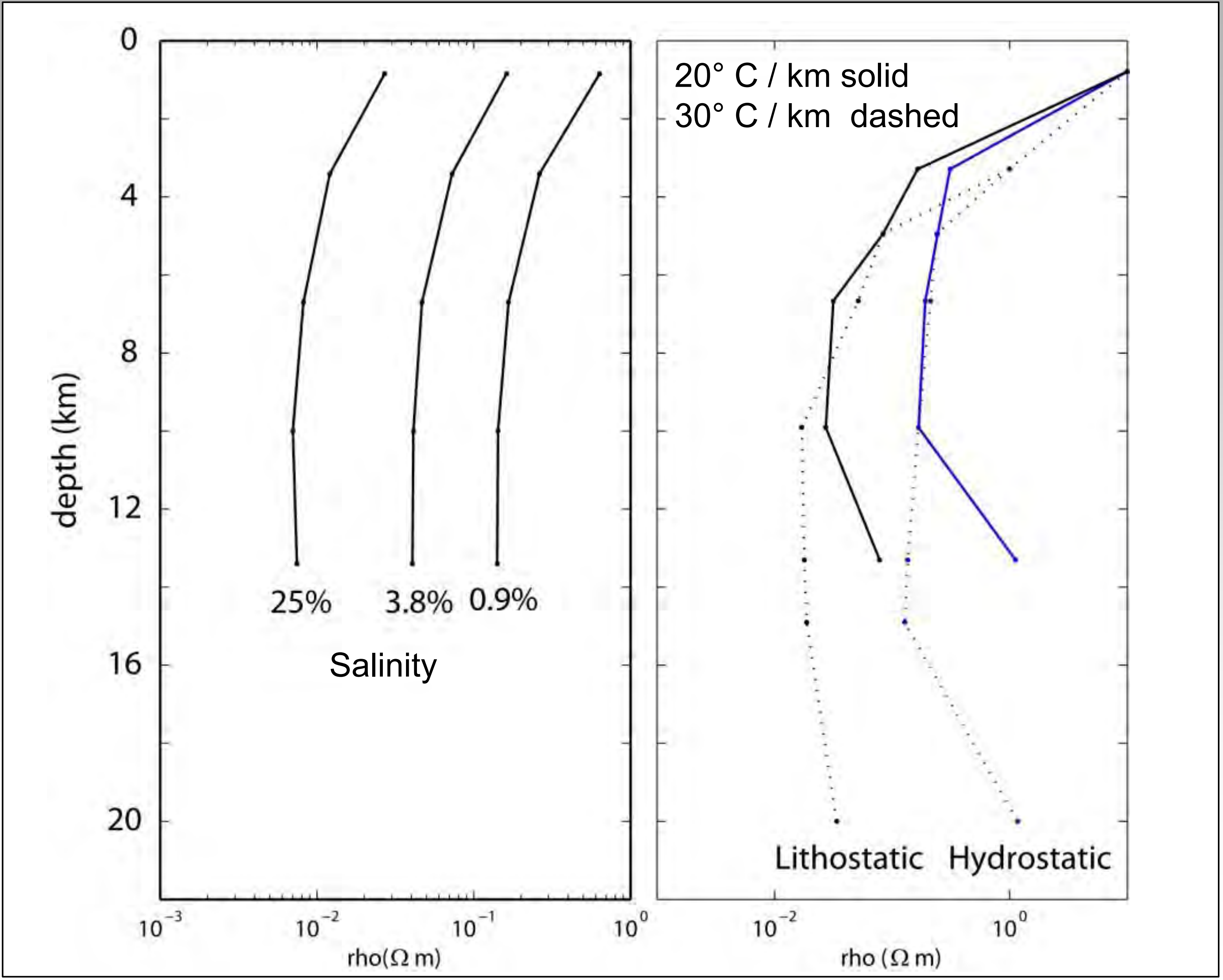


Figure 13.3 based on Nesbitt (1993)

13.2 : Electromagnetic methods – dihedral angles – free water

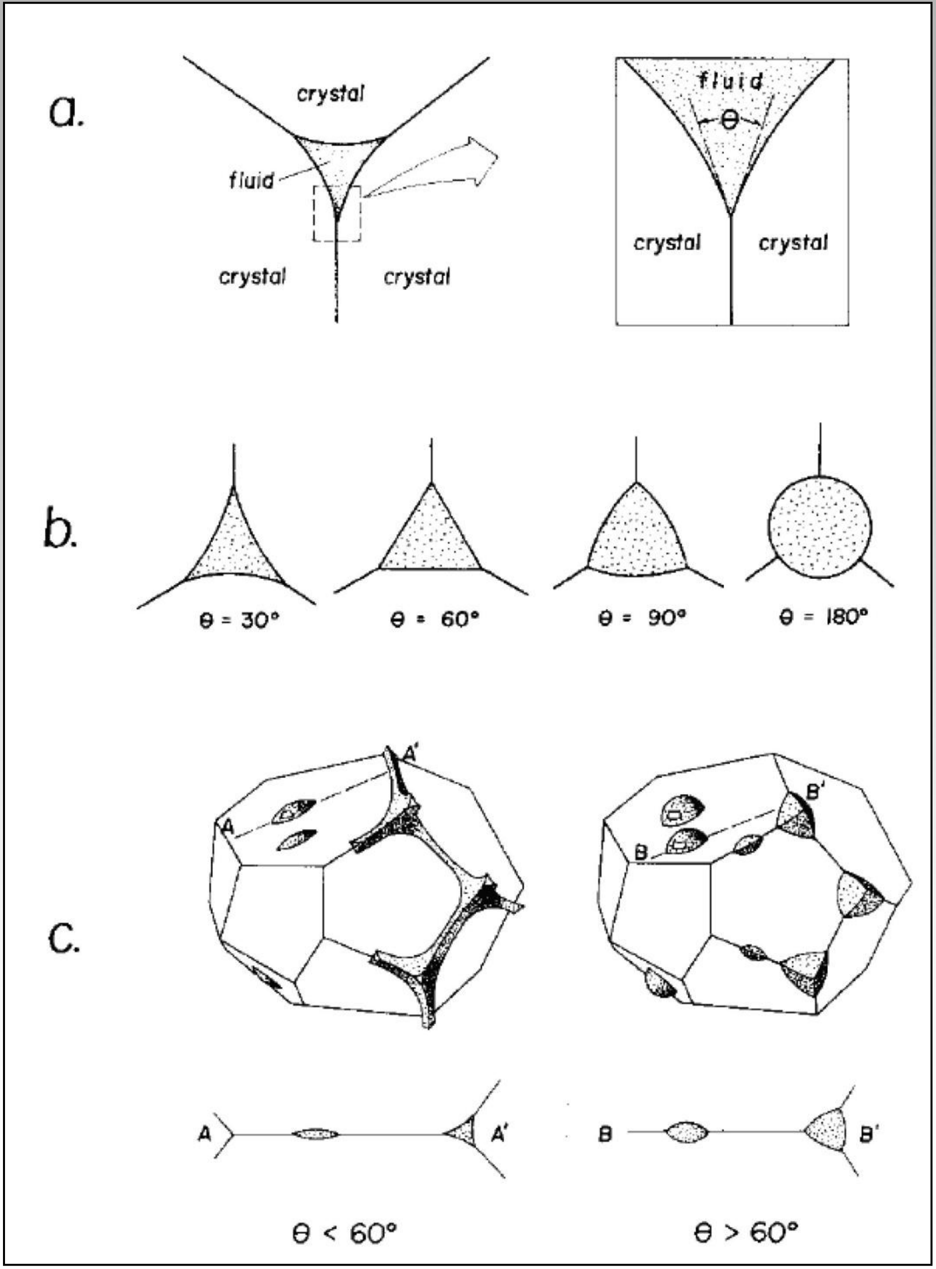
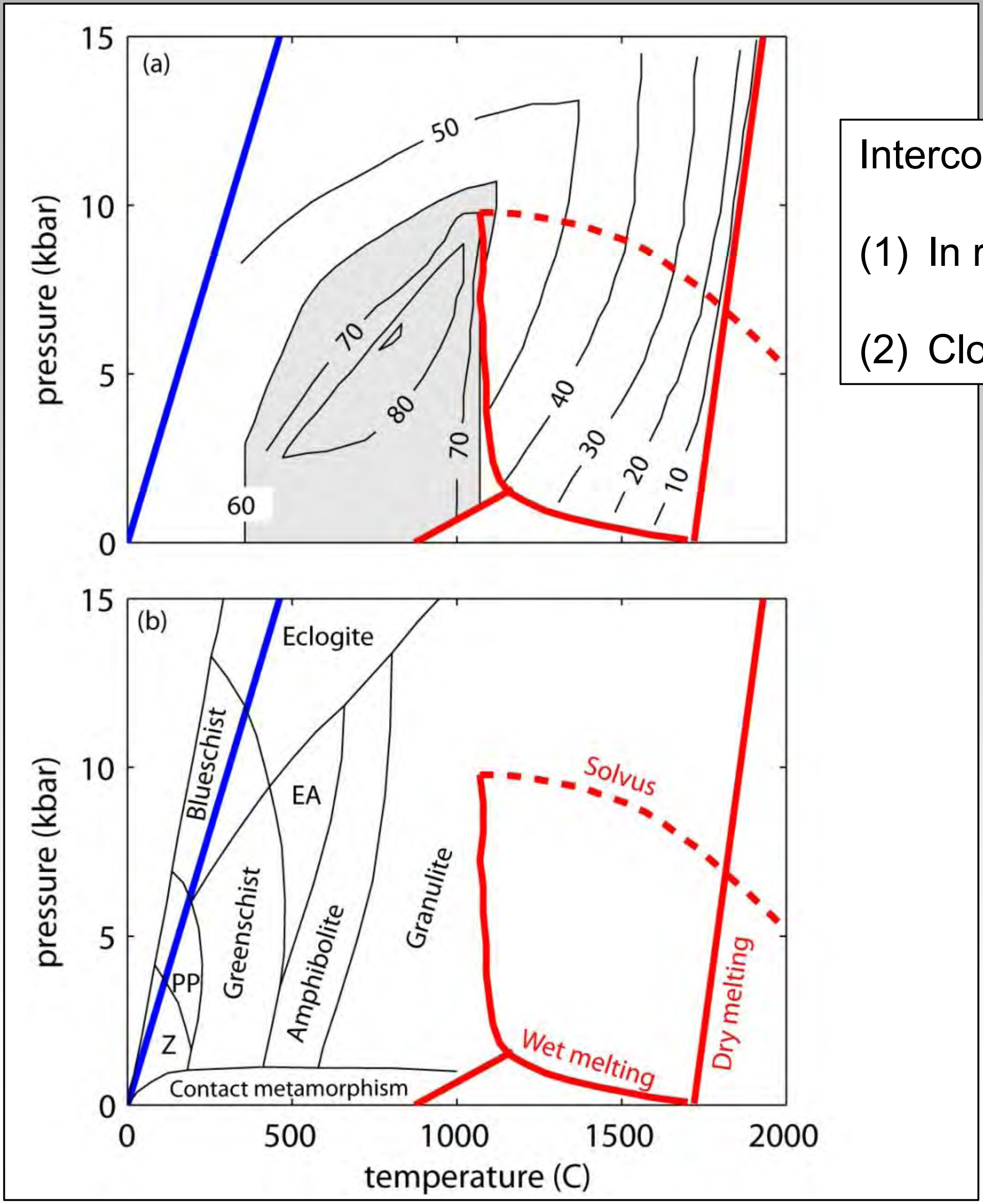


Figure 13.4



Dihedral angle from Holness (1993)

Interconnection of aqueous fluids may occur :

(1) In regions with low geothermal gradient

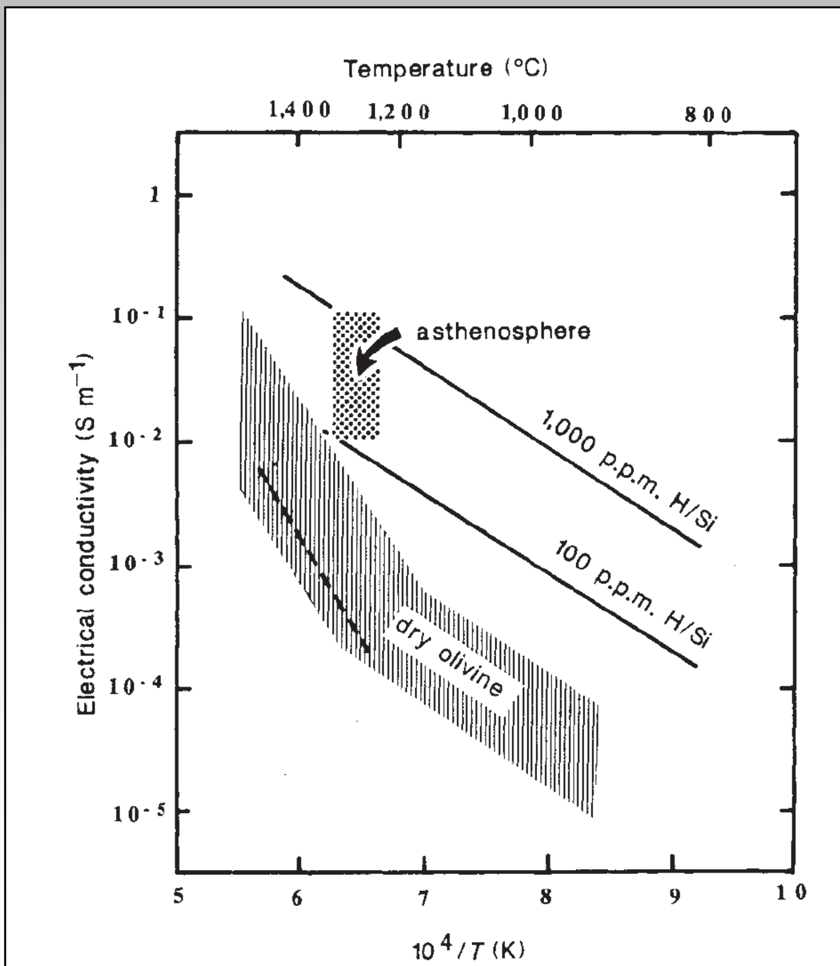
(2) Close to melting point

Figure 13.5

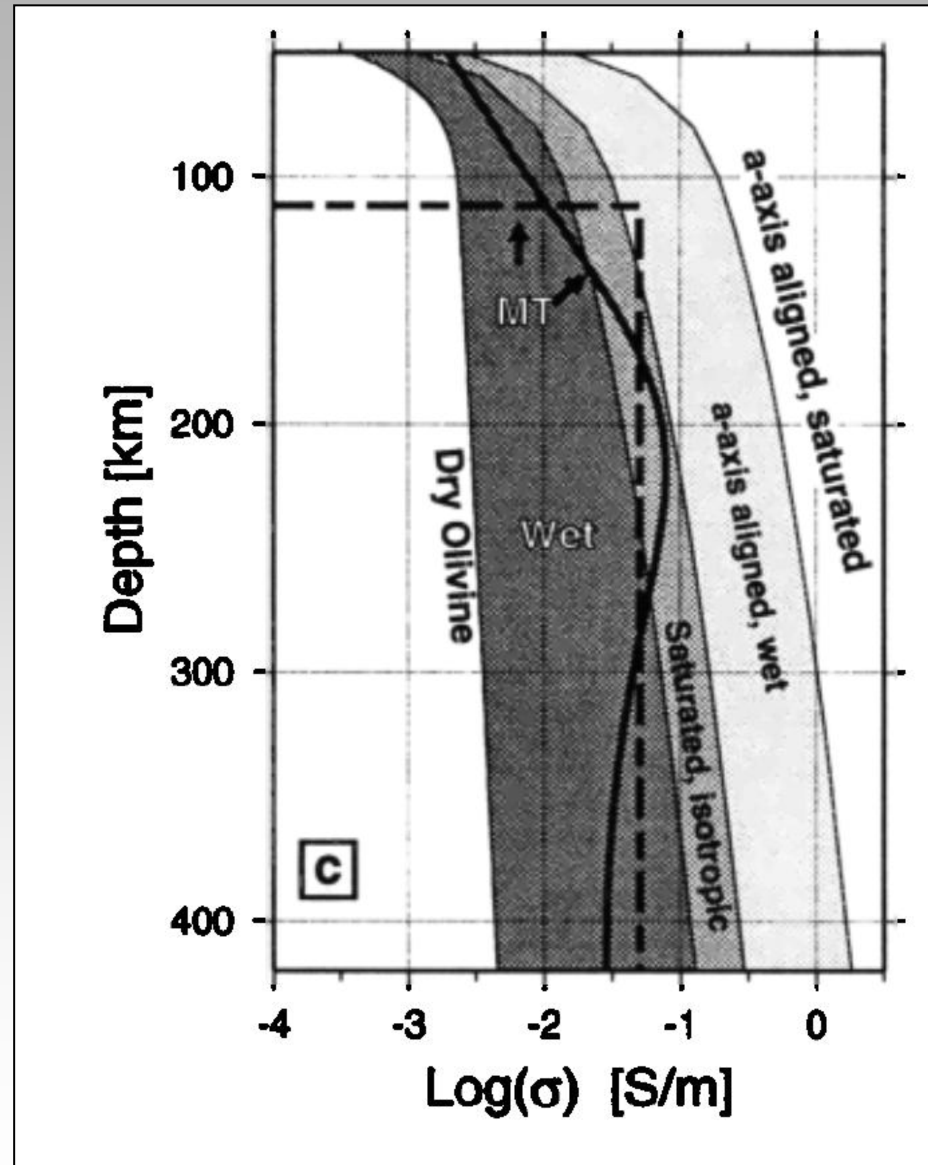
13.2 : Electromagnetic methods – water in nominally anhydrous minerals

The role of hydrogen in the electrical conductivity of the upper mantle

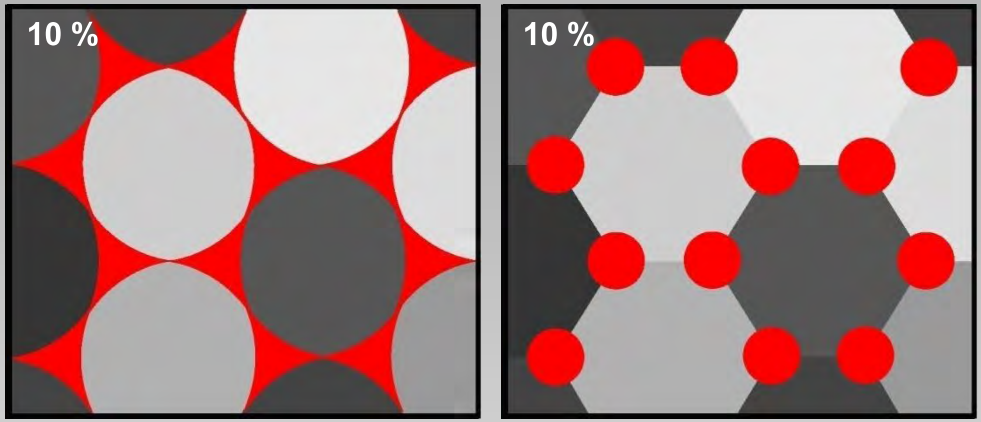
S. Karato



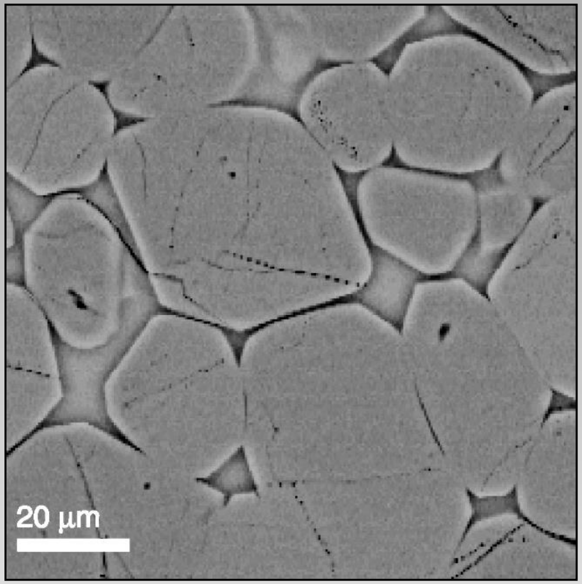
Karato, Nature, 1990

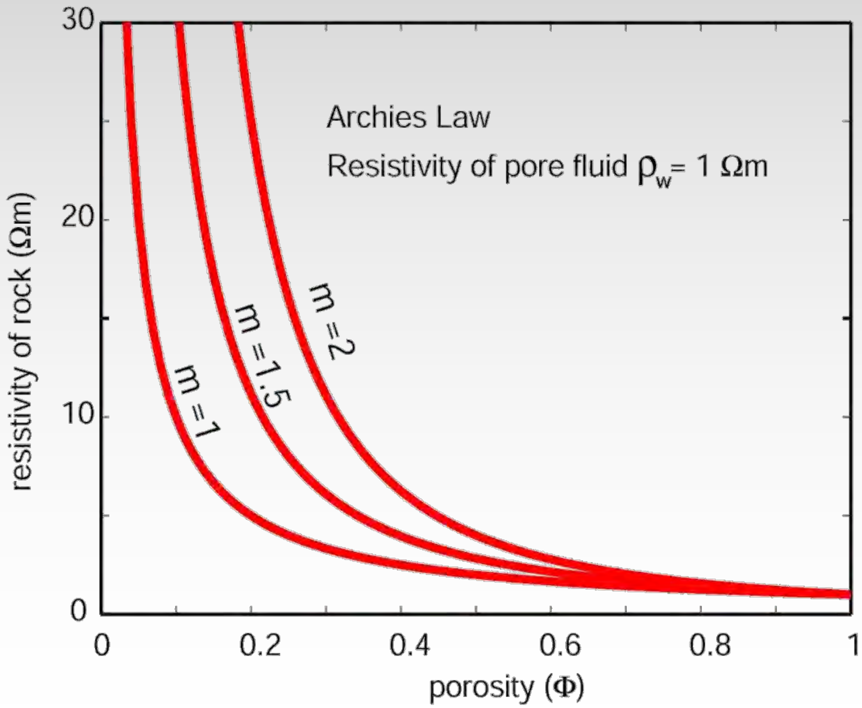


Lizzeralde et al., JGR, 1995, Figure 10c



Dihedral angle = 0°   Dihedral angle = 180°





Olivine partial melt
ten Grotenhuis et al., JGR (2005)
10% melt

m =1.3 in Archie's Law

Melt resistivity = 1 -0.1 Ωm

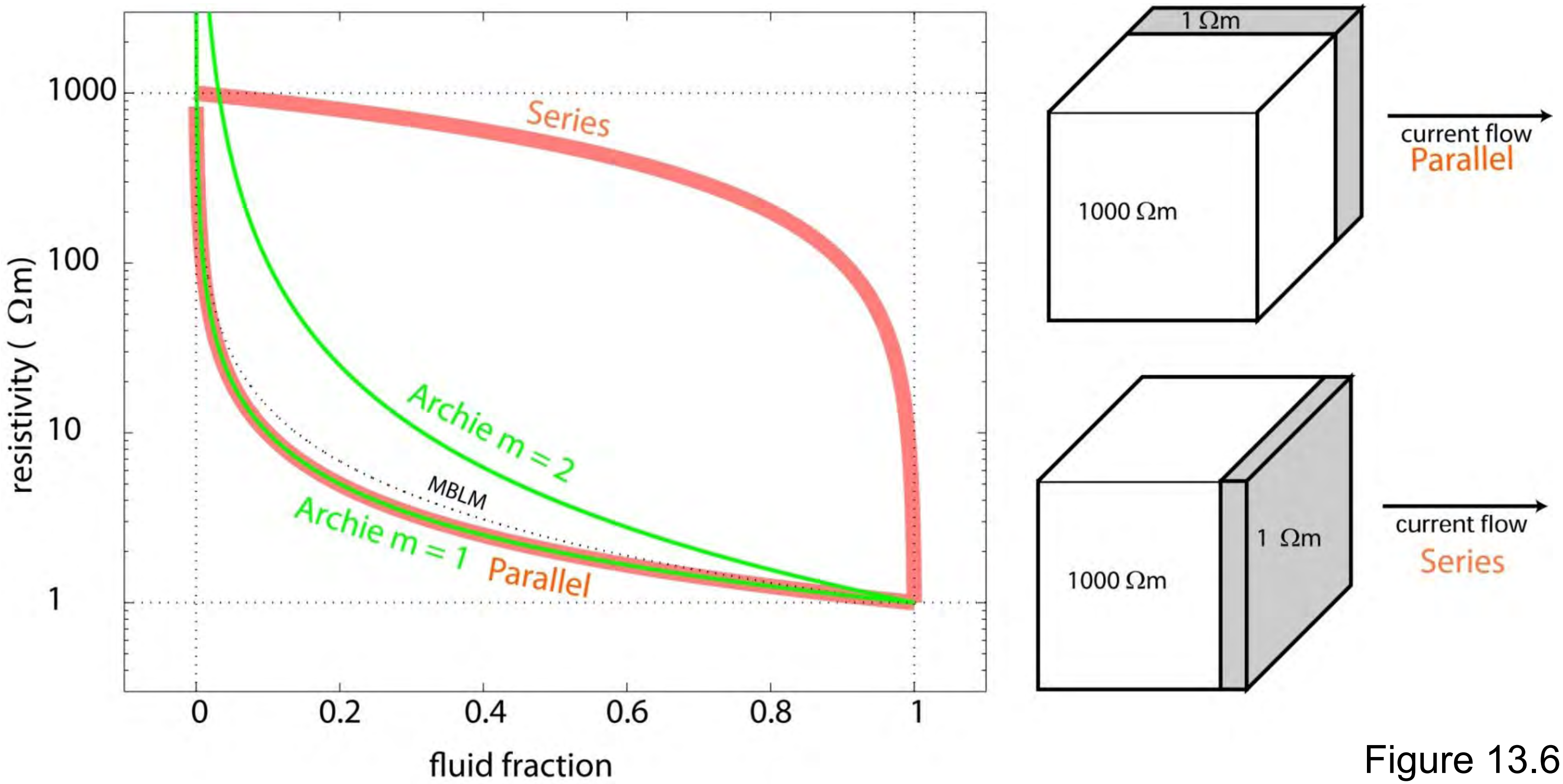
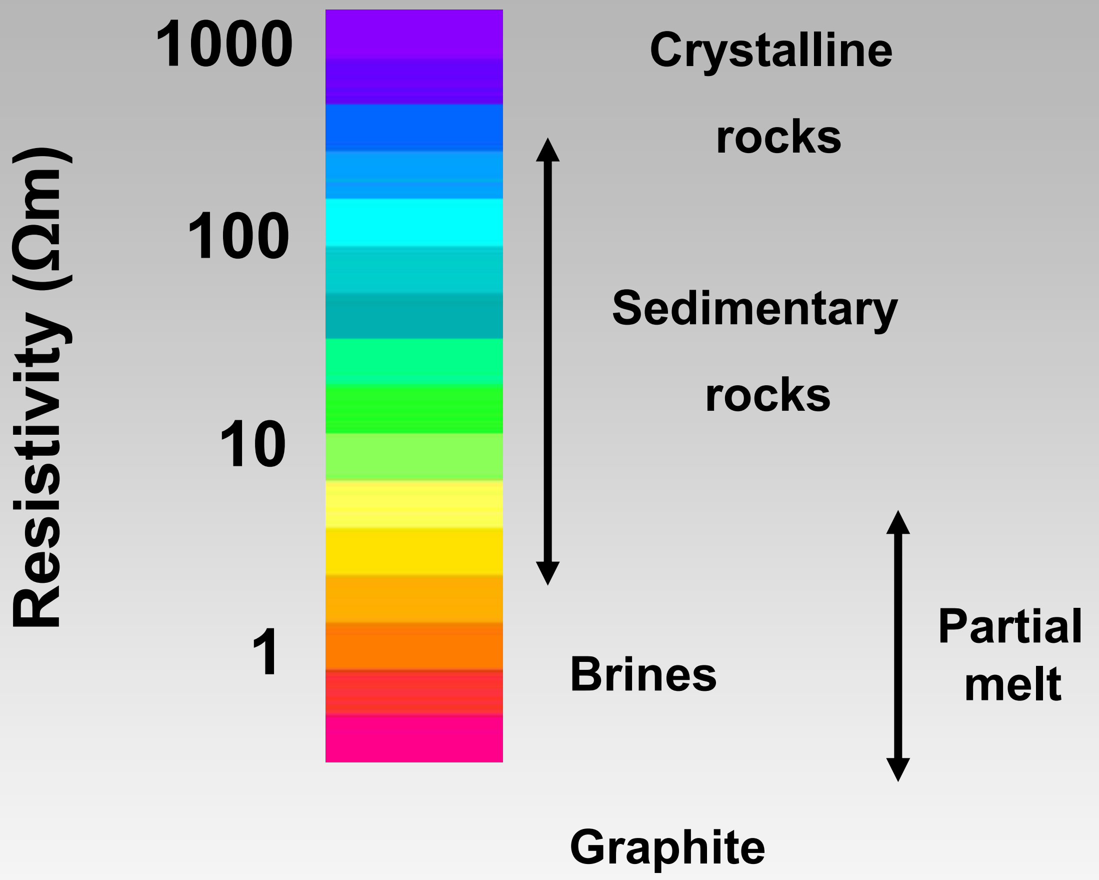

resistivity (Ωm)
1000
100
10
1
0
0.2
0.4
0.6
0.8
1
fluid fraction
Series
Archie m = 2
MBLM
Archie m = 1
Parallel
1 Ωm
1000 Ωm
current flow
Parallel
1000 Ωm
1 Ωm
current flow
Series

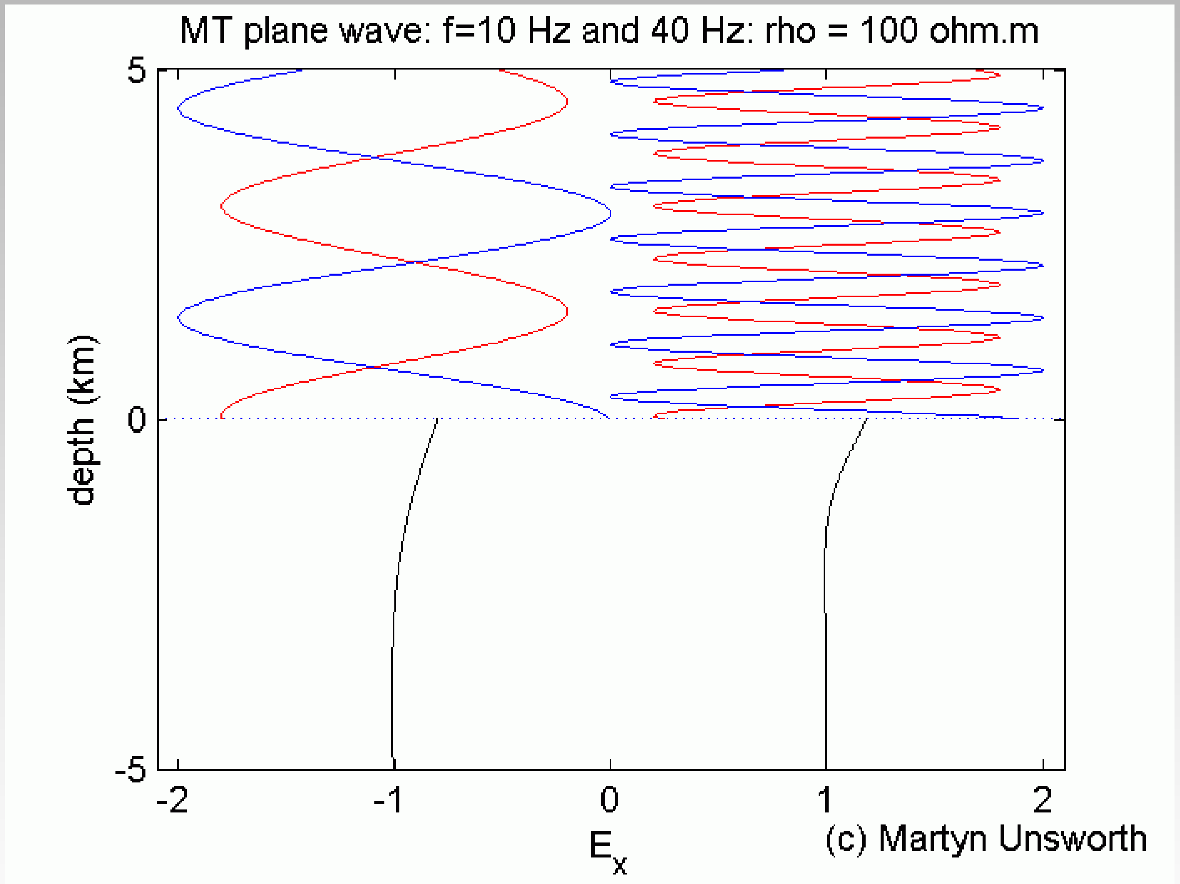
Figure 13.6



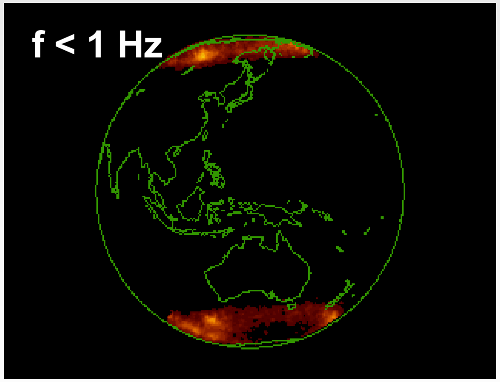
Beware of non-uniqueness in geophysics!
Low resistivity : brine, melt, graphite, sulphides …….

High conductivity = low resistivity

Figure 13.7

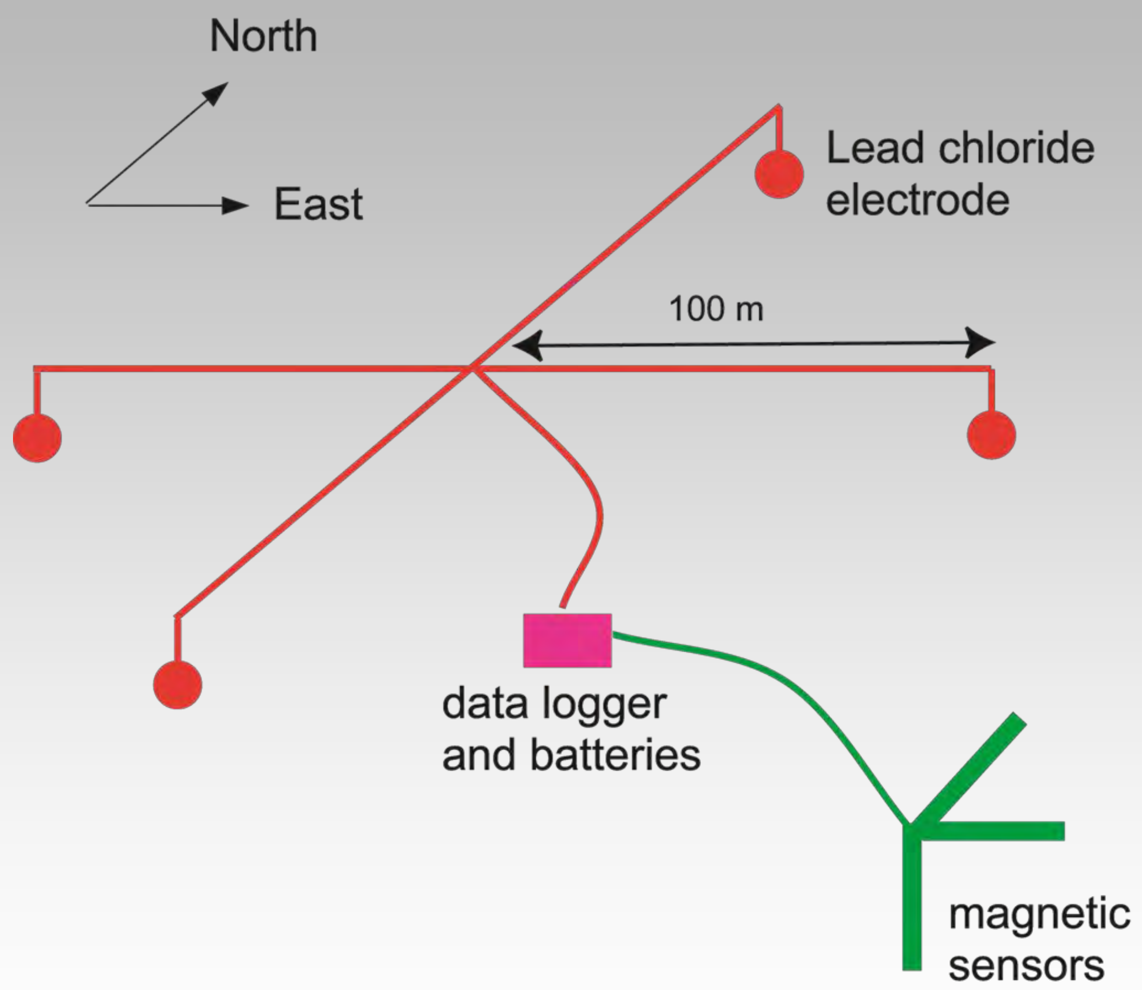


Global lightning activity



Aurora Borealis and Australis

- Ratio of electric and magnetic fields > resistivity
- Depth of investigation varies as 1/ √frequency


North
East
Lead chloride electrode
100 m
data logger and batteries
magnetic sensors


Chicxulub (2001)

Figure 13.12

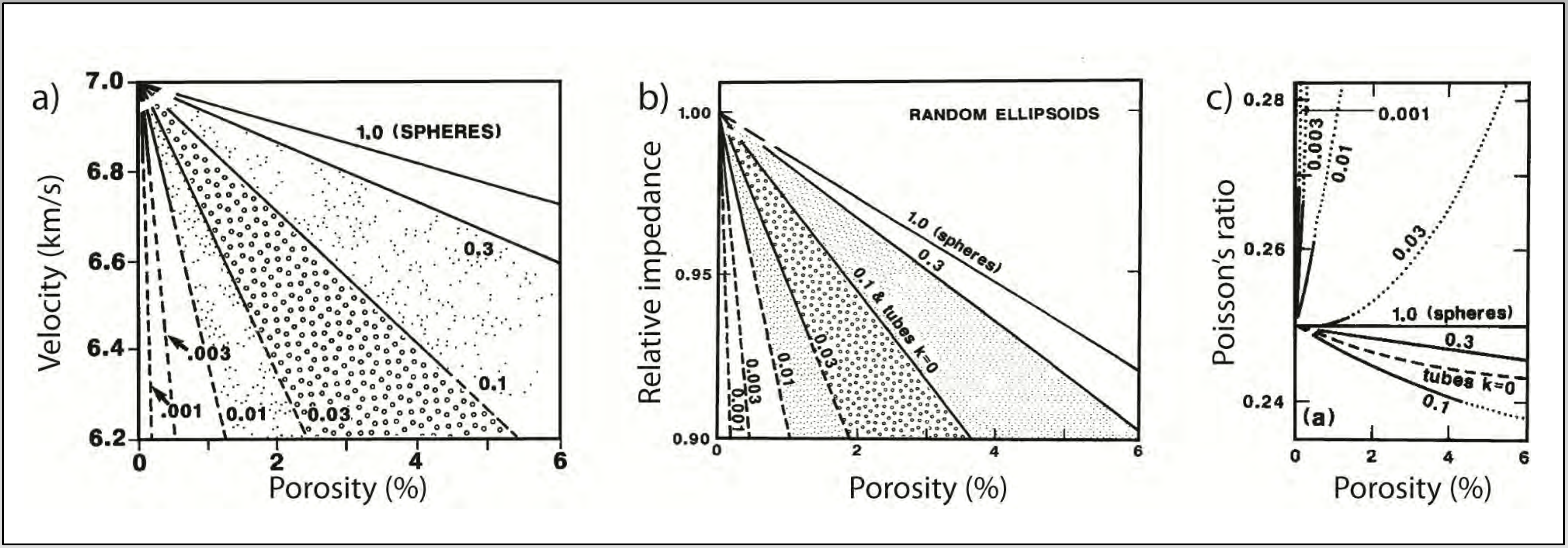


Figure 13.13
Hyndman and Shearer (1993)

Effect of free water is to
- Reduce the stiffness of the rock and lower velocity
- Increase or reduce Poisson's ratio (depending on aspect ratio of pores)
- Increase attenuation (grain boundary sliding, liquid squirt)
- Cause anisotropy

13.3 : Seismic methods - hydrous minerals

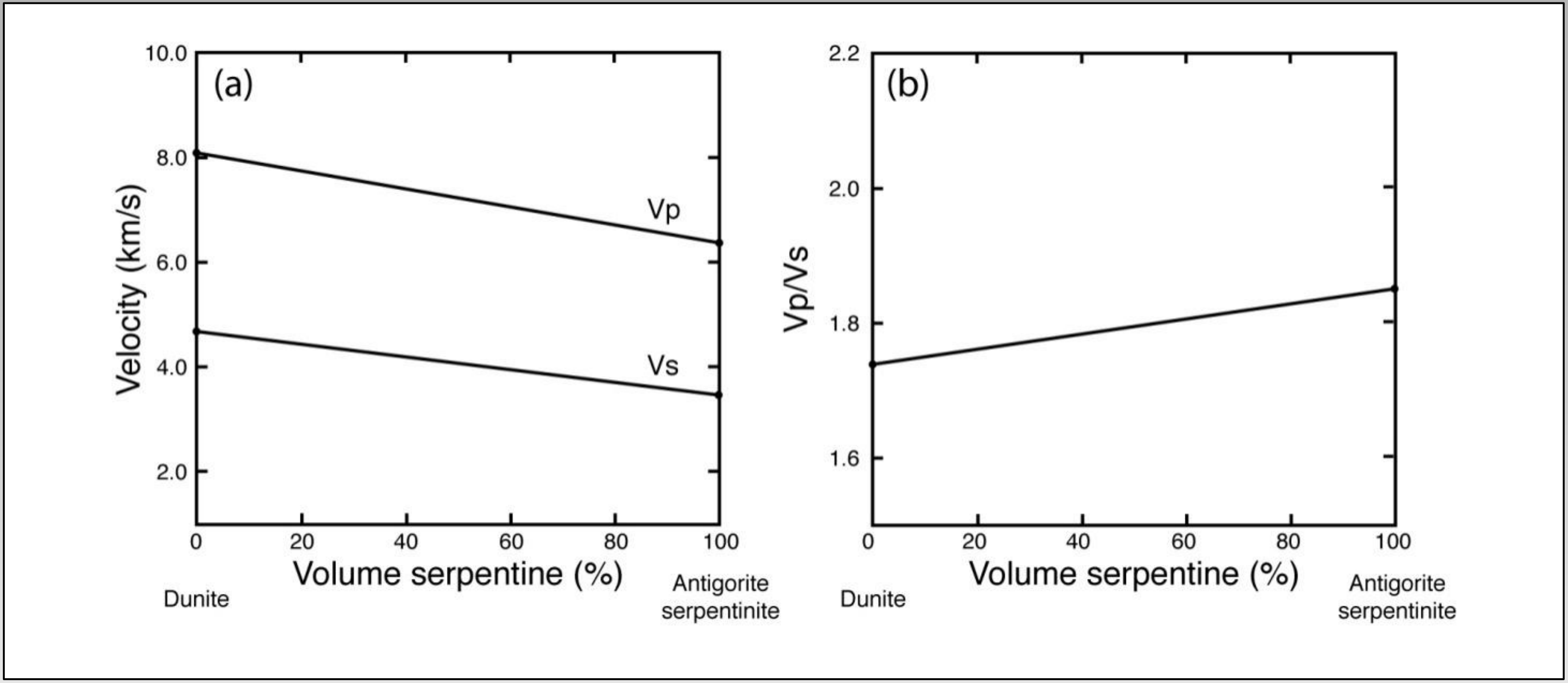


Figure 13.15

-contain water as part of chemical structure
-generally lower velocity than equivalent anhydrous mineral
-often anisotropic (antigorite P-wave = 71%; S-wave = 68%).
-macro anisotropy requires orientation by deformation

13.3 : Seismic methods - water in nominally anhydrous minerals

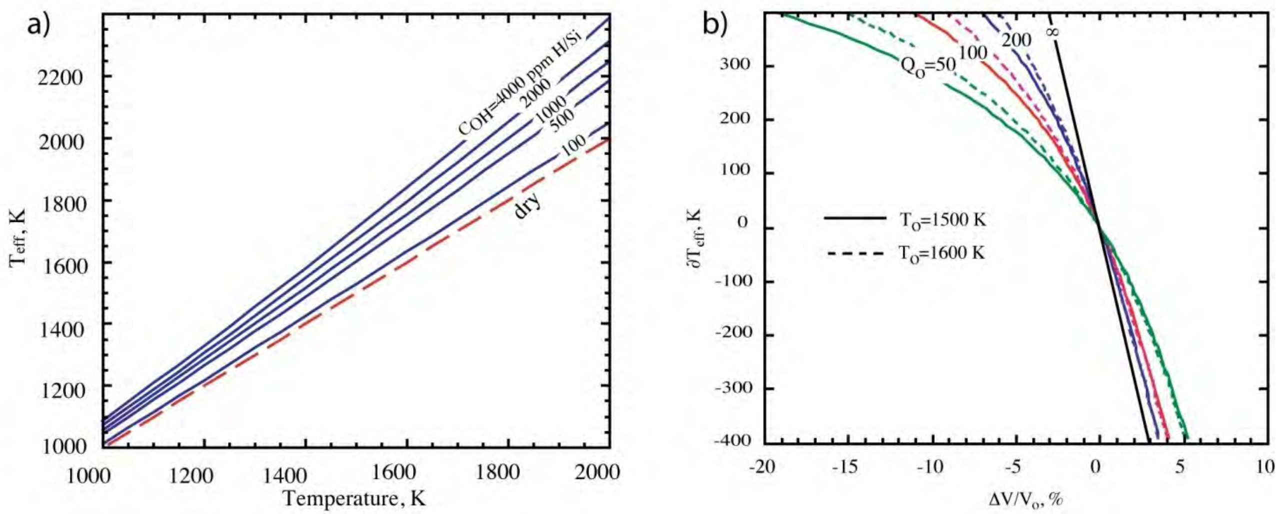
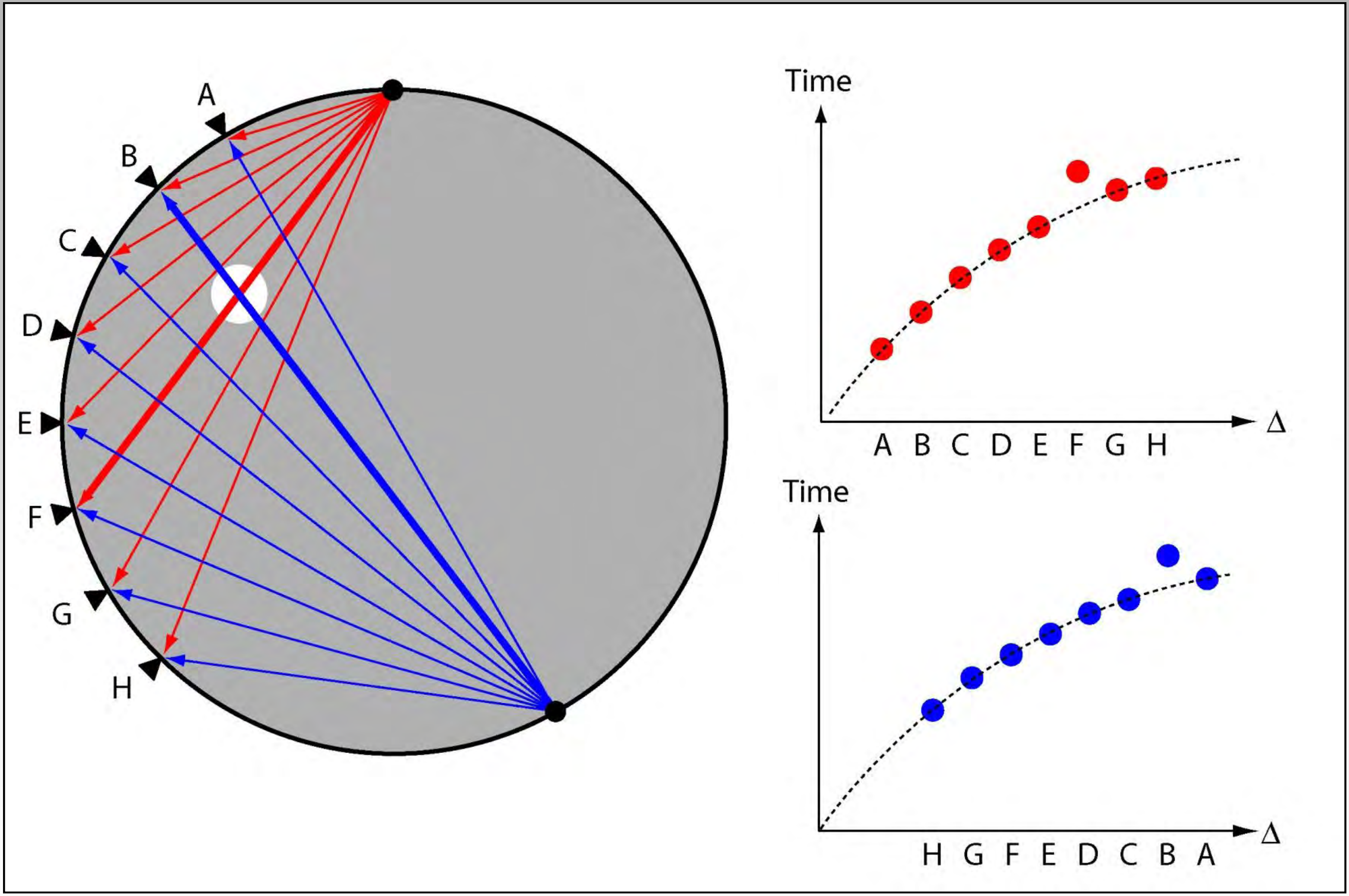


Figure 13.16

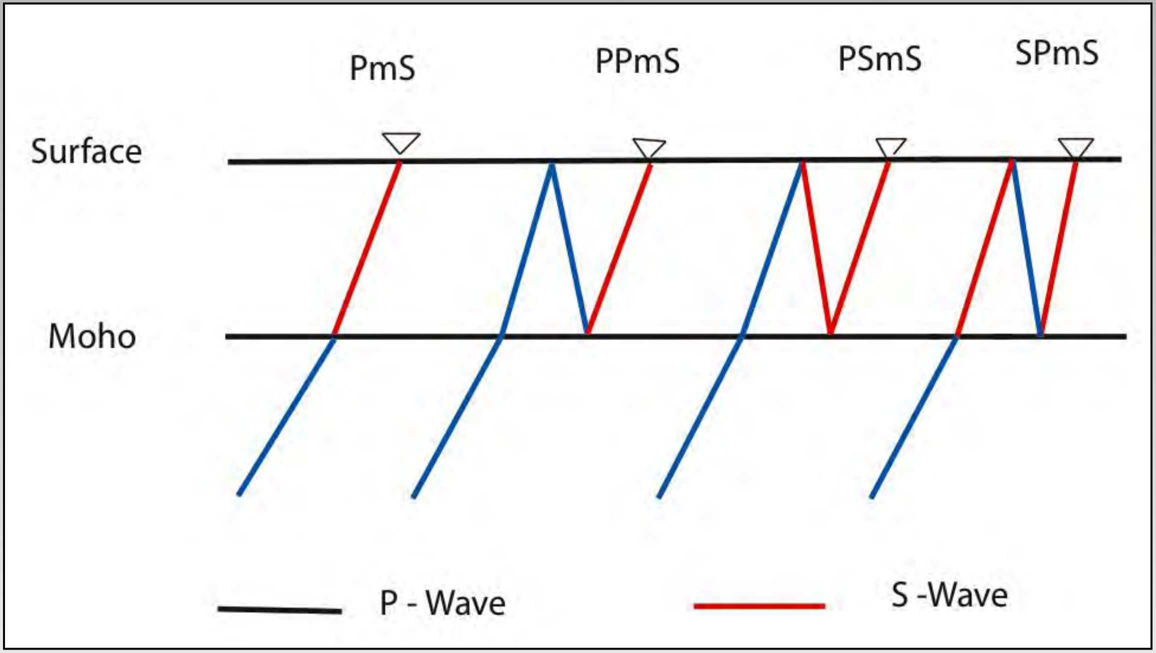
-H+ point defects in olivine
-Enhancement of anelasticity, modifies velocities
-Causes different types of olivine fabrics, development of seismic anisotropy,

Seismic tomography

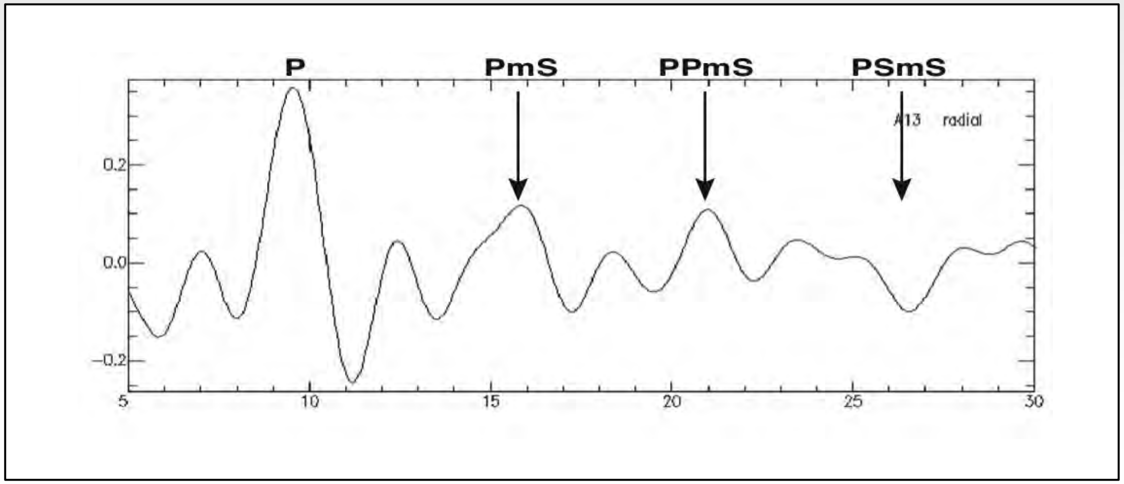


Energy sources : earthquakes, explosions
Can use travel times and waveform inversion
Fully 3-D approaches from large arrays

Receiver function analysis



Beware of deceiver functions !!!



http://gcc.asu.edu/snair/research.html

Shear wave splitting – detect anisotropy

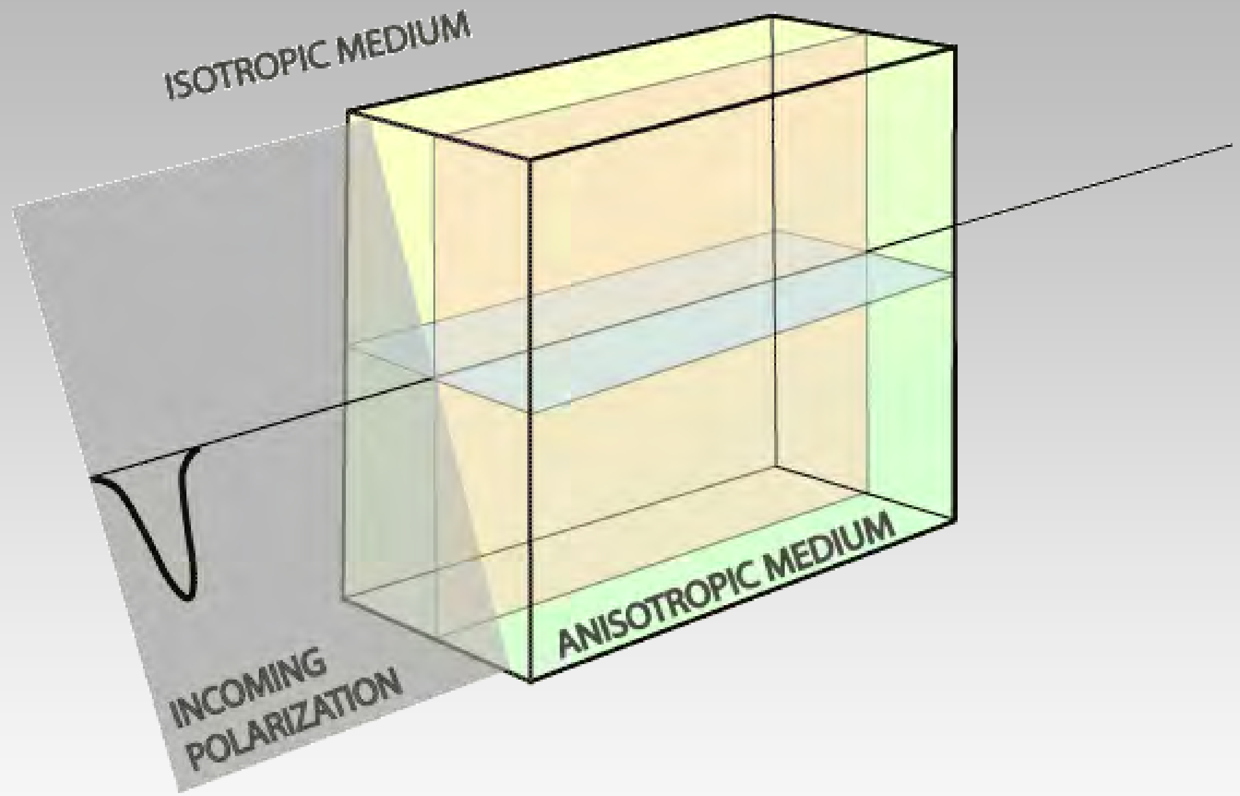
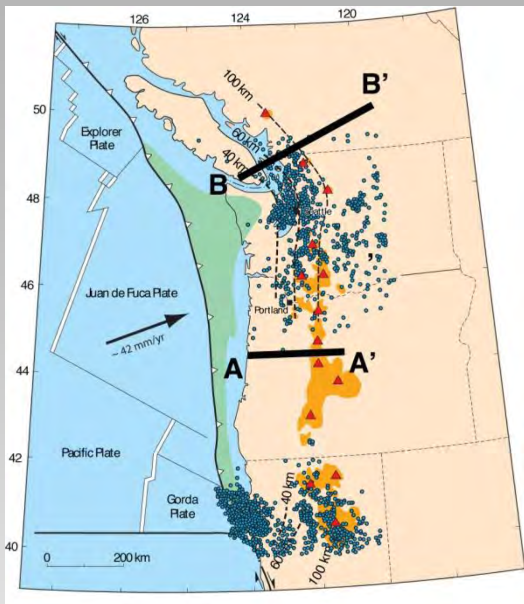
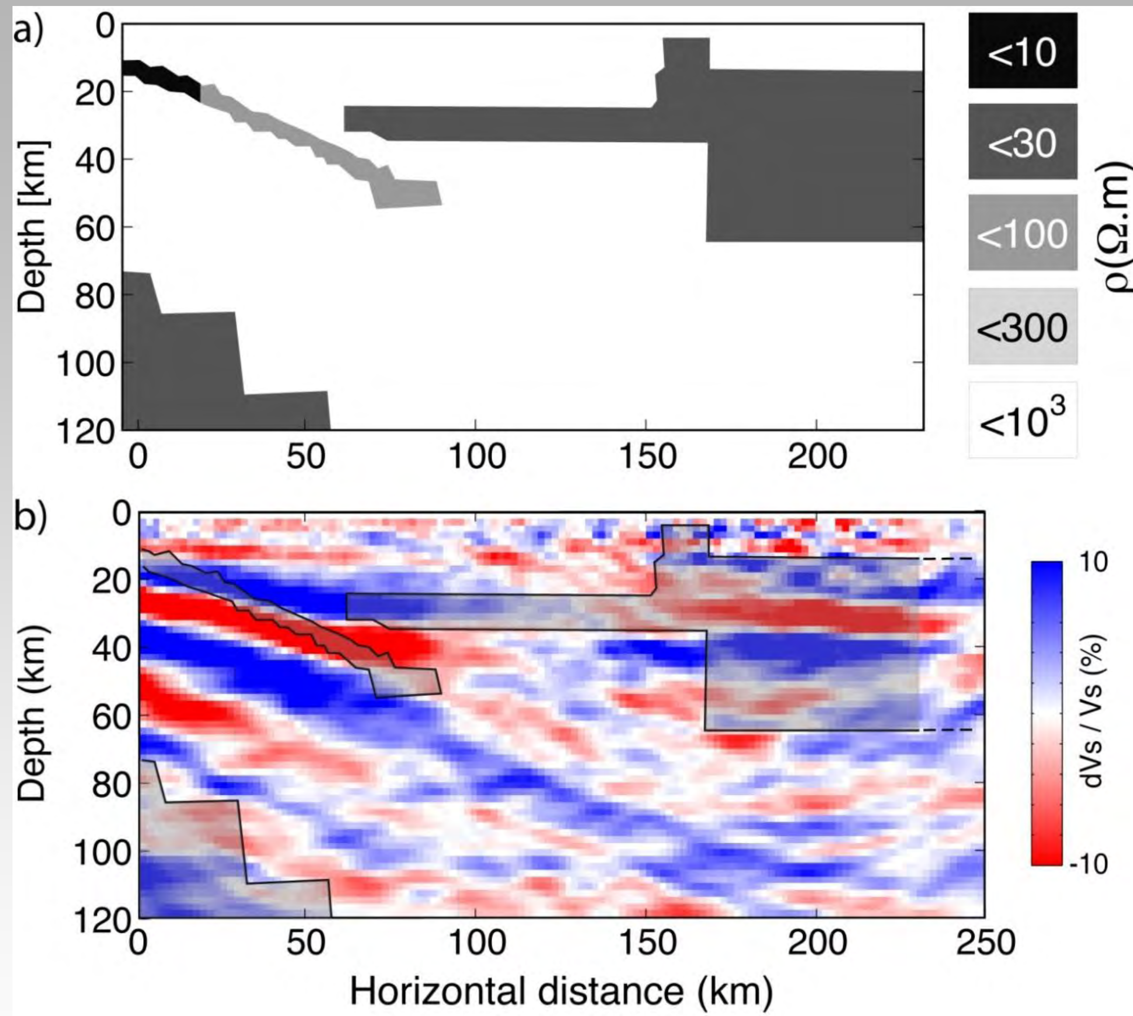


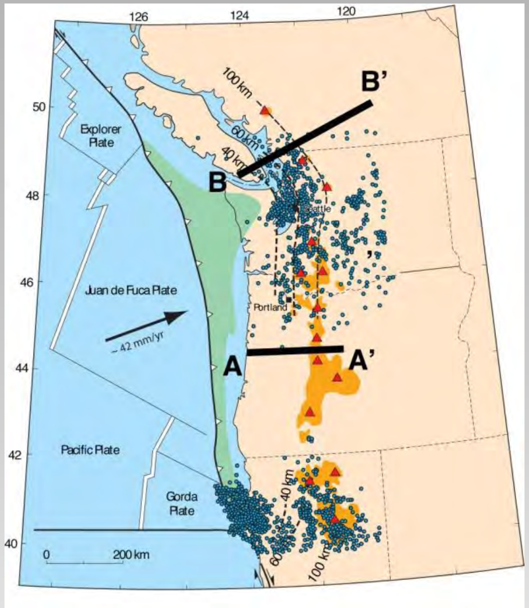
Figure by Ed Garnero, ASU

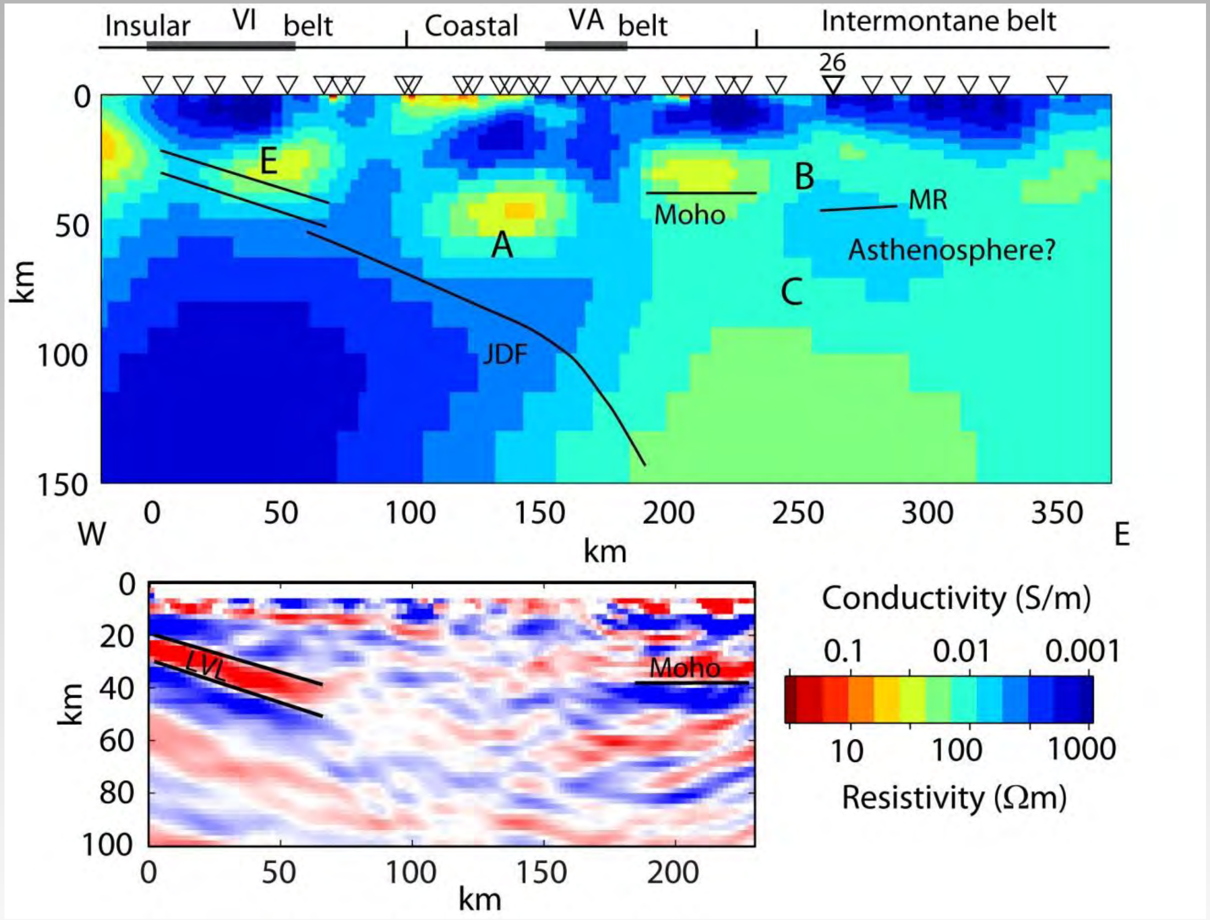




JDF plate is hot and young (6-10 Ma)

Oregon : Profile AA'
Magnetotellurics : Wannamaker et al., (1989)
Seismic RF : Rondenay et al., (2001)

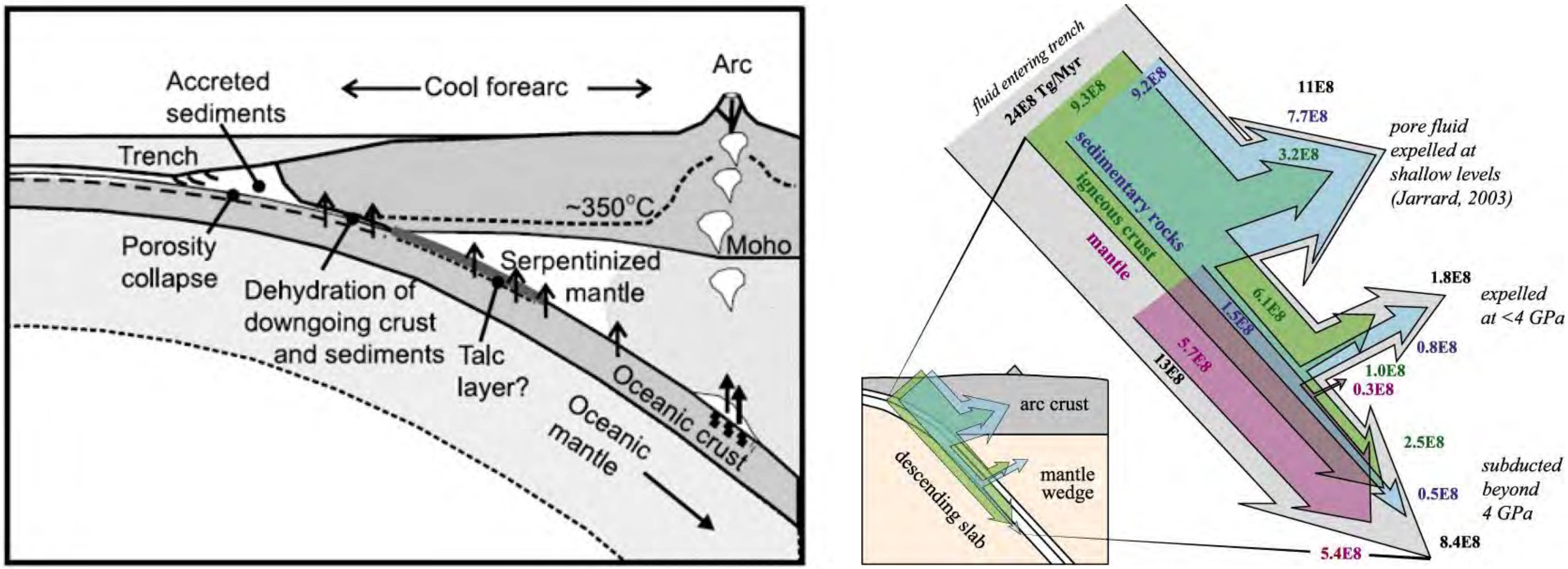




E : fluids expelled from plate into overlying crust Channel in crust or along boundary?

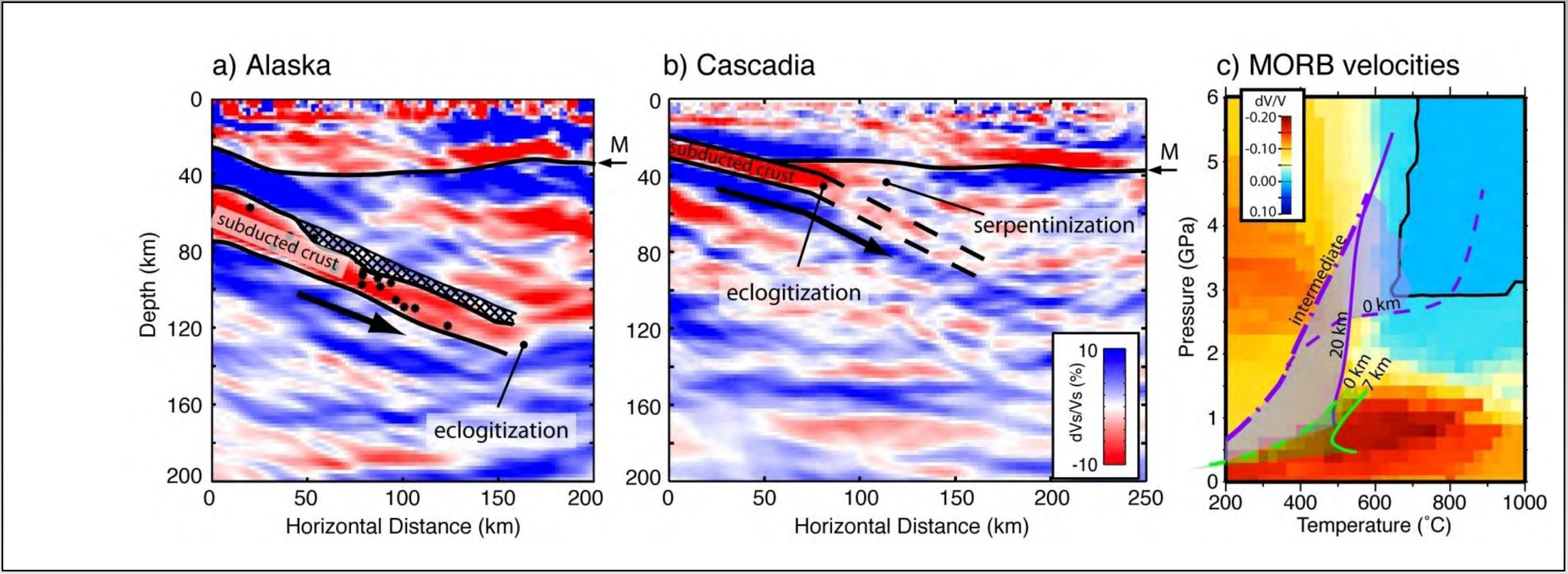
A : Mantle wedge conductor. Antigorite lowers seismic velocity, but not enough. Free fluids?

Southern British Columbia (BB')
Magnetotellurics : Soyer and Unsworth (2006)
Seismic RF : Nicholson et al., (2005)



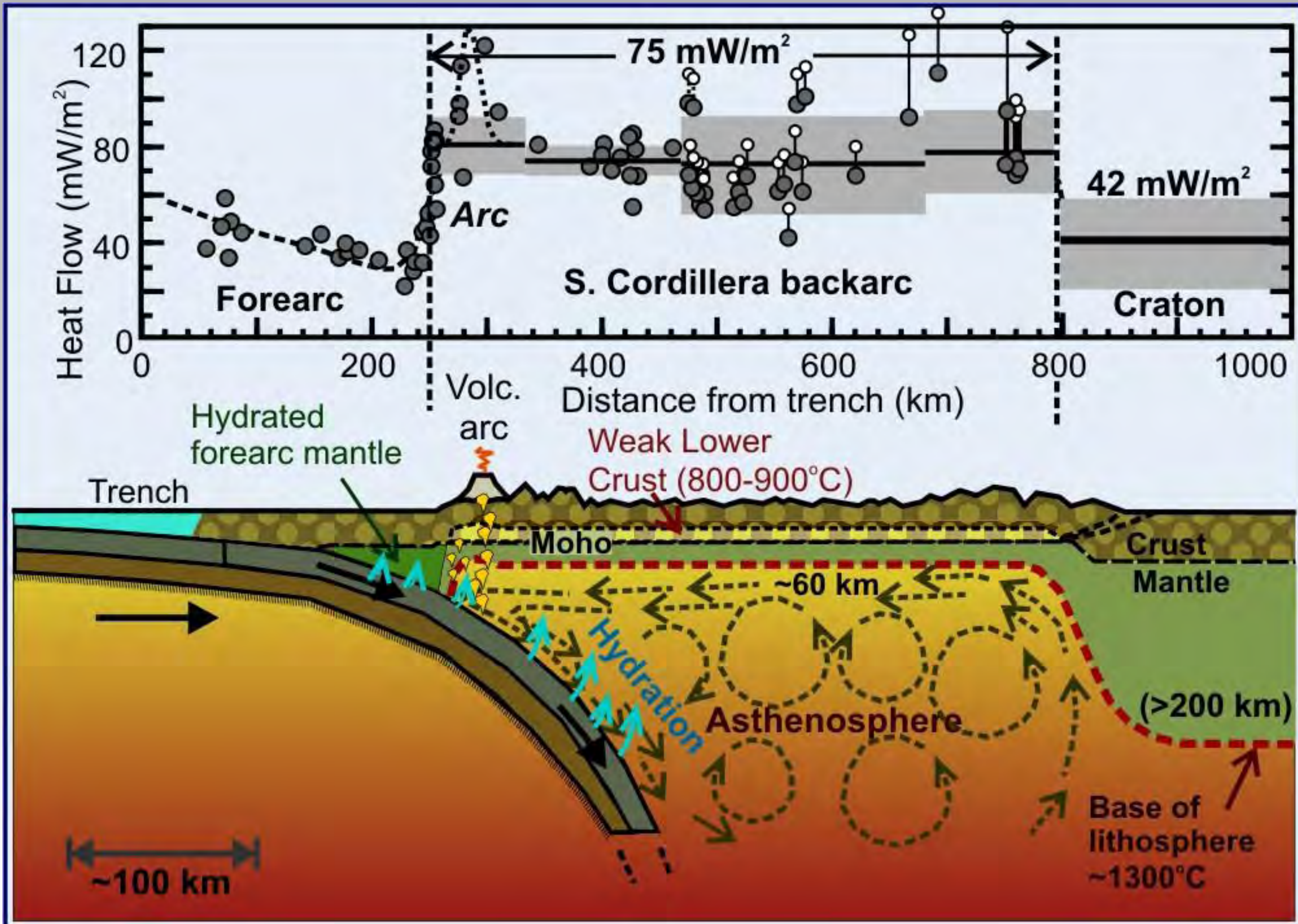
Hacker (2008)

Water transported to depth as
-Free water in sediments and oceanic crust
-Hydrated minerals in oceanic crust and upper mantle (serpentine)

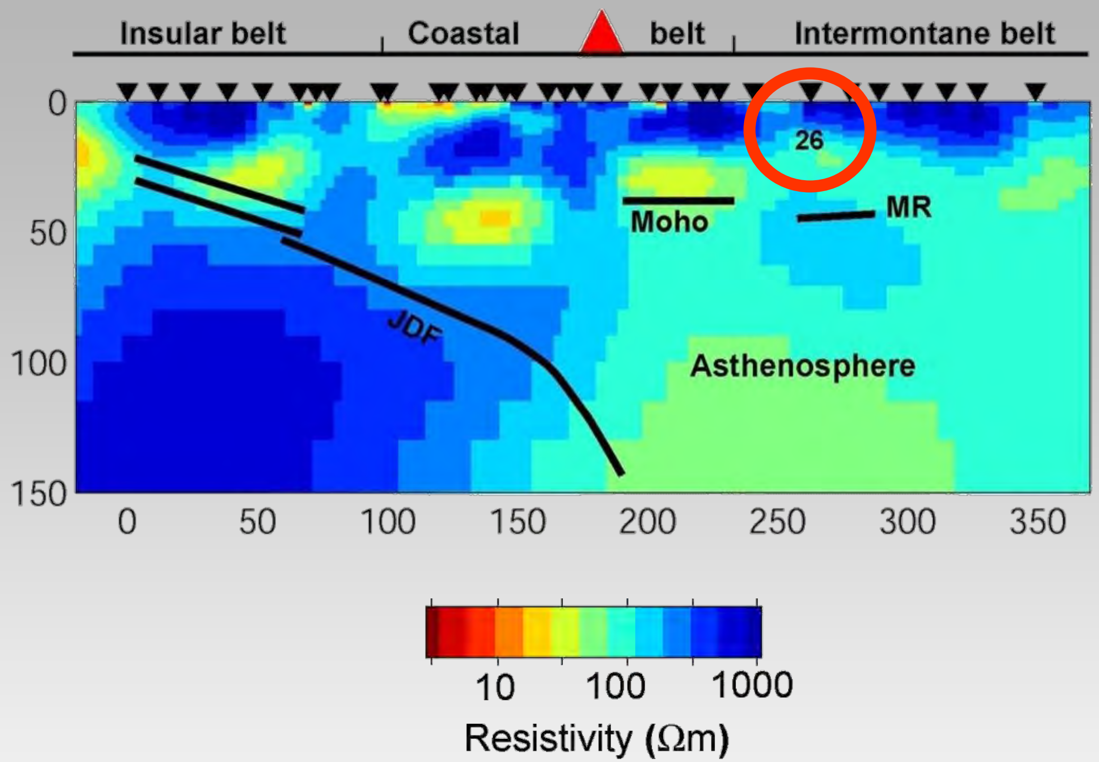


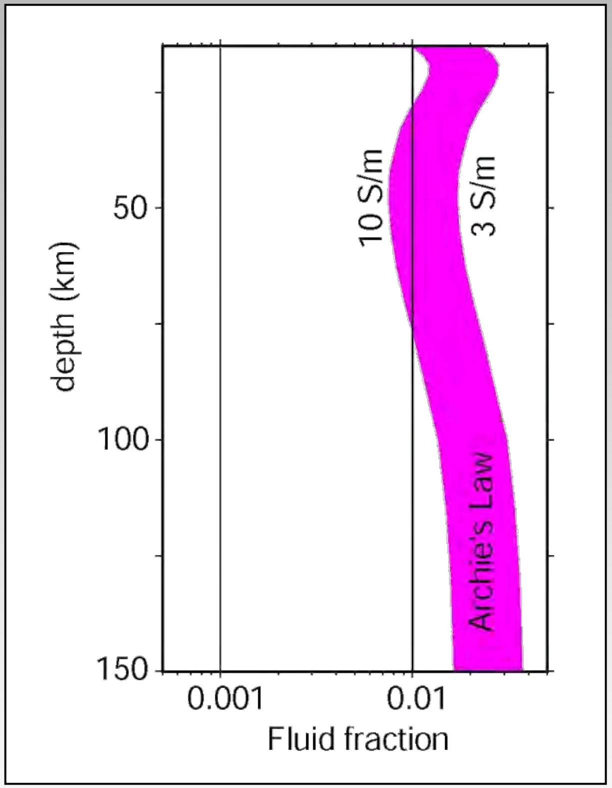
PT paths : Alaska Cascadia

Rondenay et al., 2008



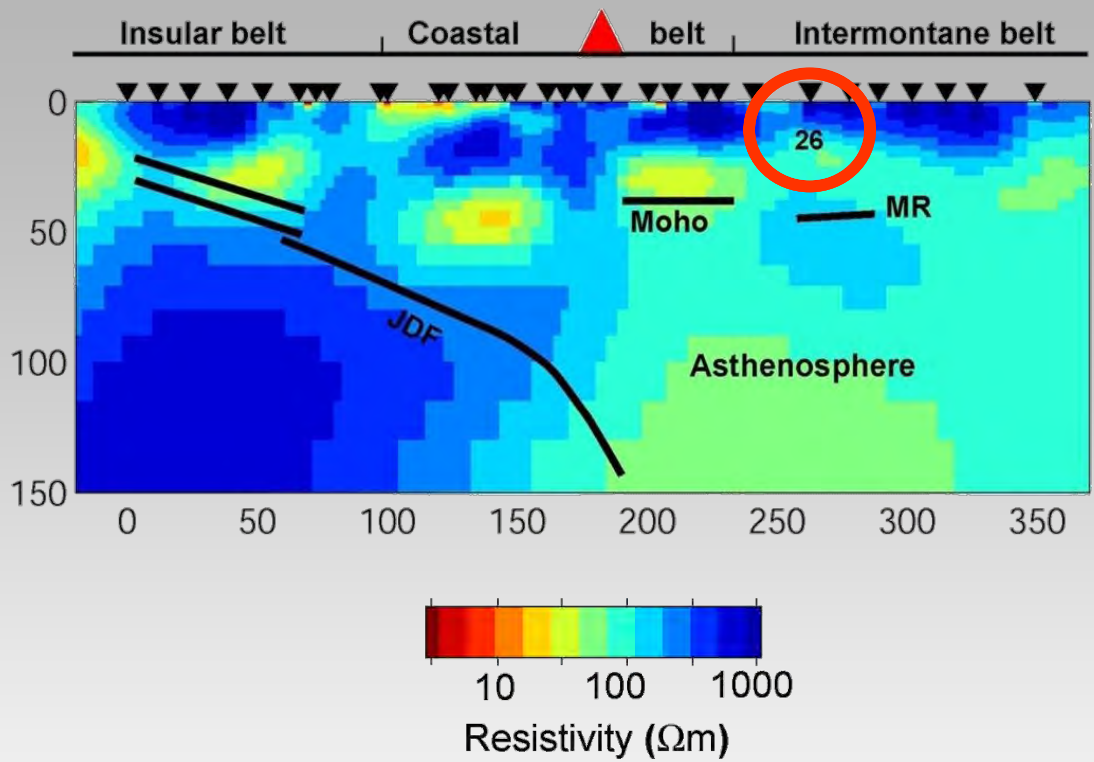
Hyndman et al., *GSA Today*, (2005)

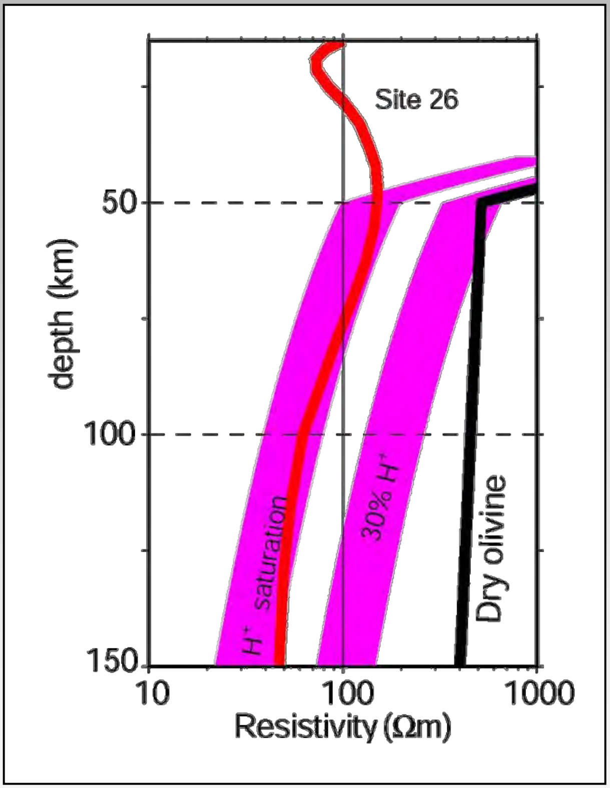




Soyer and Unsworth, *Geology*, 2006

Is the low resistivity in back arc due to melt / aqueous fluids?

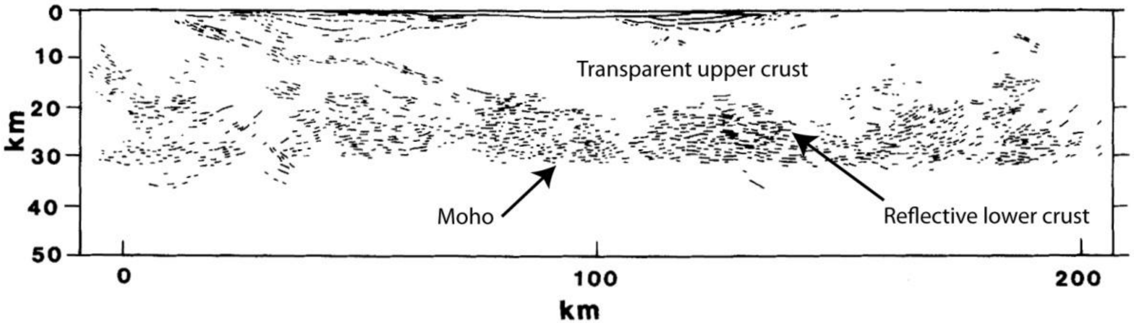




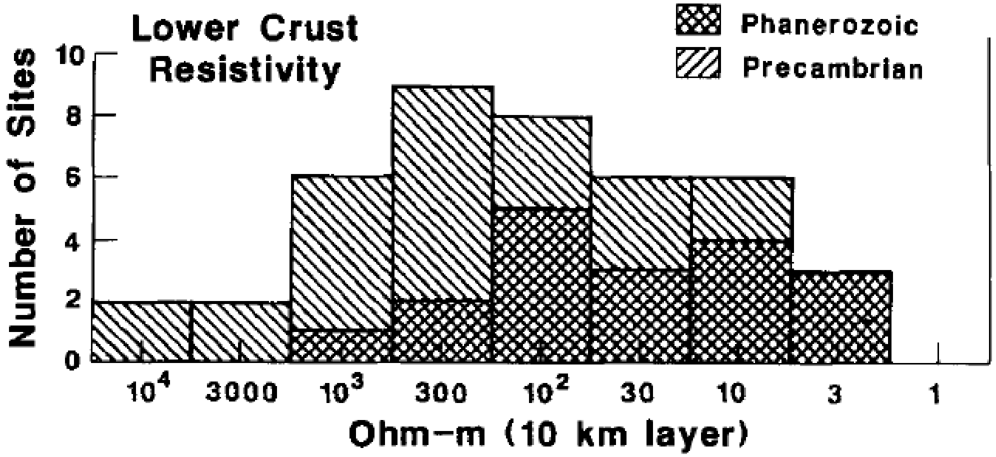
Soyer and Unsworth, *Geology*, 2006

Is the low resistivity in back arc due to hydrogen diffusion?

13.6 : Metasomatism in the stable continental lithosphere (Phanerozoic Crust)

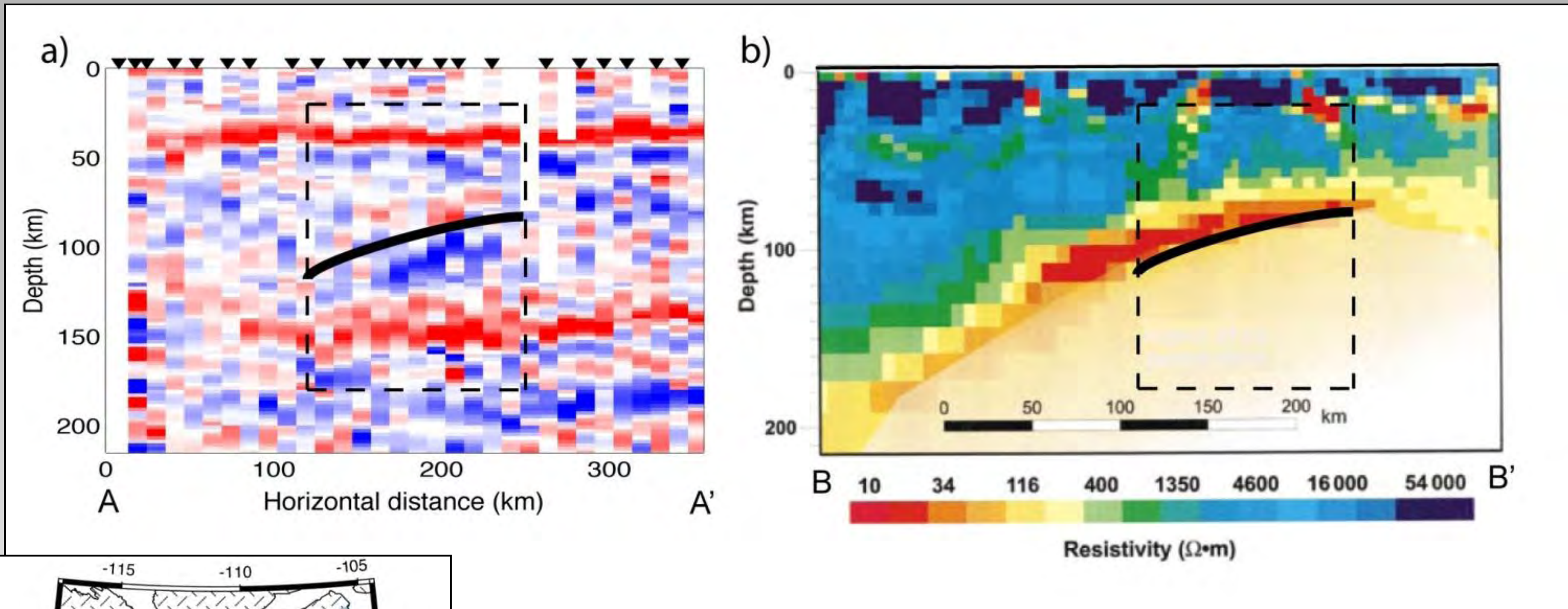


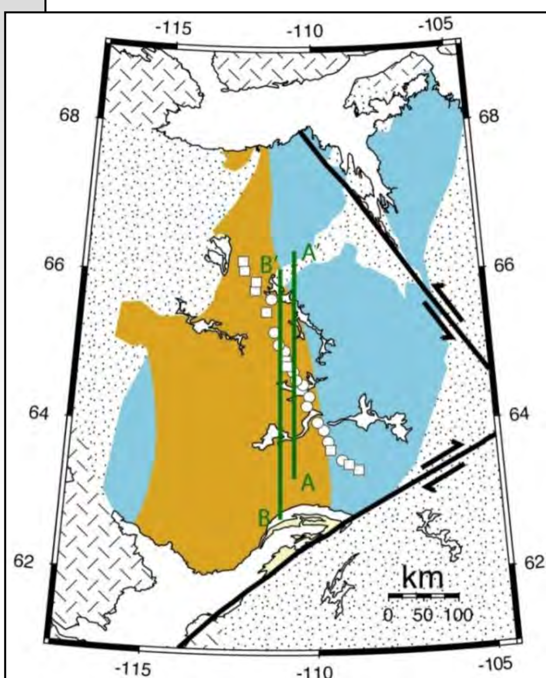
Matthews(1986)
Seismic reflections from lower continental crust



Hyndman and Shearer (1989)

Phanerozoic crust often characterized by
-Elevated conductivity in lower crust
-Enhanced seismic reflectivity
-Lower velocities than predicted by measurements on dry xenoliths



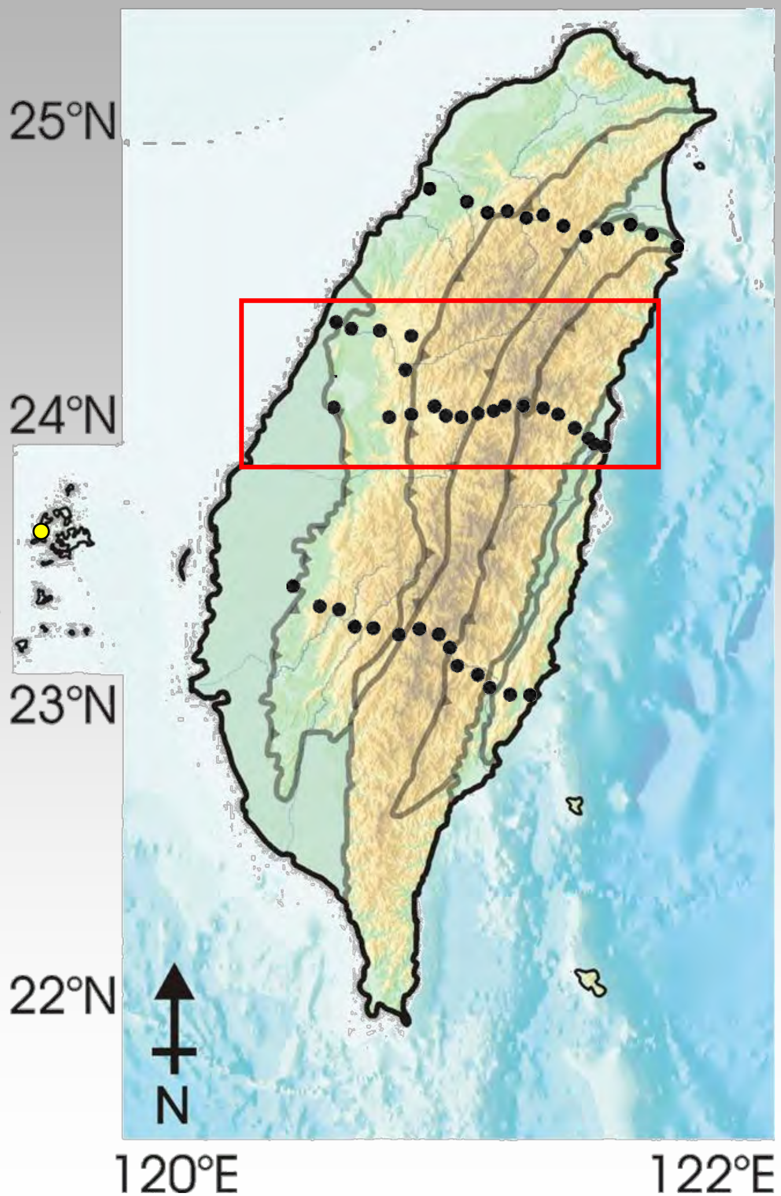


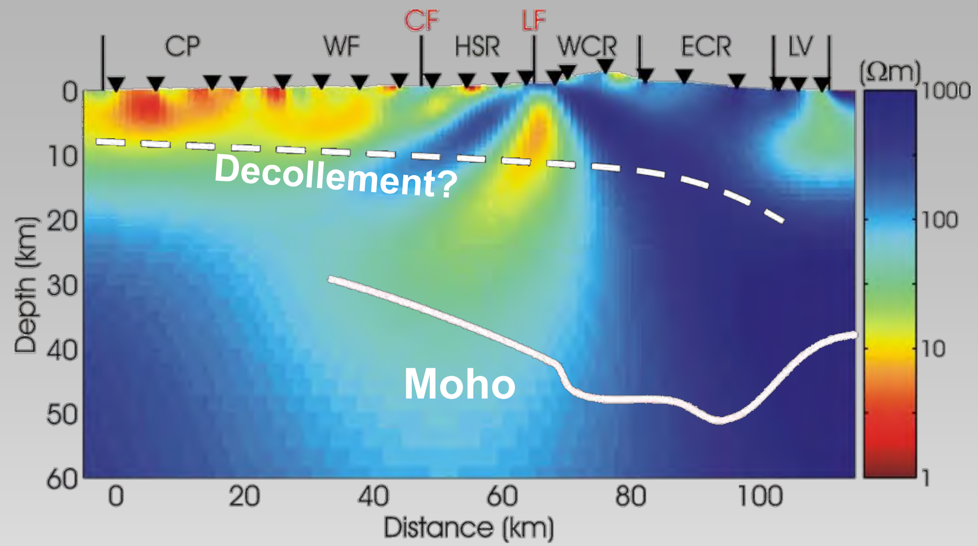
Slave Craton, Canada

Chen et al., (2009)
9-21% seismic velocity reduction – hydrated minerals
Resistivity decrease – graphite
Subduction event at 3.5 Ga

Jones and Ferguson (2001)
Decrease in resistivity at Moho (50000 – 5000 Ωm)

13.7 : Fluids generated in collision zones (arc-continent collision)

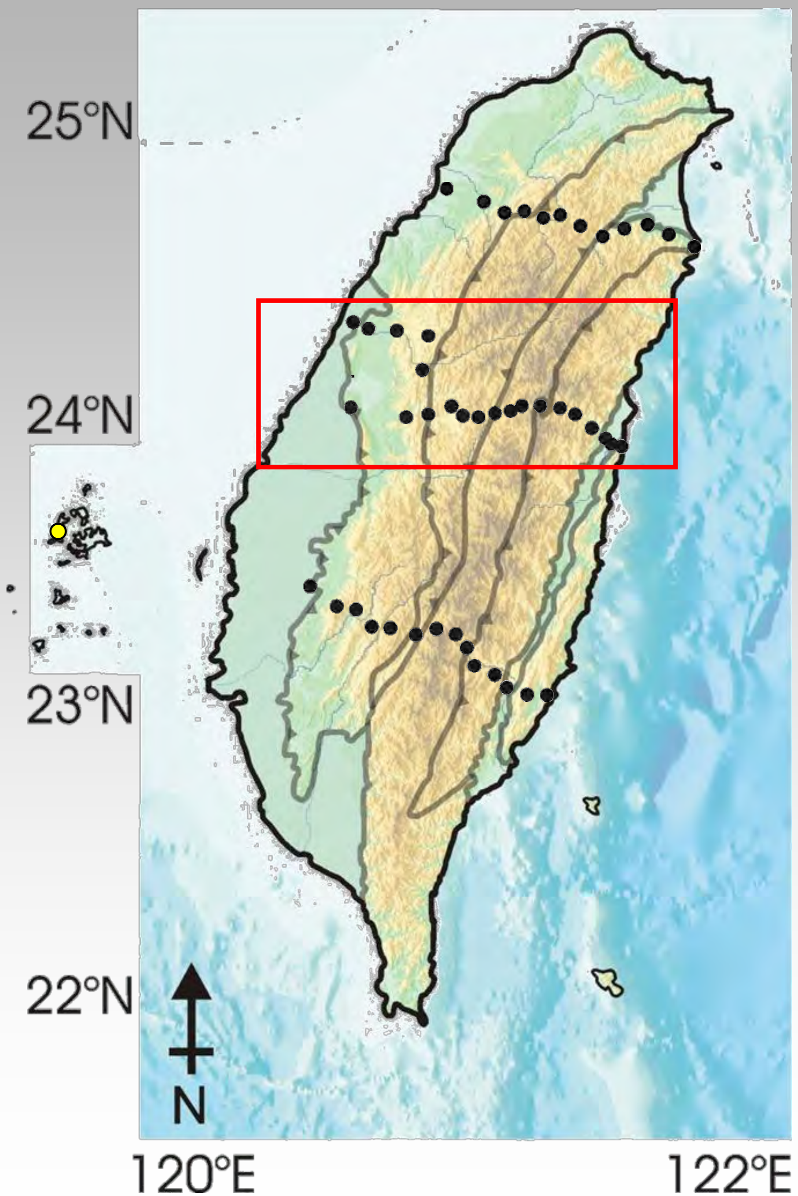


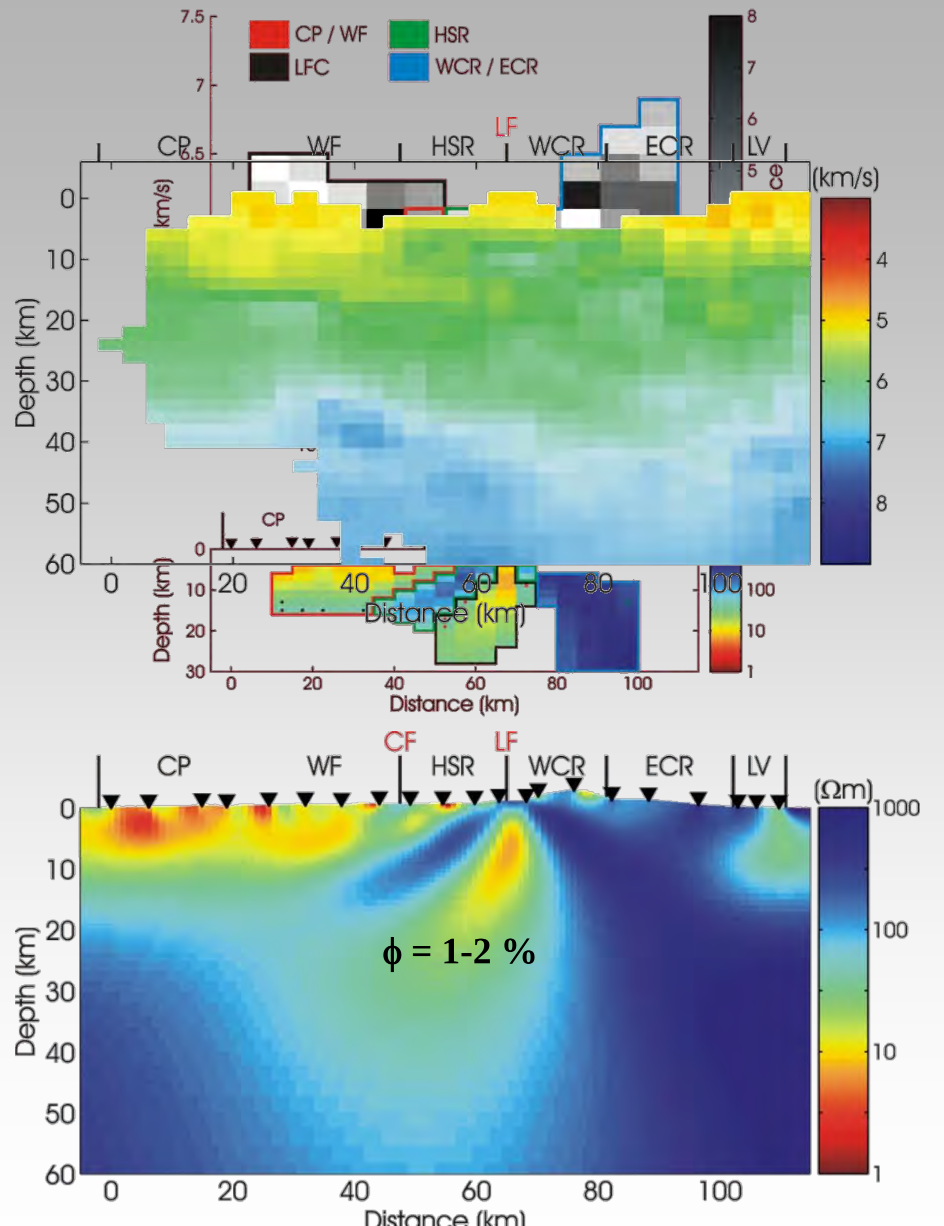


Bertrand et al., *Geology*, 2009

- Lishan fault conductor extends across inferred decollement
- Inconsistent with thin-skinned model
- Fluid originates in crustal root (prograde metamorphism)

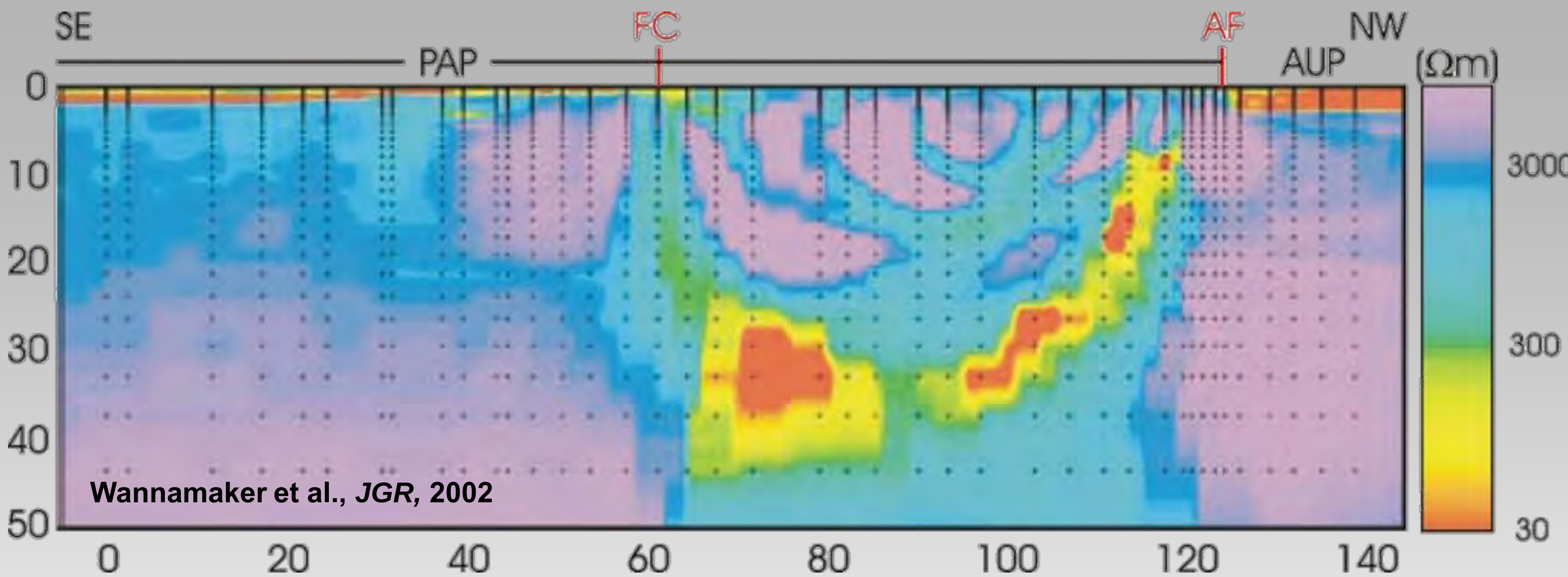
13.7 : Fluids generated in collision zones (arc-continent collision)



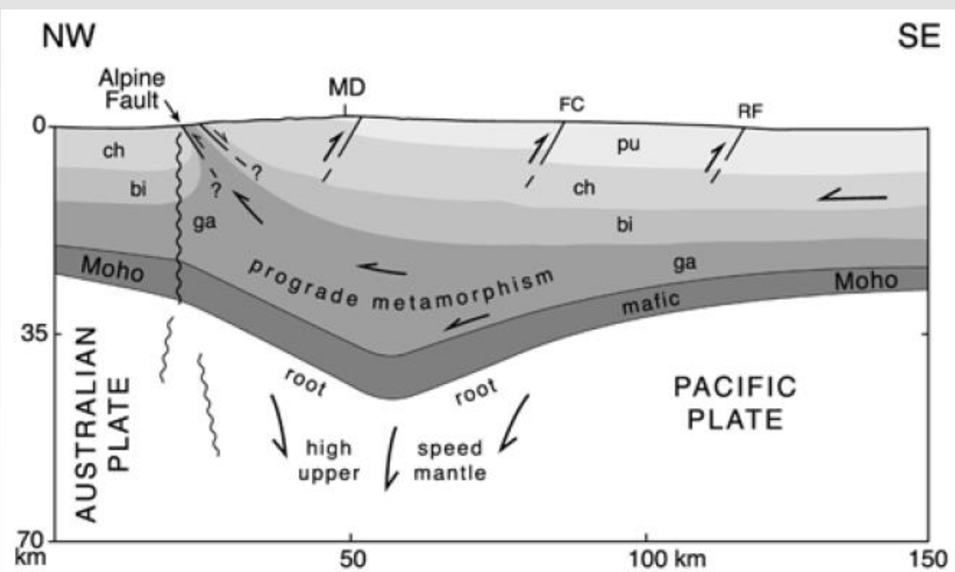


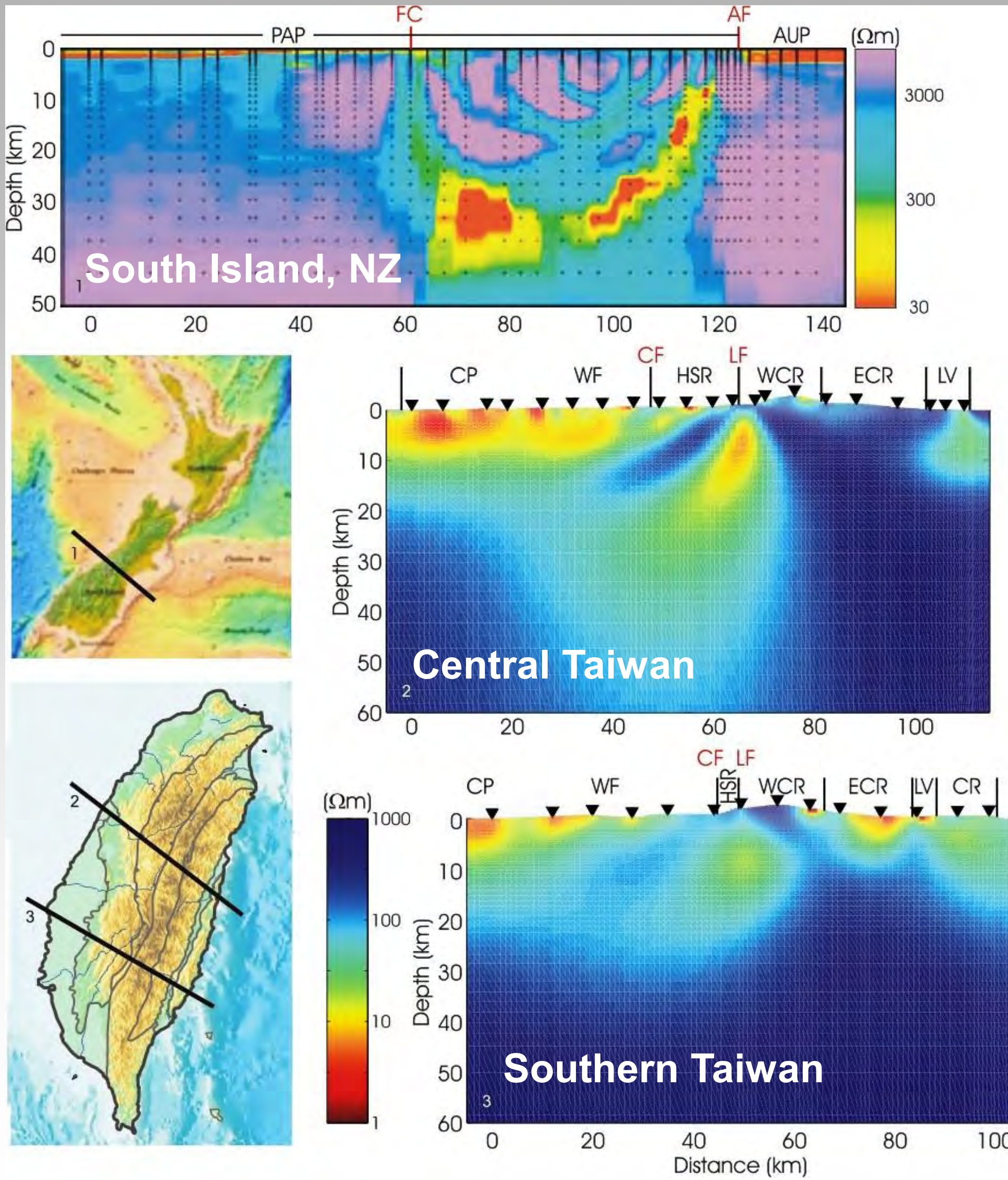
Bertrand et al., *Geology*, 2009

13.7 : Fluids generated in collision zones



Wannamaker et al., *JGR,* 2002

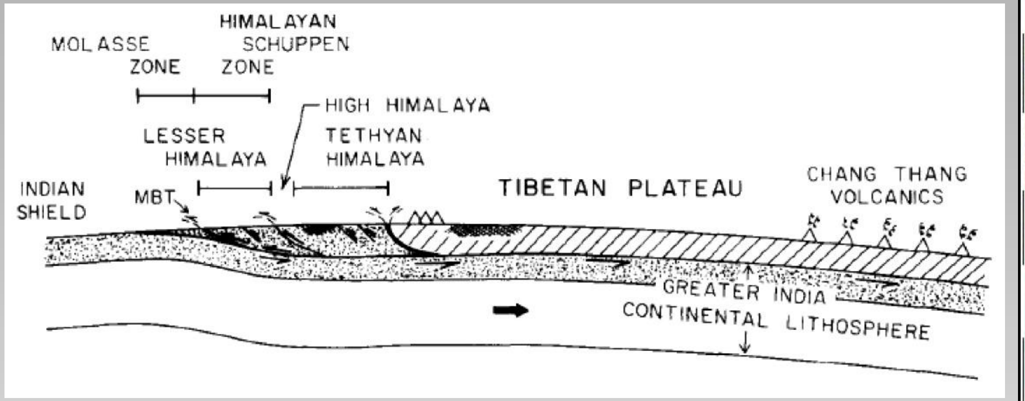




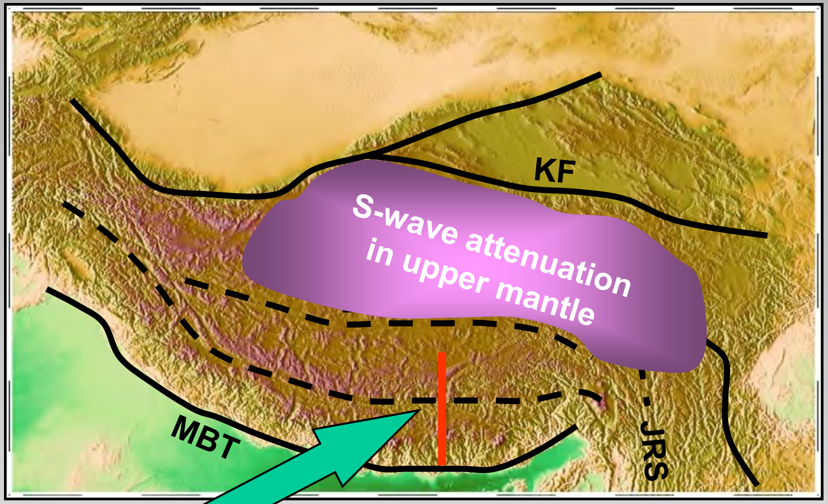
Wannamaker et al., (2002)

Bertrand et al., (2009)

13.7 : Fluids generated in collision zones (Himalaya and Tibetan Plateau)

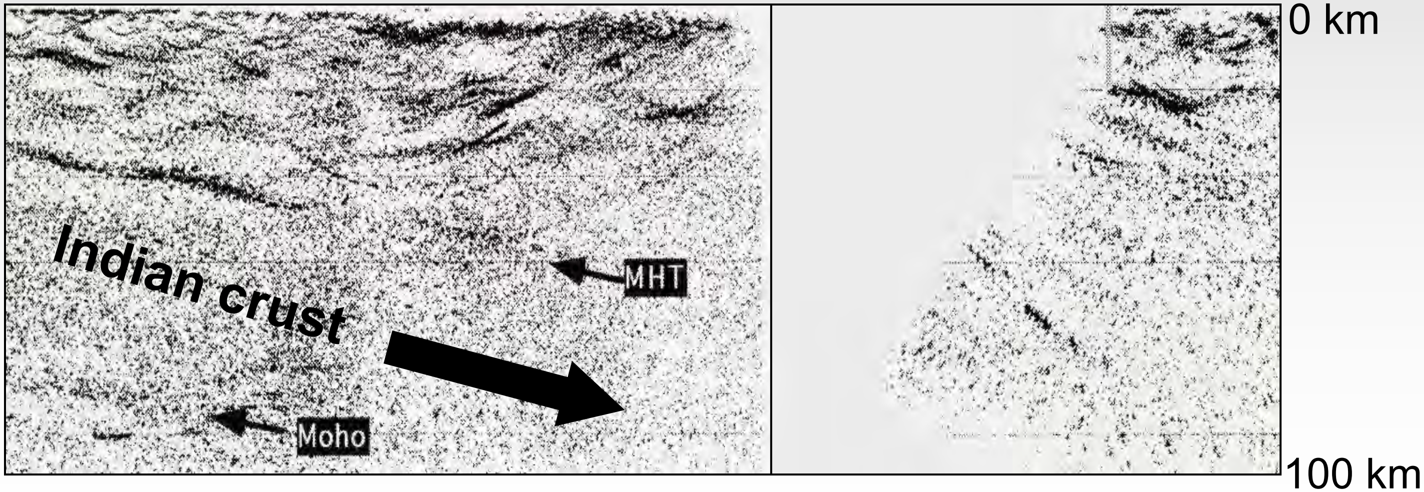


Ni and Baranzangi, *JGR*, (1982)



INDEPTH-I 1992

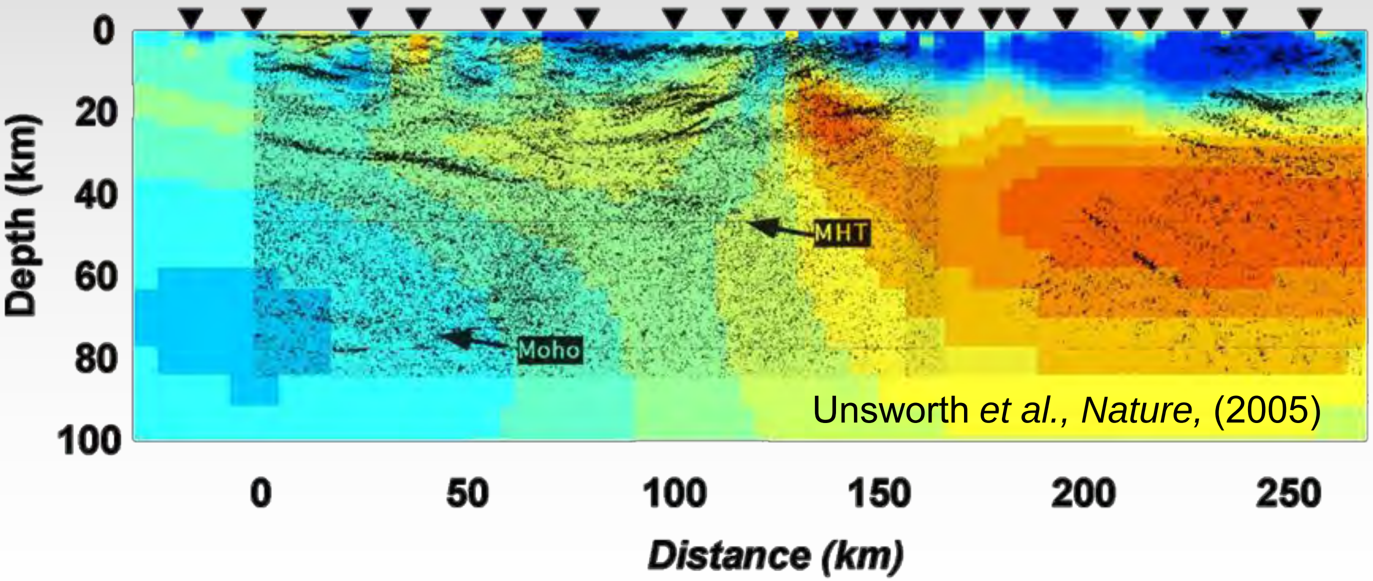
INDEPTH-II 1994

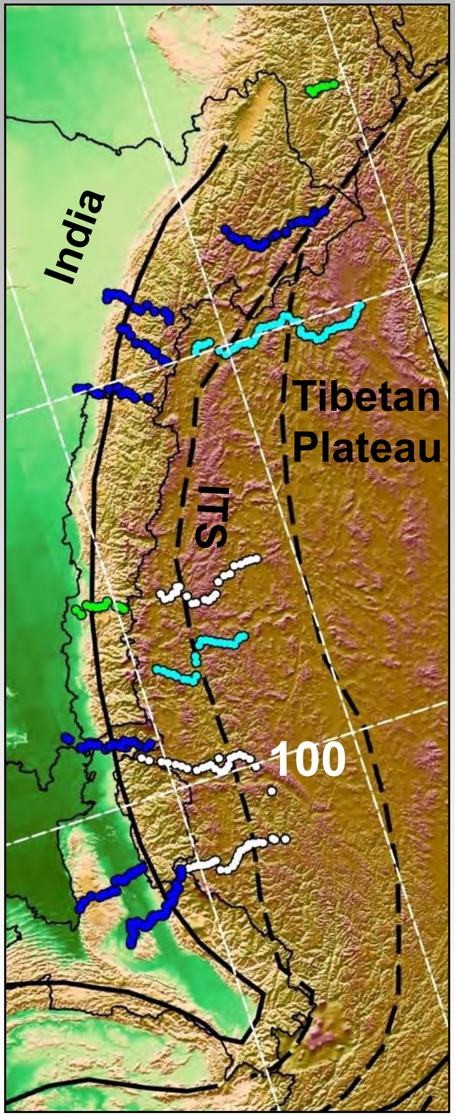


Nelson et al., Science, (1996)

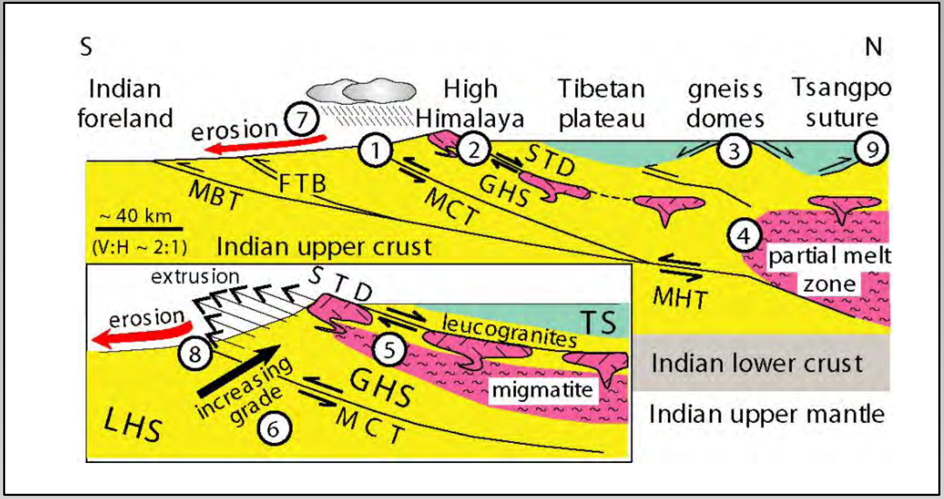
13.7 : Fluids generated in collision zones (Himalaya and Tibetan Plateau)

13.7 : Fluids generated in collision zones (Himalaya and Tibetan Plateau)



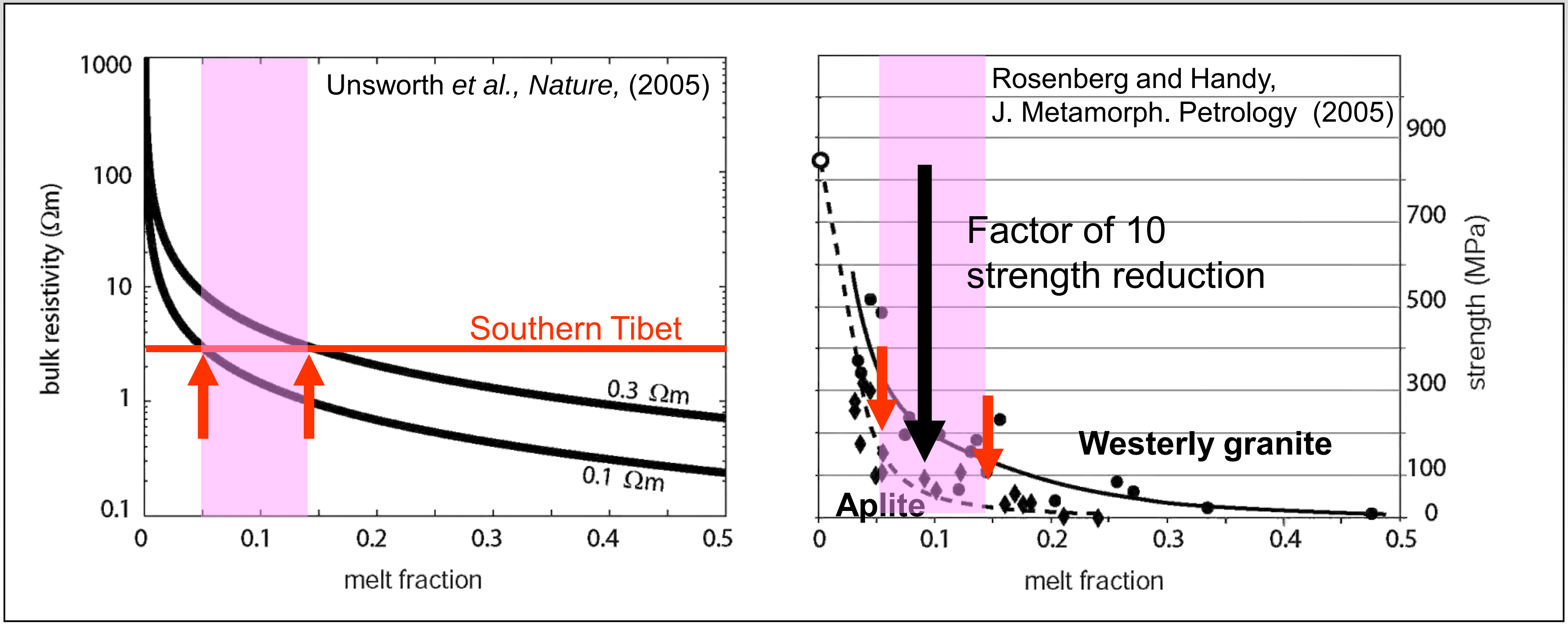


13.7 : Fluids generated in collision zones (Himalaya and Tibetan Plateau)

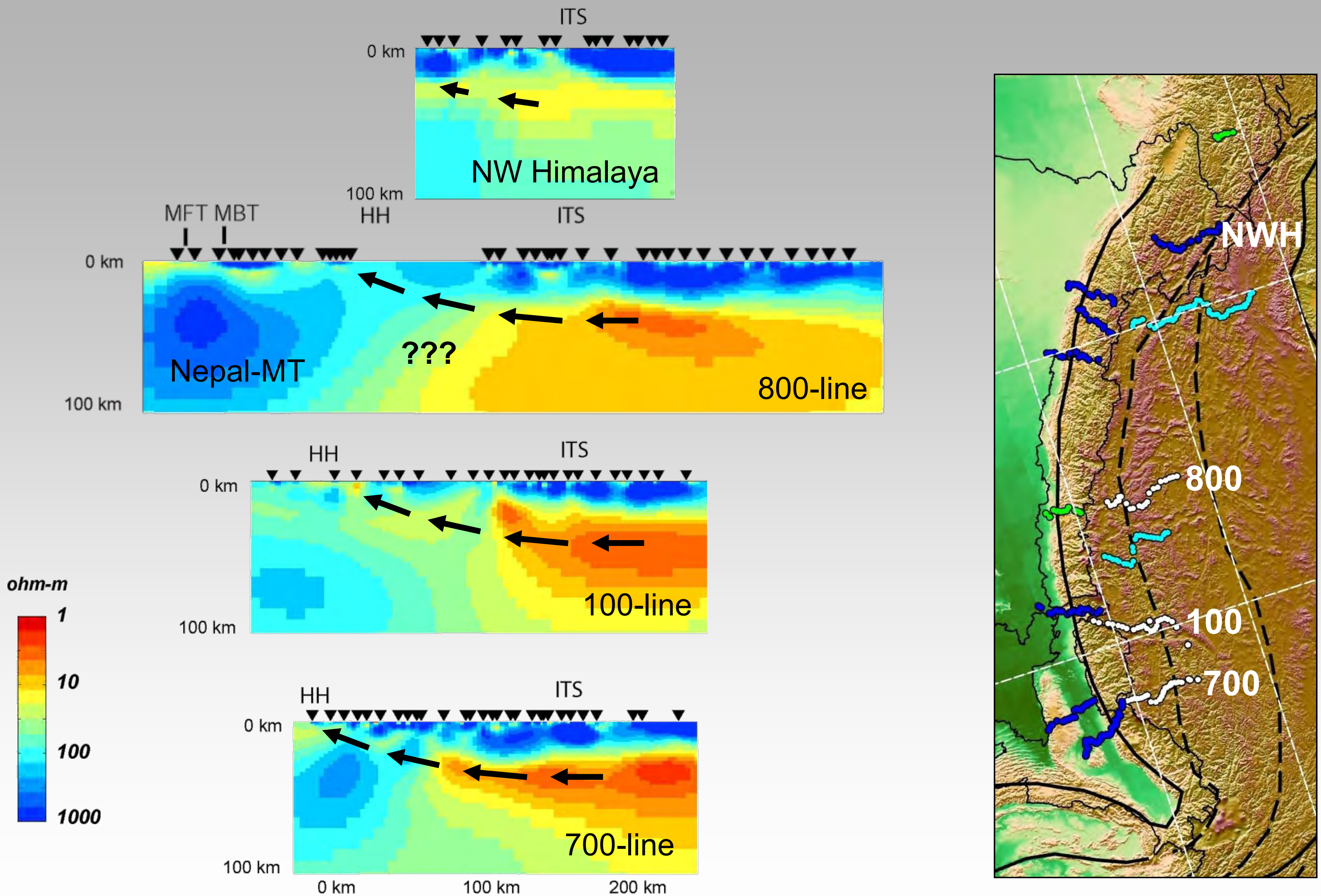


•Beaumont et al., *Nature* (2002) model requires factor of 10 reduction in viscosity for crustal flow to occur

•MT data require 5-12% melt. This is consistent with a factor of 10 strength reduction.

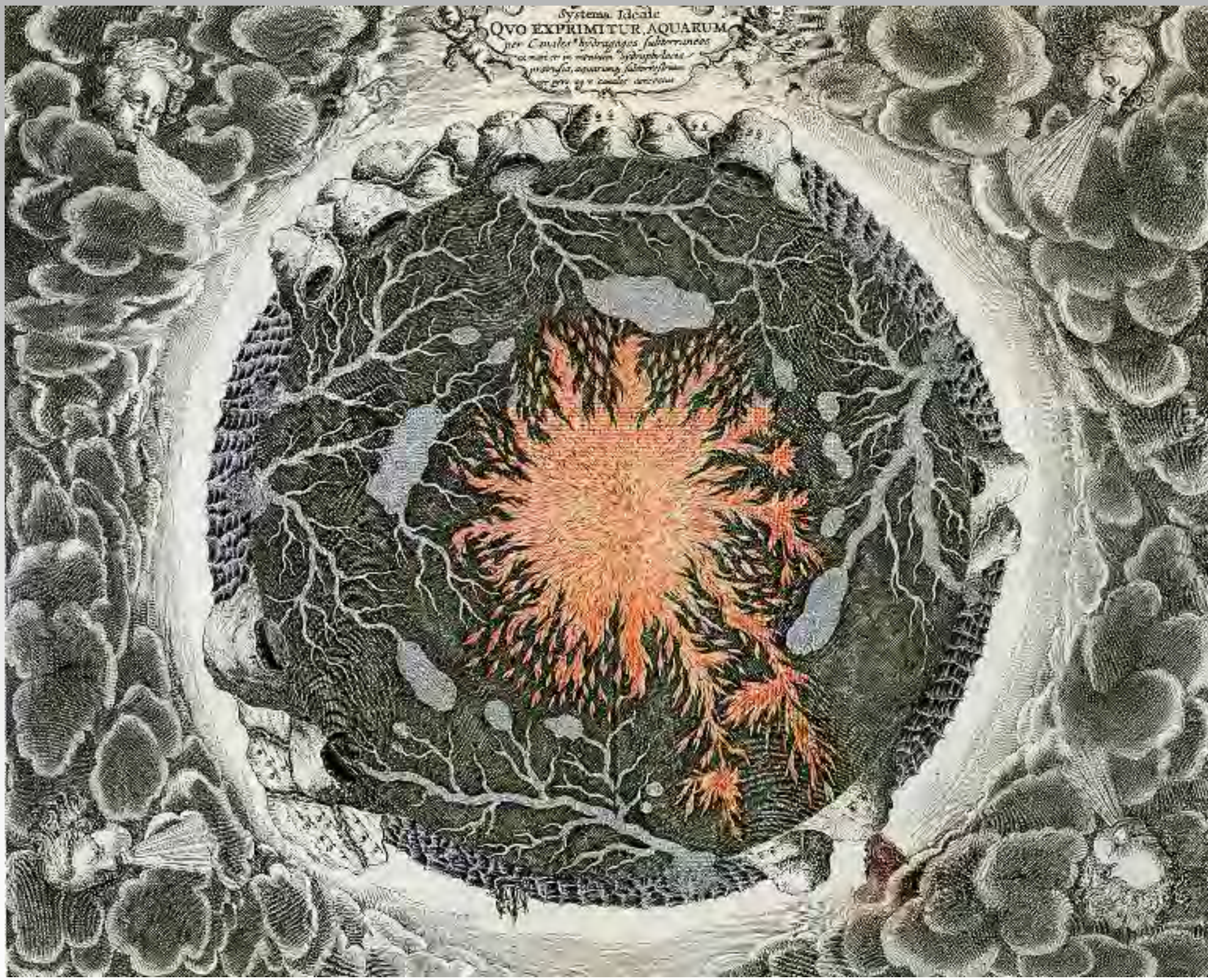


13.7 : Fluids generated in collision zones (Himalaya and Tibetan Plateau)



Unsworth *et al.*, *Nature*, (2005) NLCG6 inversions using code of Rodi and Mackie (2000)

13.8 : Conclusions



ACKNOWLEDGEMENTS

- Invitation from Dan Harlov and Tom Chacko to attend Goldschmidt meeting in 2008.
- Models and data from many colleagues.
- Funding from NSF, NSERC, DOE, US Geological Survey, Alberta Ingenuity fund and University of Alberta
- Many people who worked in the field to collect the data