Speed of Melt Extraction at Mid-Ocean Ridges

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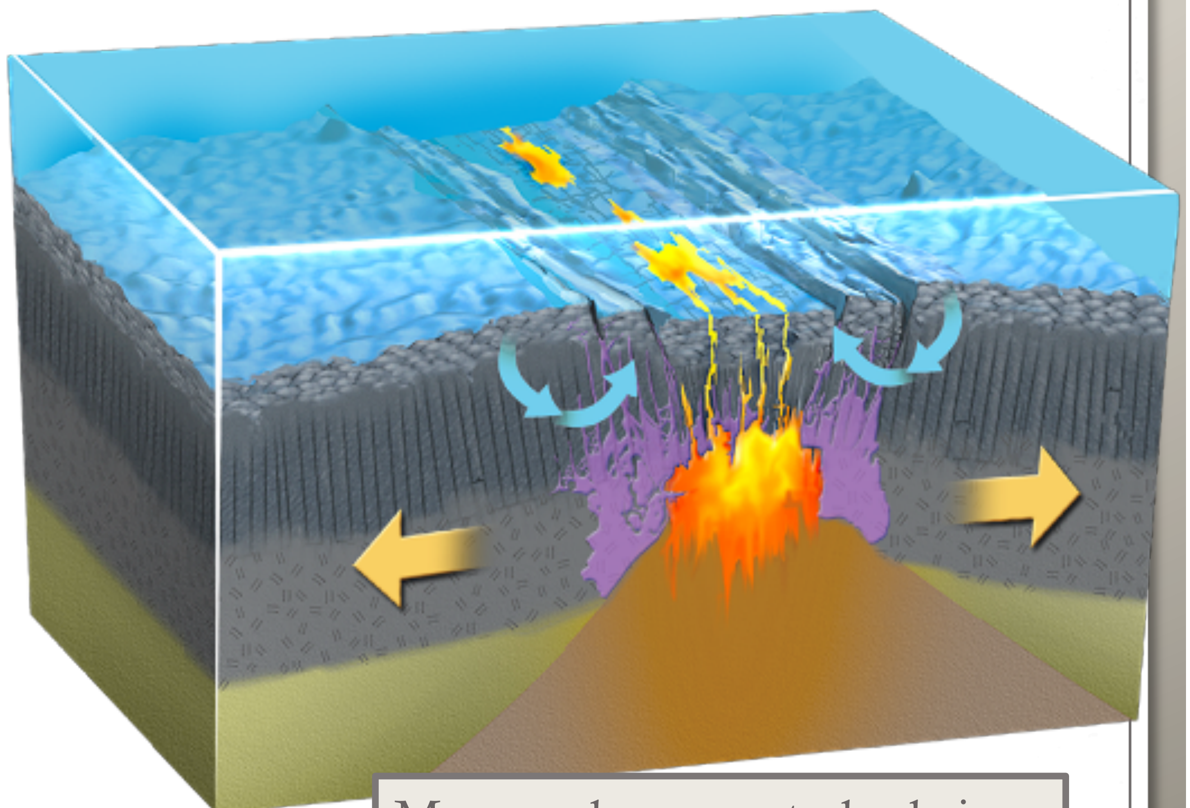
Importance of Mid-Ocean Ridges

- Central component of Earth systems
  - Largest volcanic outpouring
  - Creation of "lithosphere"
  - Facilitates plates tectonics
  - Hydrothermal circulation
  - Biological communities

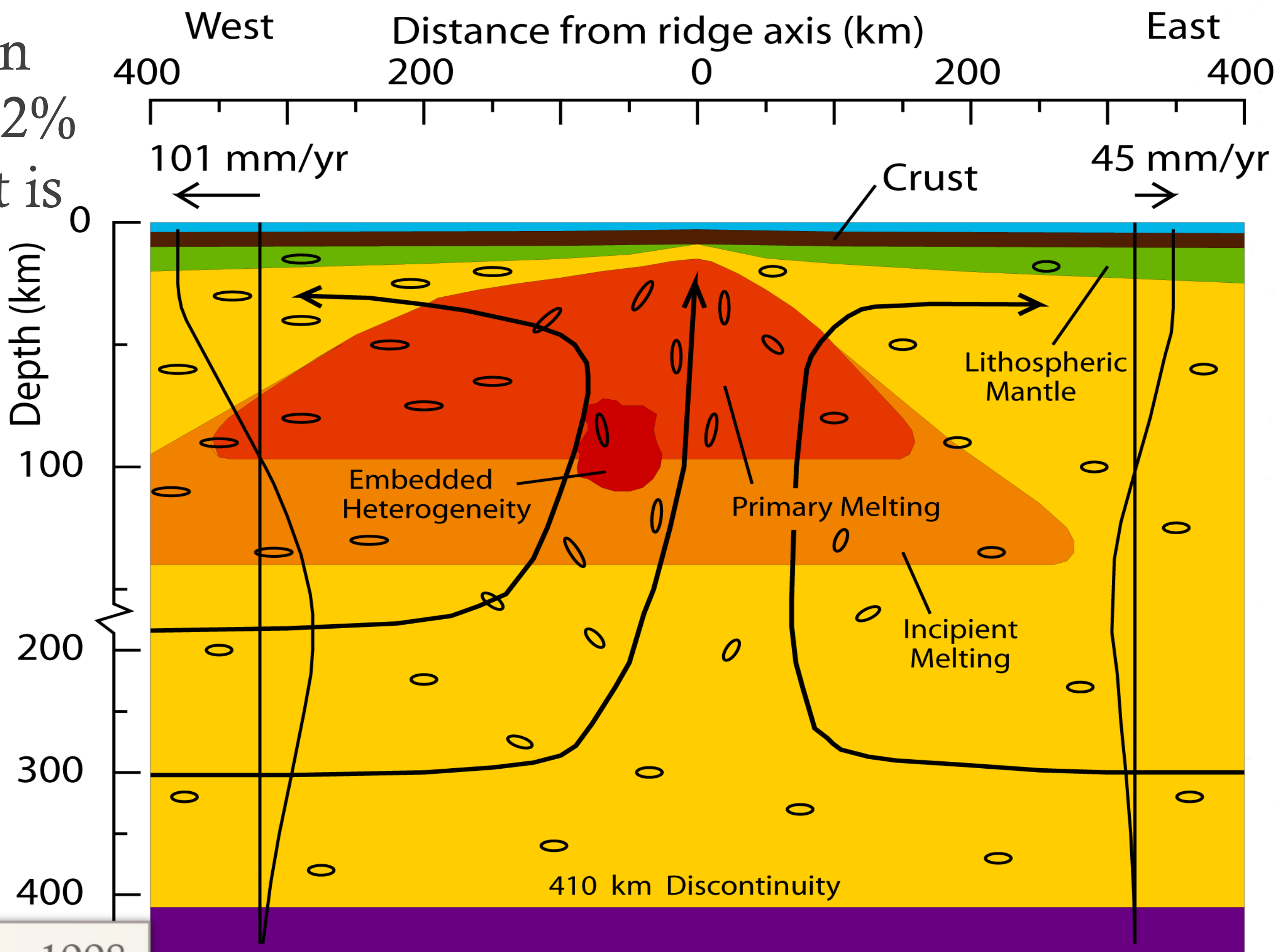


Magma plays a central role in mid-ocean ridge systems

Reynolds et al., Exploring Geology

Melting at Depth

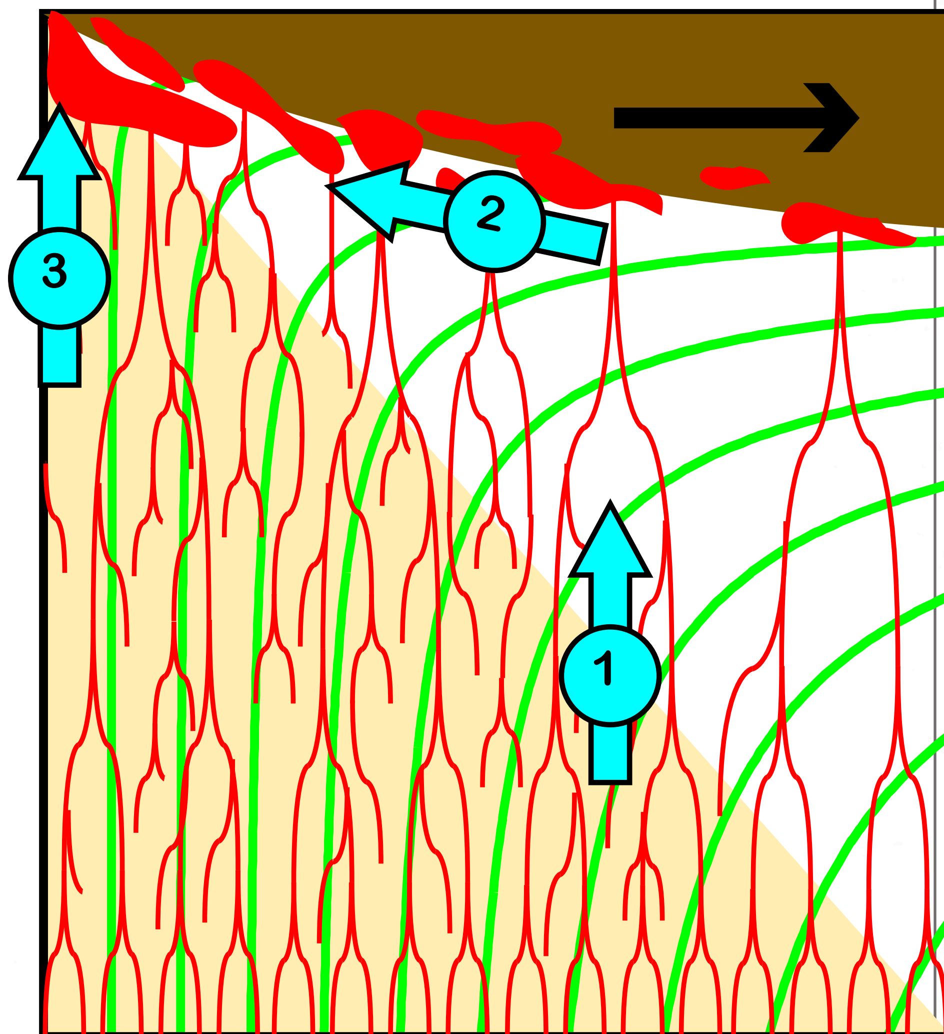
- Wide region where 1 to 2% partial melt is present



Melt Seismic Team, 1998

Simplified melt migration model

- 1) Rapid, subvertical melt extraction below the plate
- 2) Sub-horizontal migration along a permeability barrier at the base of the lithosphere
- 3) Subvertical extraction at tectonized plate boundary

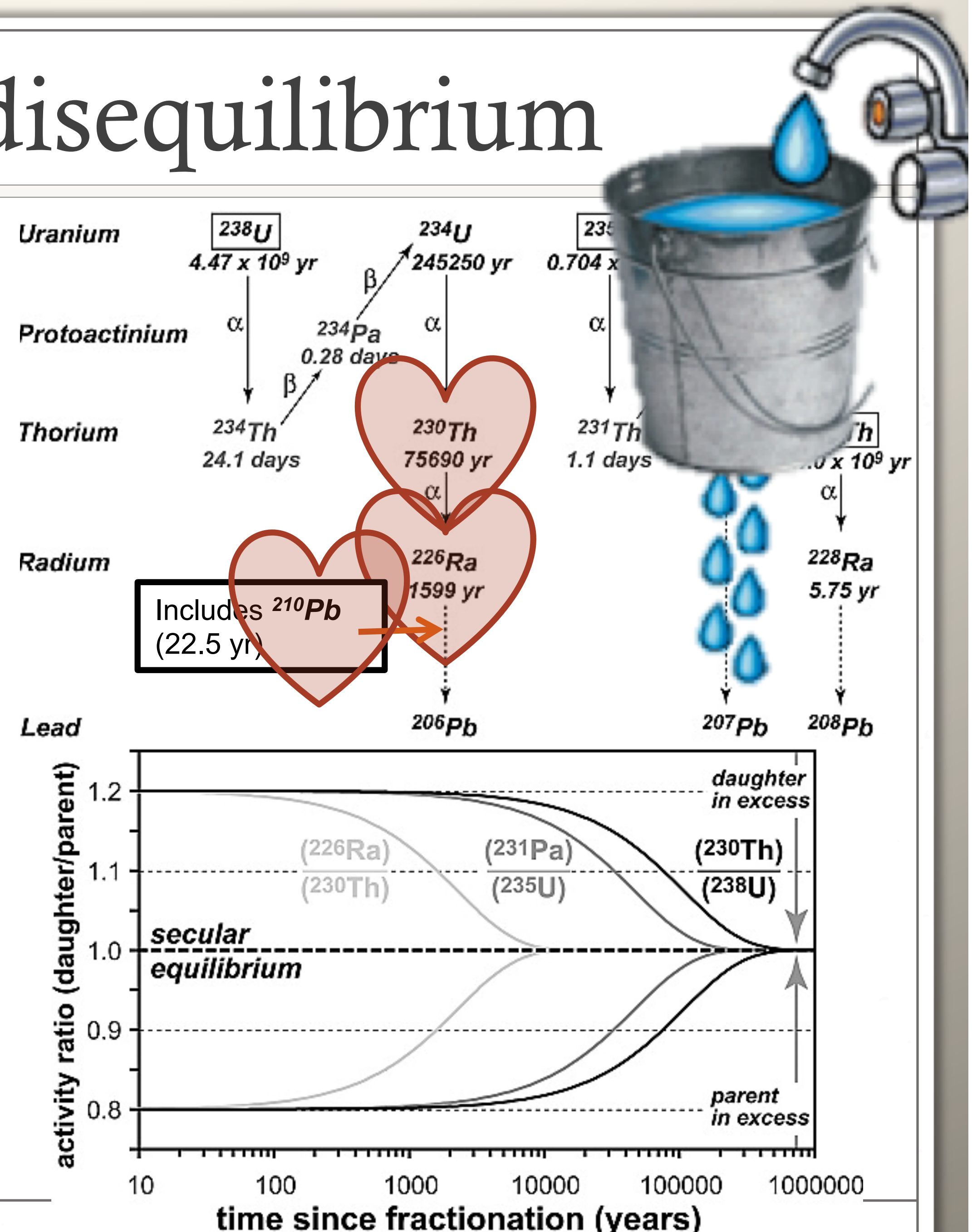


Gregg et al., 2012

Inspired by Sparks and Parmentier, EPSL, 1991

U-series disequilibrium

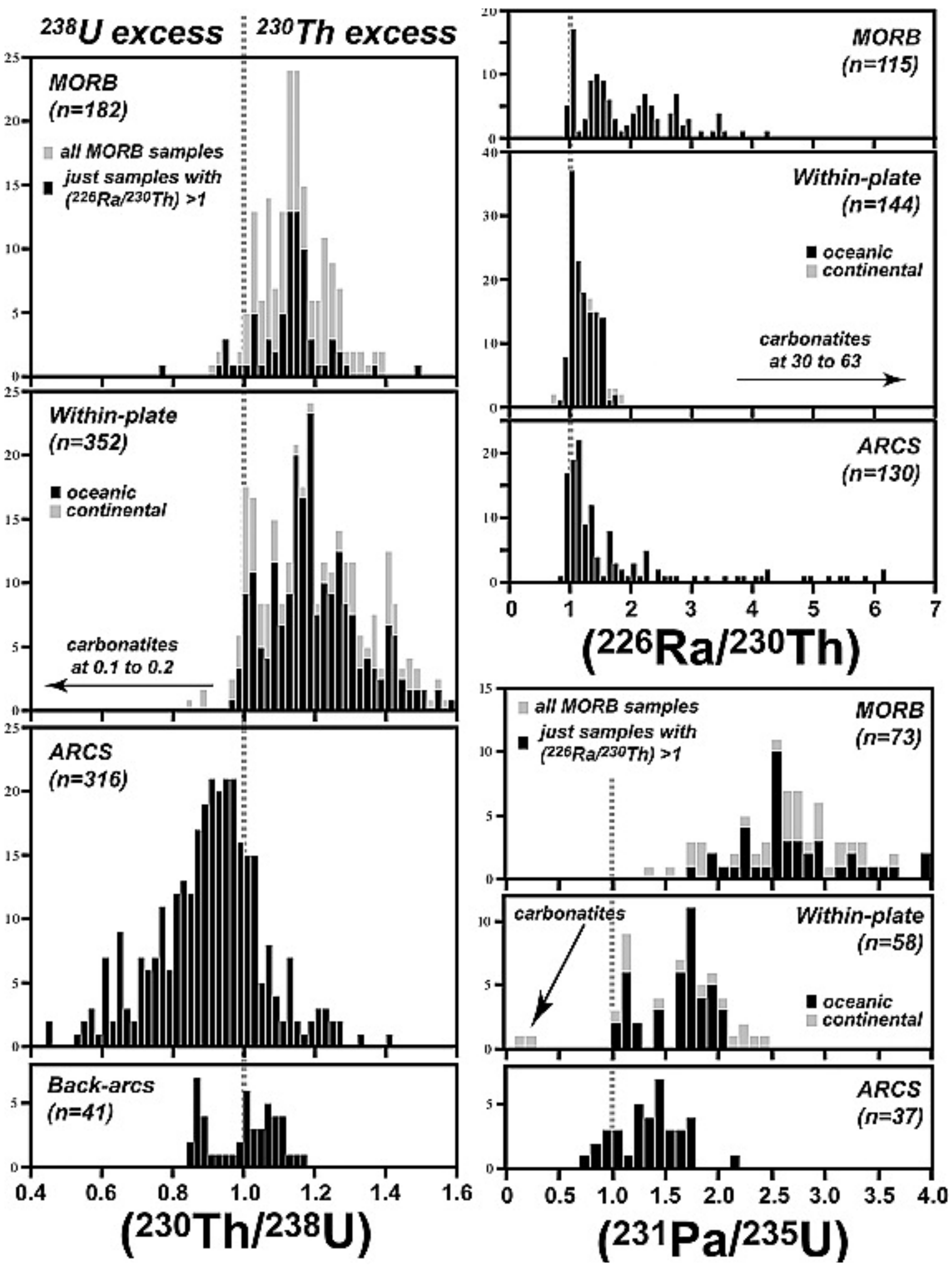
- Decay chains reach equilibrium where generation exactly balances decay
- Melting can perturb equilibrium during to partitioning
  - Needs melting deeper than 60 km
- Equilibrium recovered after a few half lives



Peate and Hawkesworth 2005

Disequilibrium at Mid-ocean ridge

- Excess of isotopes with half lives less than 10^5 years.
  - ^{230}Th: 76 kyr
  - ^{231}Pa: 33 kyr
  - ^{236}Ra: 1.6 kyr
- Rise from 60 km depth in less than 2000 years
  - 30 m/yr
  - 10^{-6} m/s



Peate and Hawkesworth 2005

Required permeability

- Melt driven upward by buoyancy

$$\phi\left(v_f - v_s\right) = \frac{k}{\mu}\nabla P = k\,\Delta\rho g/\mu$$

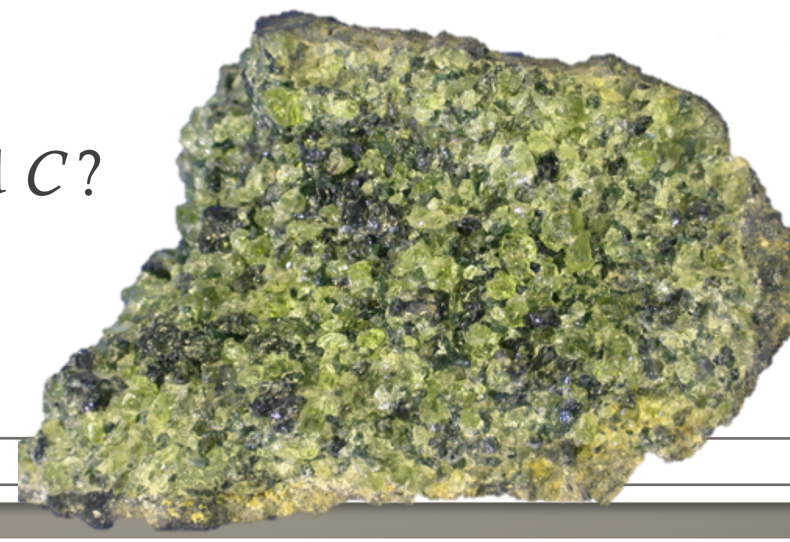
  - Density contrast: 300 kg/m^3
  - Gravity: 10 m^2/s
  - Melt viscosity: 10 Pa s
  - Porosity: 10^{-2}
  - Extraction velocity: 10^{-6} m/s

- Required permeability: k=3x10^{-11} m^2

$$k = \frac{\phi^n D^2}{C}$$

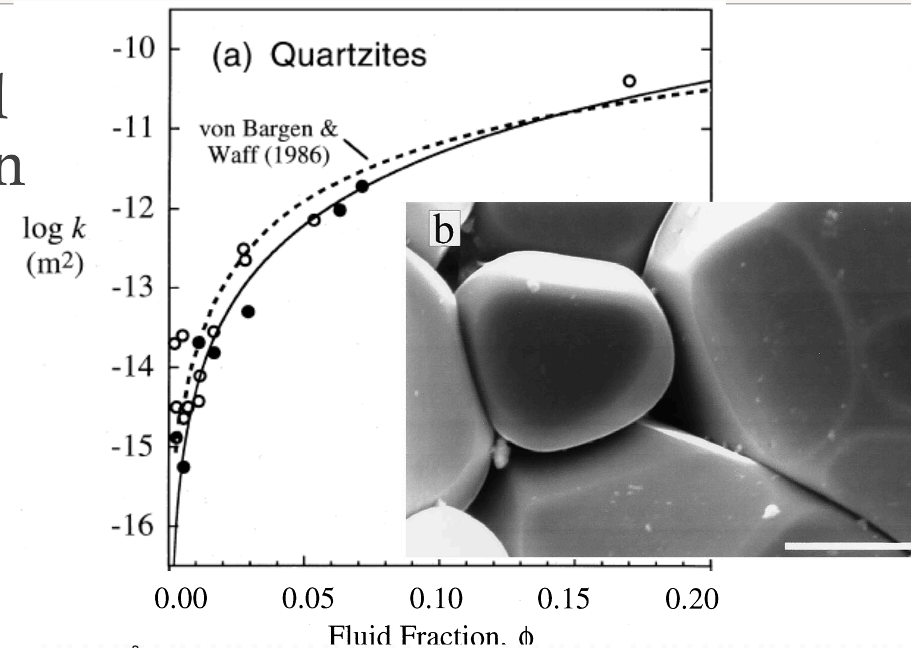
  - Grain size: 10^{-2} m

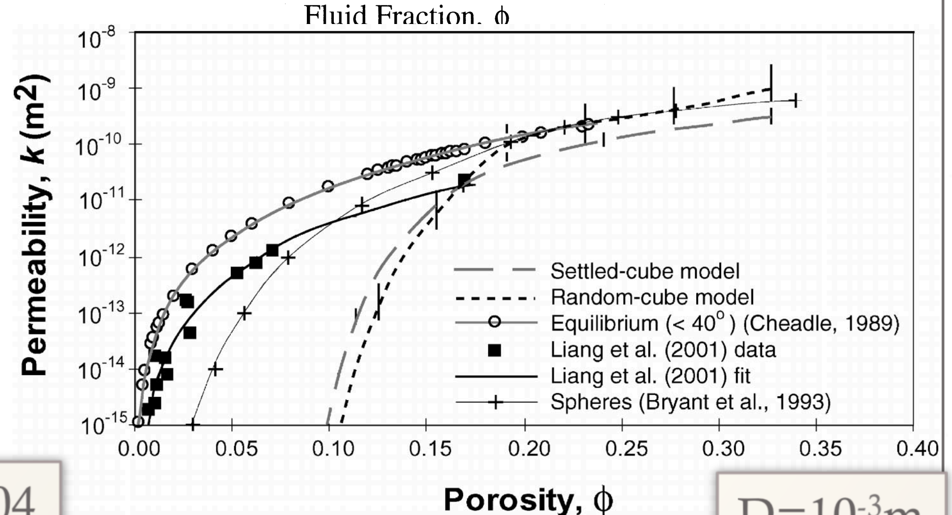
- What are the values of n and C?



Previous permeability estimates

- Quartz/calcite + H_2O NaCl analogues Wark and Watson (1998) and Liang et al., (2001)
  - n=3, C=270, k~4x10^{-13} m^2
- Centrifuge experiments Connolly et al., (2009)
  - n=3, C=10, k~10^{-11} m^2
- Theoretical estimates (idealized networks, von Bargen and Waff, 1986; Cheadle et al., 2004)
  - 10^{-11} m^2

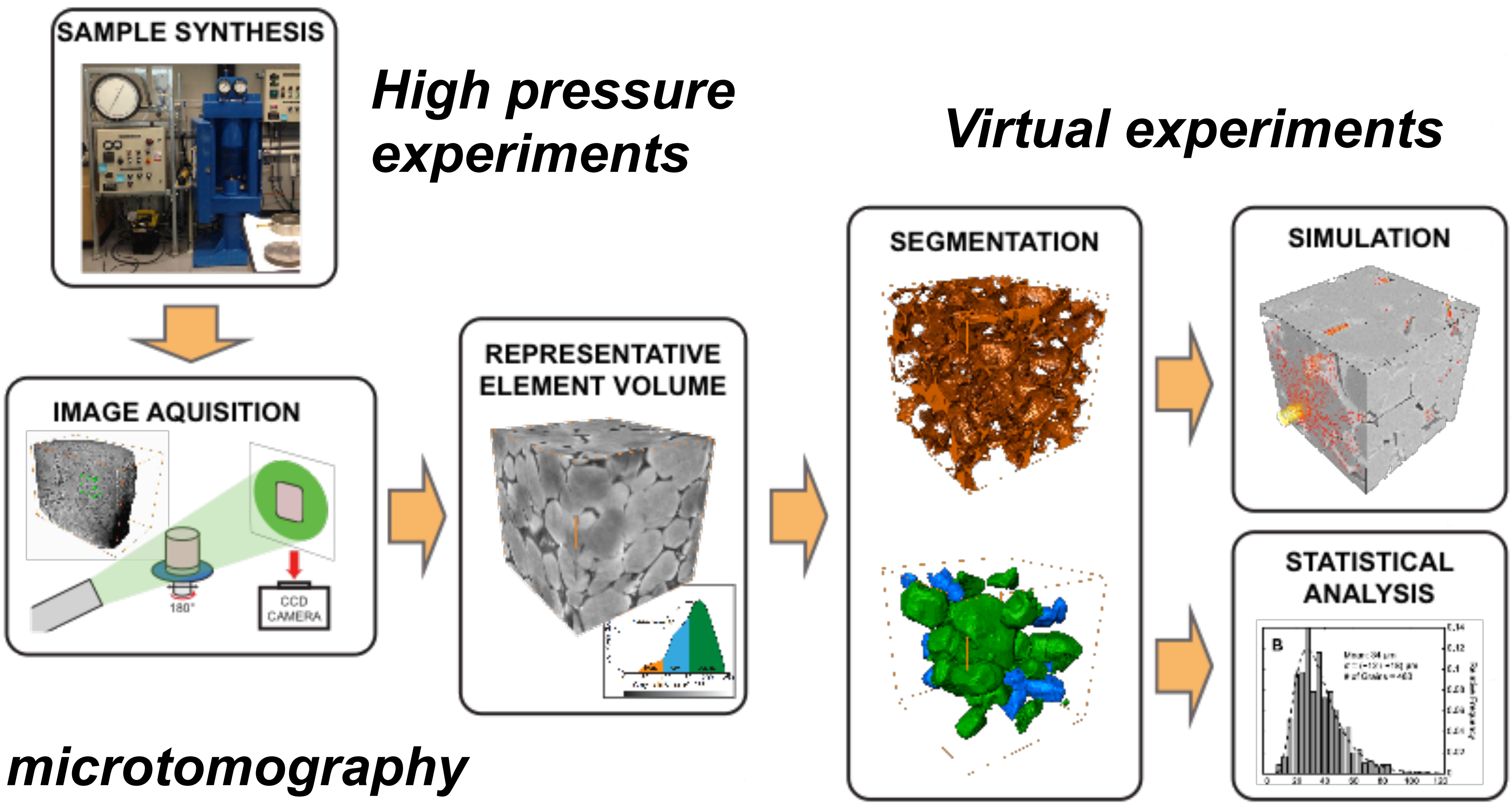




Cheadle et al., 2004

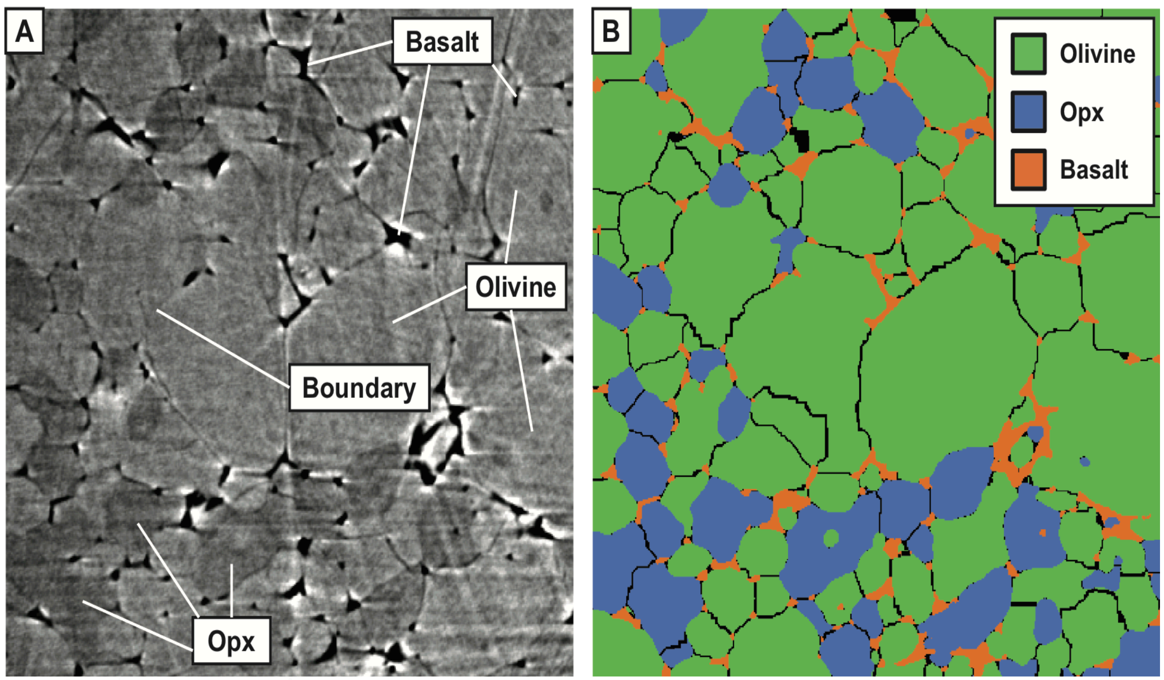
D=10^{-3}m

Digital Rock Physics (DRP)



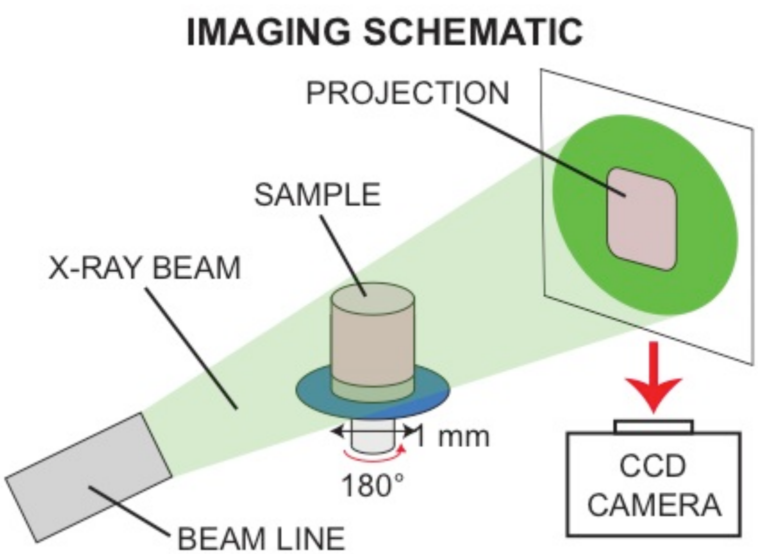
Experimental charges

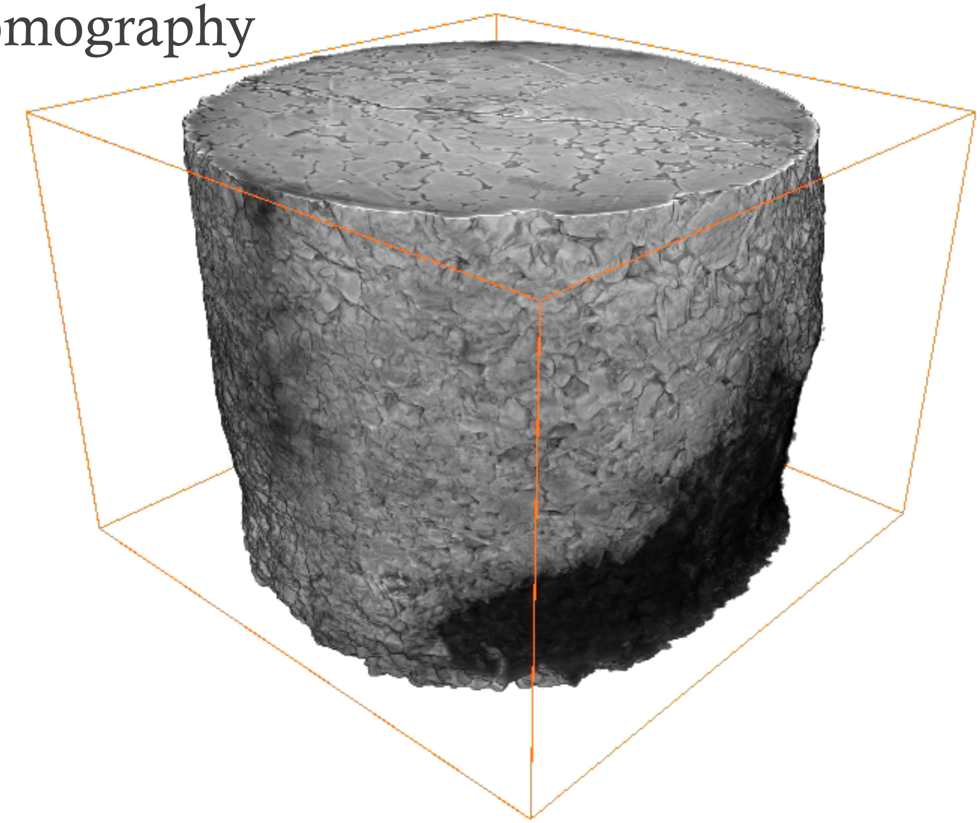
- Starting materials
  - San Carlos olivine
  - Oxide mixture to produce olivine ± orthopyroxene (0%, 18%, 40%)
  - Basalt (1%, 2%, 5%, 10%, 20%)
- Procedure:
  - Piston cylinder experiments
  - Pressure 15 Kbars (1.5 GPa)
  - Temperature 1350°C
  - Quenched for cylindrical cores



Imaging melt microstructure

- Experimental charges Olivine ± orthopyroxene + basalt (WHOI)
- Imaging at the Advance Photon Source (Argonne National Lab)
- Synchroton X-Ray microtomography

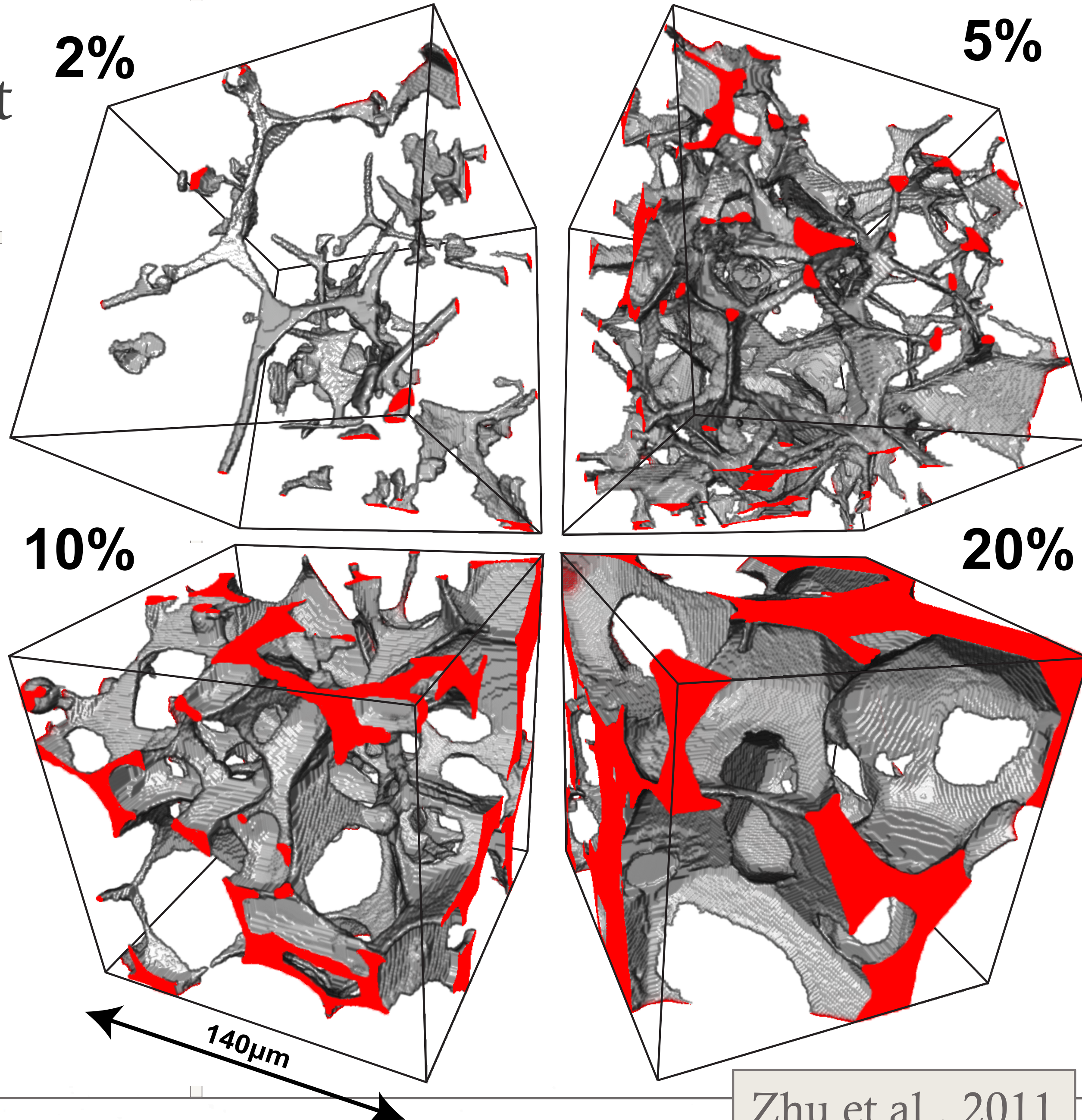




Miller et al., 2014

Microscale melt distribution

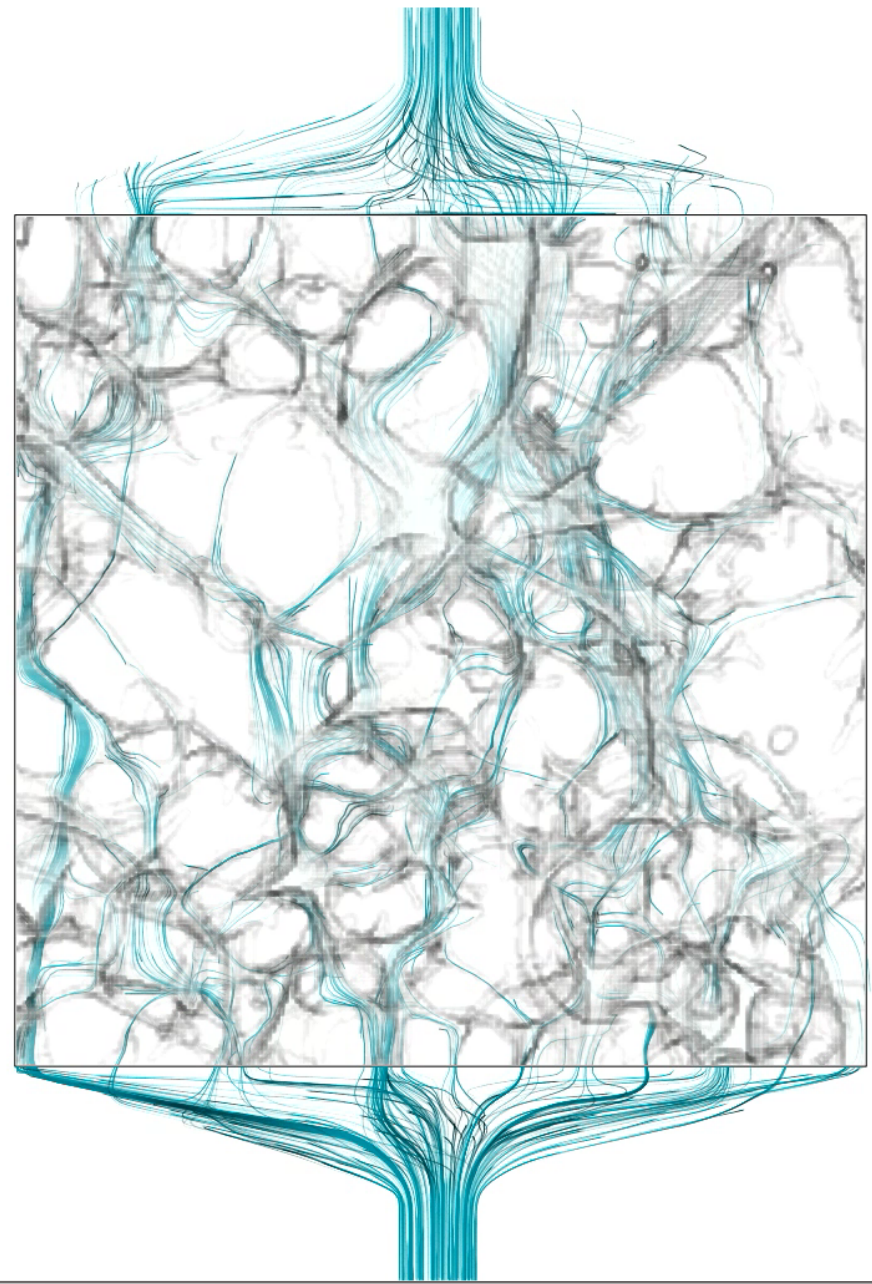
- Interconnected network along grain edges even at 2% volume melt fraction
- Importance of wetted grain faces at larger melt fraction



Zhu et al., 2011

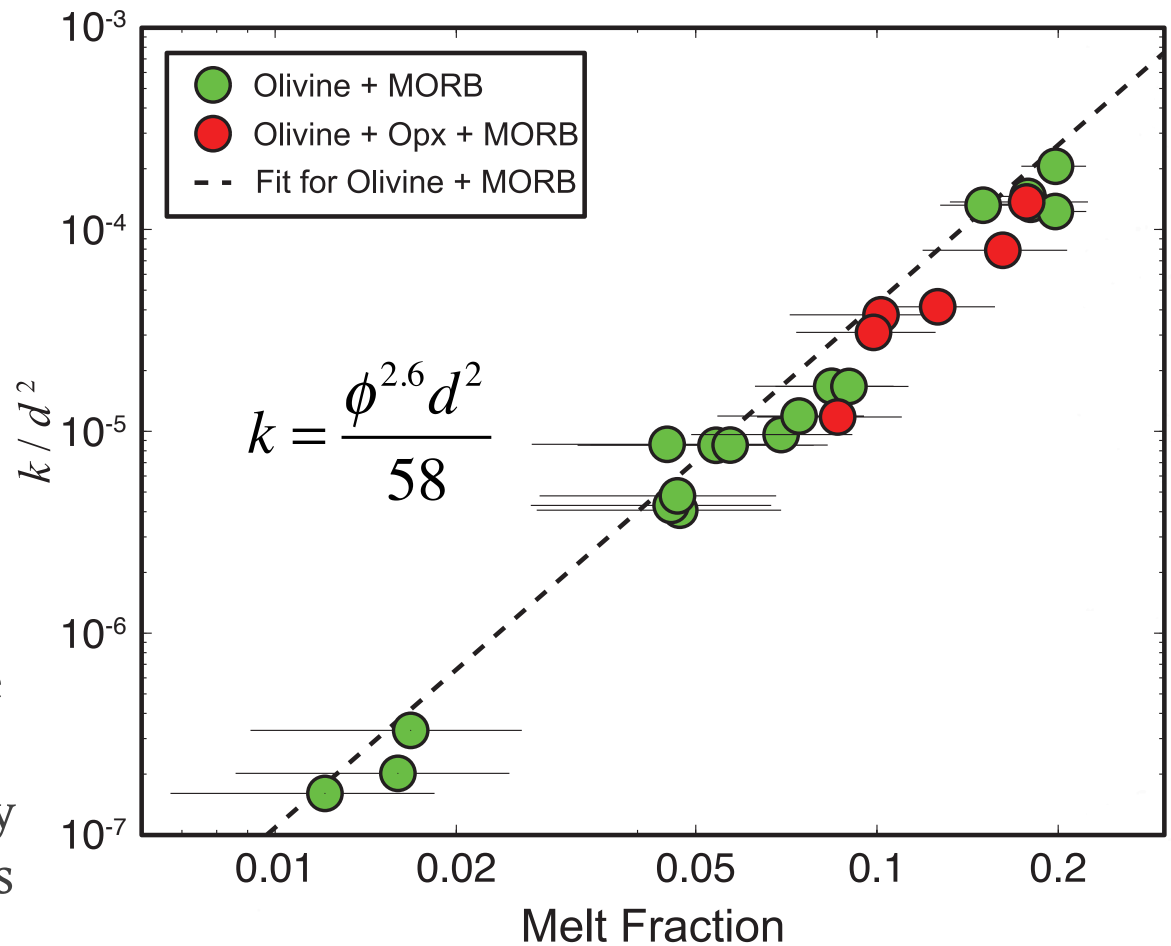
Digital Rock Physics

- Recognize melt and olivine
- Document interconnectivity of melt network
- Simulate fluid flow through the melt network (permeability)
- Simulate currents through olivine and melt (conductivity)



Permeability of melt/rock samples

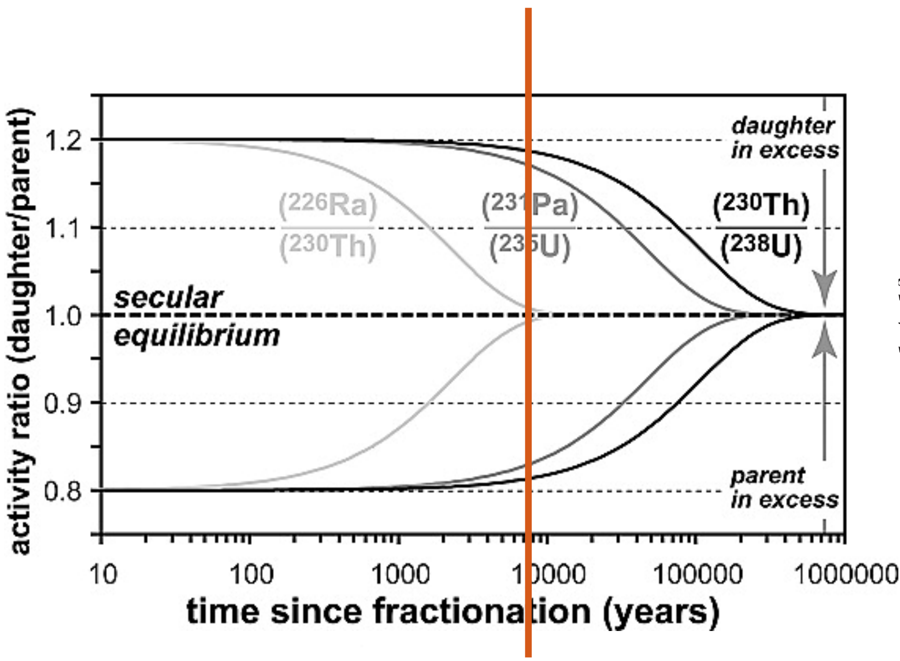
- Compute permeability for each subvolume.
  - Finite-volume Avizo® XLab Hydro module
- Power law relation between melt fractions and permeability
  - Exponent 2.6 indicate an heterogeneous network dominated by melt at triple junctions

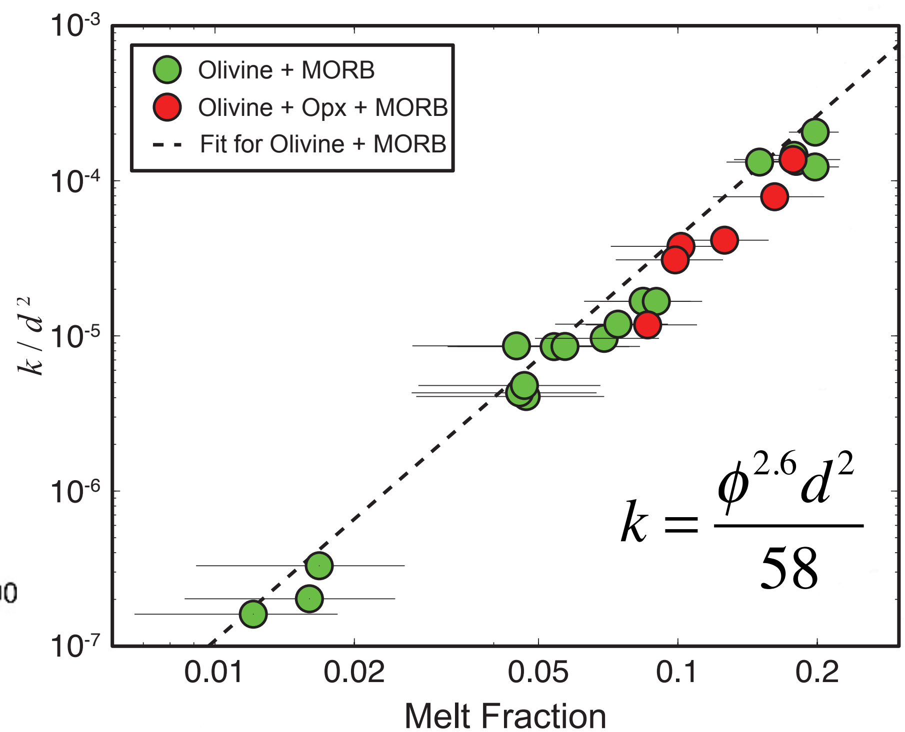


Miller et al., 2014; 2016

New Permeability Estimates

- n=2.6, C=58, k~10^{-11} m^2, ϕ=1% => melt velocity: 10 m/yr
- Transport time from 60 km: 6000 yr.
  - ^{226}Ra need other explanation





Peate and Hawkesworth 2005

Miller et al., 2014; 2016

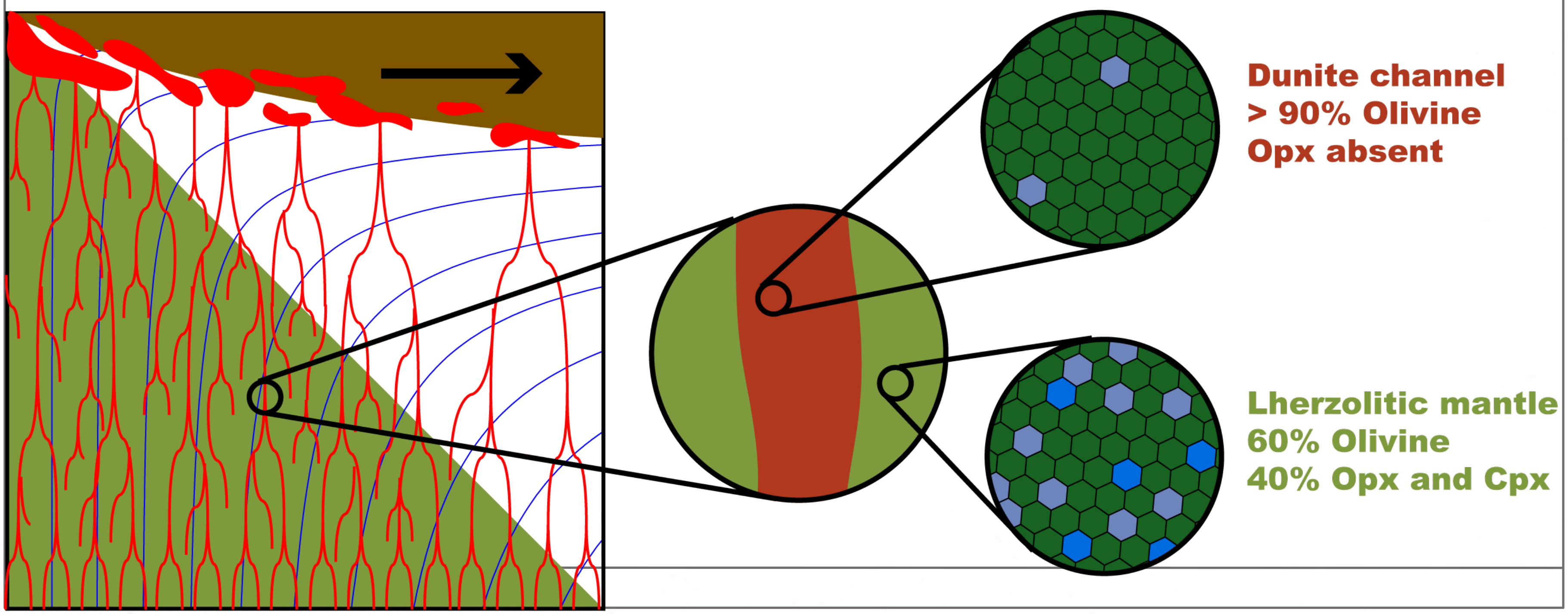
Dissolution Channel

- Interconnected channel network
  - Melt-rock reaction (incongruent melting)
  - Porosity/viscosity/grain size feedback
  - Surface tension

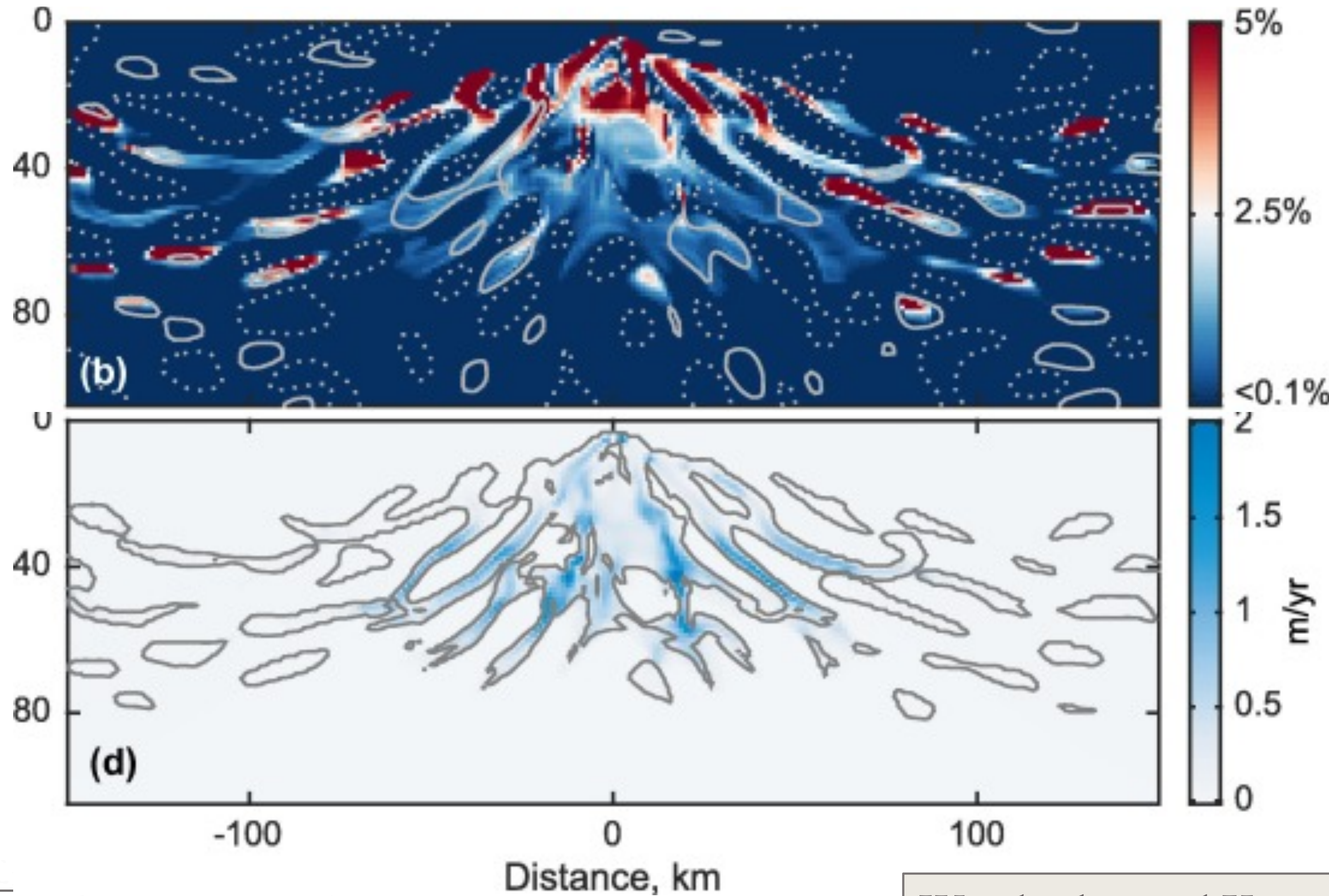
- If porosity is $X\phi_0$ in channels, channels take $1/X$ of space

$$v_f - v_s = \frac{k\Delta\rho g}{\mu\phi}$$

- Velocity increases by factor X^{n-1}
  - ^{226}Ra: Rise in 2000 yr if X=2
  - ^{310}Pb: Rise in 100 yr if X=40



Channelization at mid-ocean ridges



Weatherley and Katz, 2006