Magmas to Mush: Old Rocks and New Ideas

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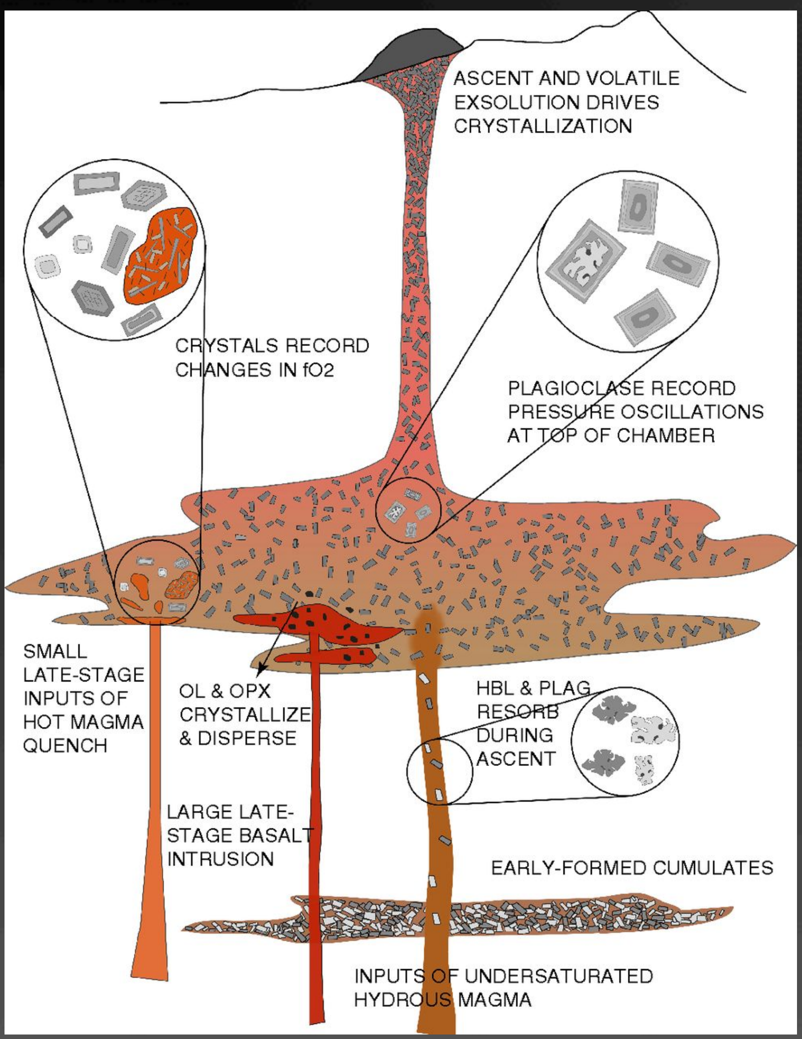
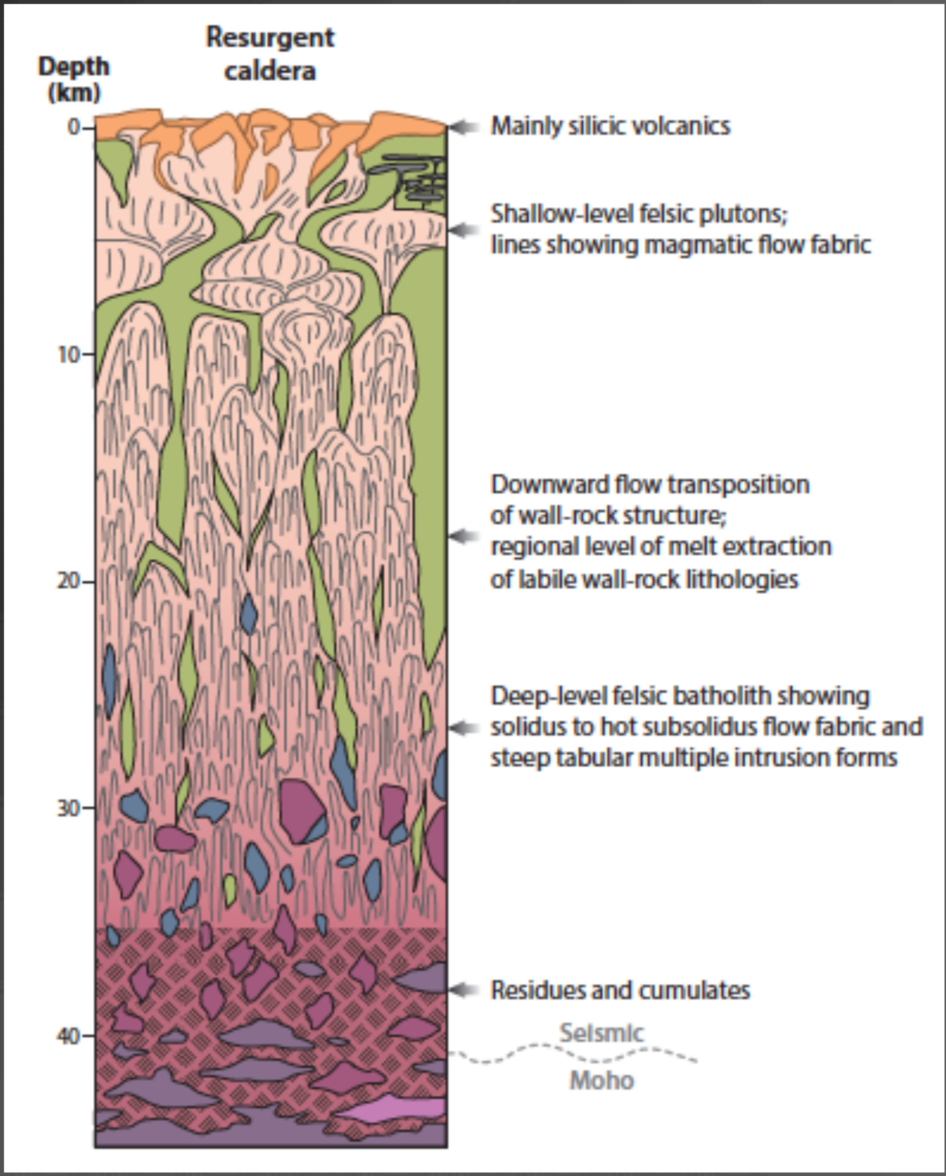
If we understood MSH… would we necessarily understand magmatic systems?

$\stackrel{?}{=}$

Processes that are shared and those that are unique



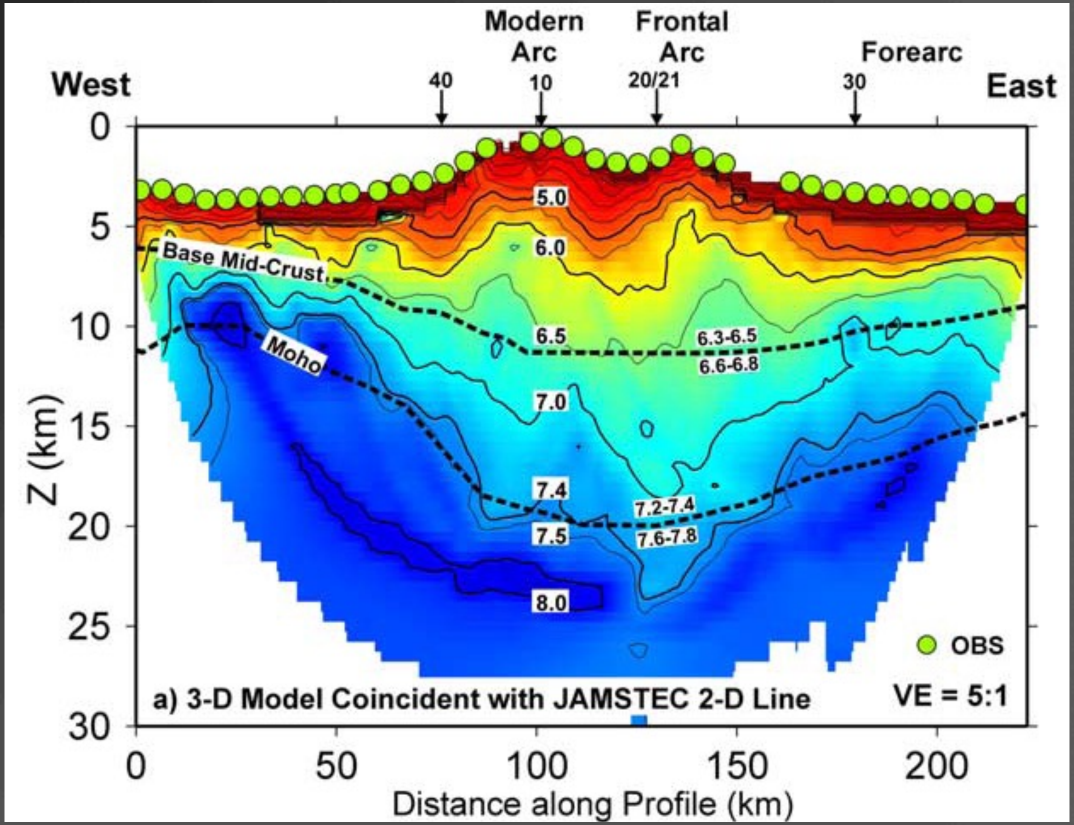
Cashman et al., 2013, GSA Bull.



Ducea et al., 2015, AREPS

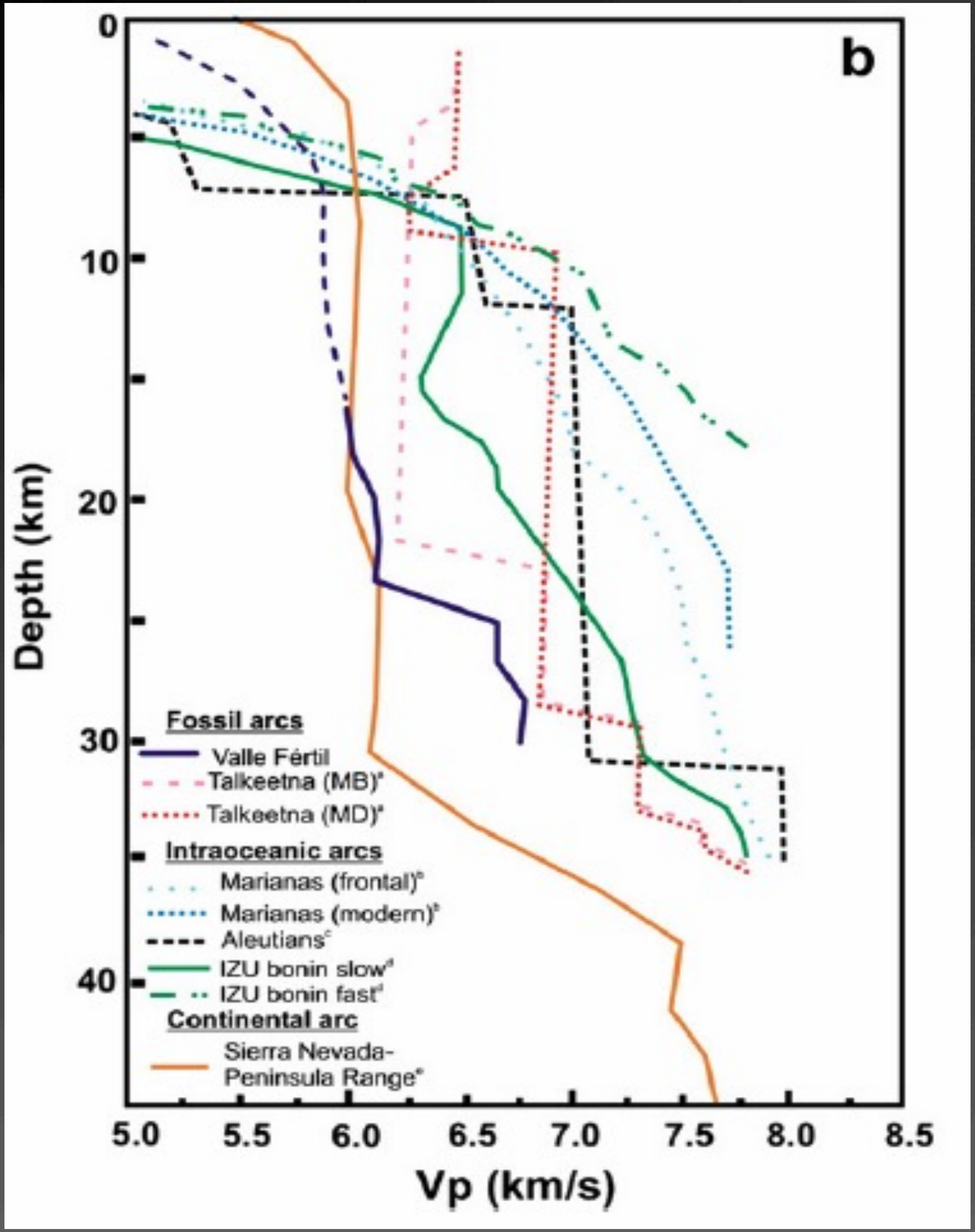
"Right" Physical model for formation of igneous crust?

- Controls on architecture?
- Rationalize geochemical, geophysical perspectives?



Mariana arc, Calvert et al., JGR, 2008

Commonalities From Geophysical Structure



But what are the time scales?

Is this a uniform process?

Tibaldi et al. Tectonophysics, 2013

Some Crustal Sections:

- Kohistan 100 – 50 my, 0 – 55 km
- Talkeetna 200 – 150 my, 0 – 10, 20 – 30 km
- North Cascades 95 – 65 my, 10 – 35 km
- Sierra Nevada/BC 180 – 50 my, 5 – 30 km
- Fiordland 170 - 100 my, 15 – 50 km
- Ivrea Zone 286 – 282 my, 5 – 30 km
- Famatina 473 - 468 my, 9 – 35 km

Most fragmented spatially and temporally

Missing the mafic “mothership” which drives arc magmatism

Average magma flux rates km^3/yr-

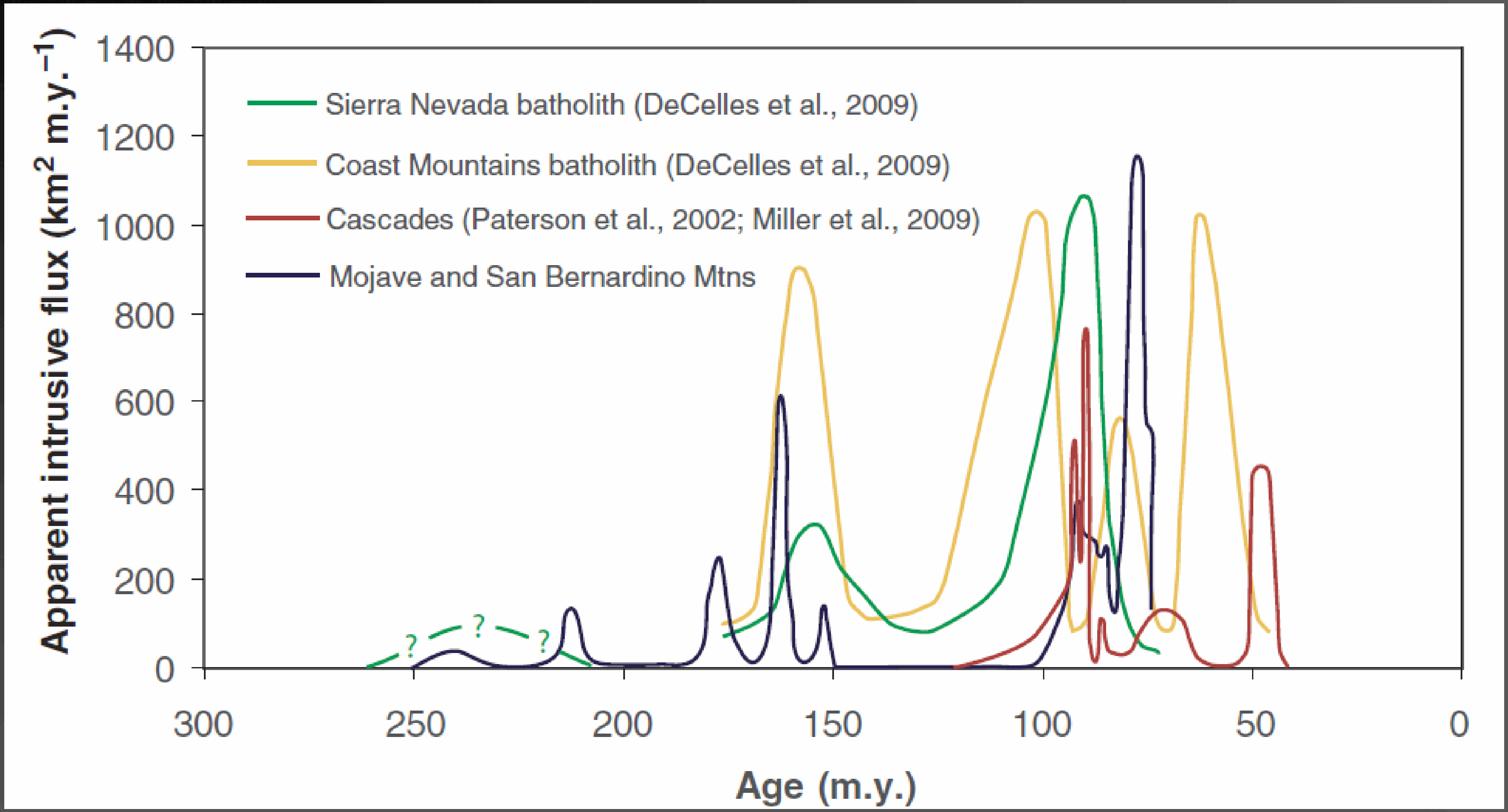
Large Silicic Provinces:

Altiplano-Puna:	$4x10^{-3} – 1.2x10^{-2}$
Central San Juan:	$8x10^{-3}$
Sierra Nevada:	$3 - 9x10^{-3}$
North Cascades:	$3x10^{-3}$
Boulder, B.C. batholith:	$6x10^{-3} – 1x10^{-2}$
Famatina	$1.5x10^{-2}$

Other Arc systems *(but see Jicha, Singer):*

Klyuchevskoy:	$3.2x10^{-2}$
Mt. Shasta:	$6x10^{-3}$
Tatara-San Pedro:	$6x10^{-5}$
Mt. Adams (field):	$2.5x10^{-4}$
Ceboruco- Pedro:	$1x10^{-4}$
Santorini:	$4.6x10^{-4}$

Tempo- not simple…Global arc crust growth rates of about 2.6 km^3/yr *(Jagoutz and Schmidt, 2013)*

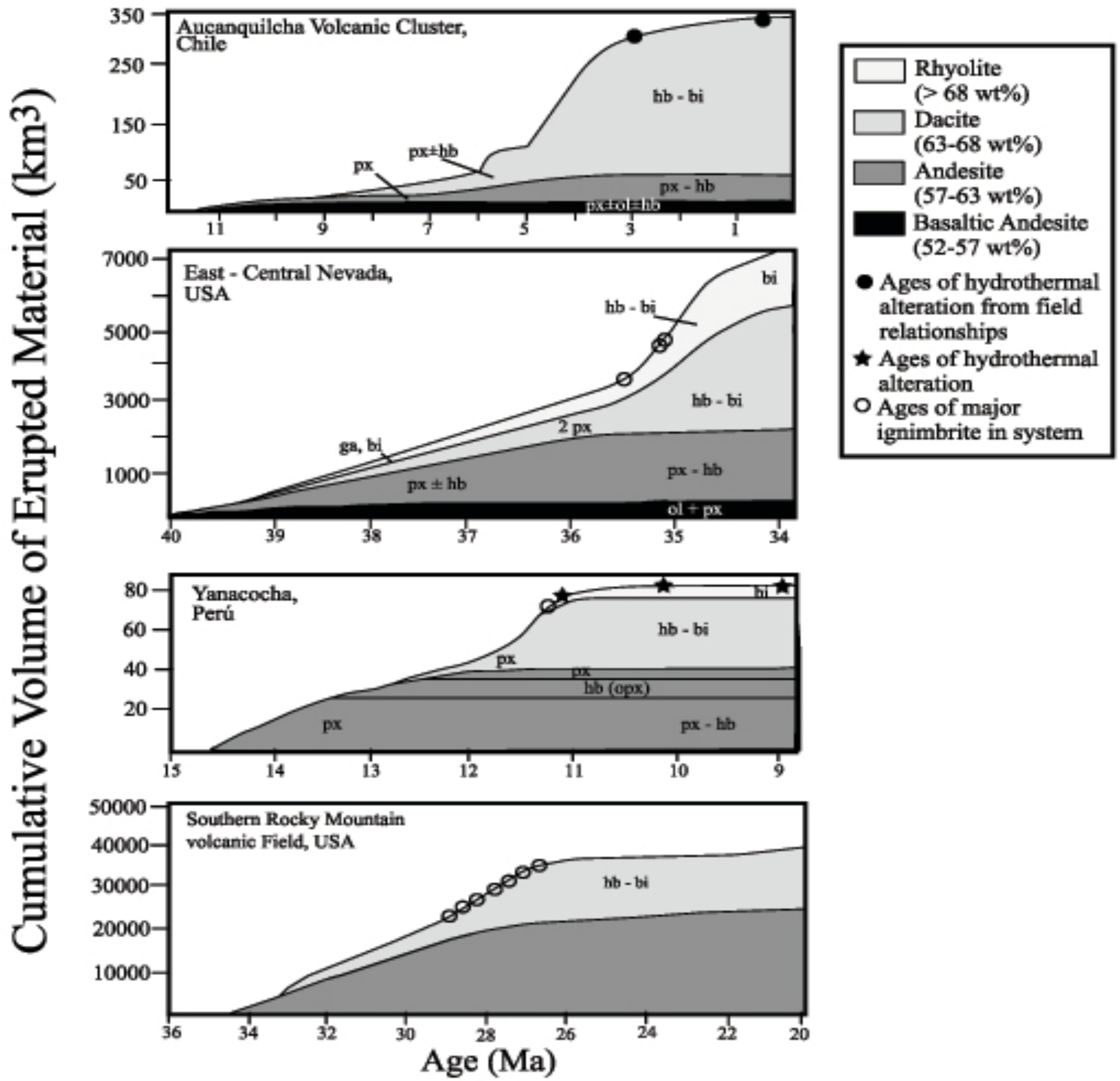


Paterson et al., 2011, Geospheres

Lifespans of Cascade Arc Volcanoes

- GP, MR, MA, MH, MM inception ages of 400 – 600 kyr
- MSH, MJ, NV, MS, L,   200 – 300 kyr
- Sisters, MB less than 50 kyr
- Ancestral volcanoes have similar total durations 200 – 600 kyr
- *Elevated* behavior .1 – 100 kyr

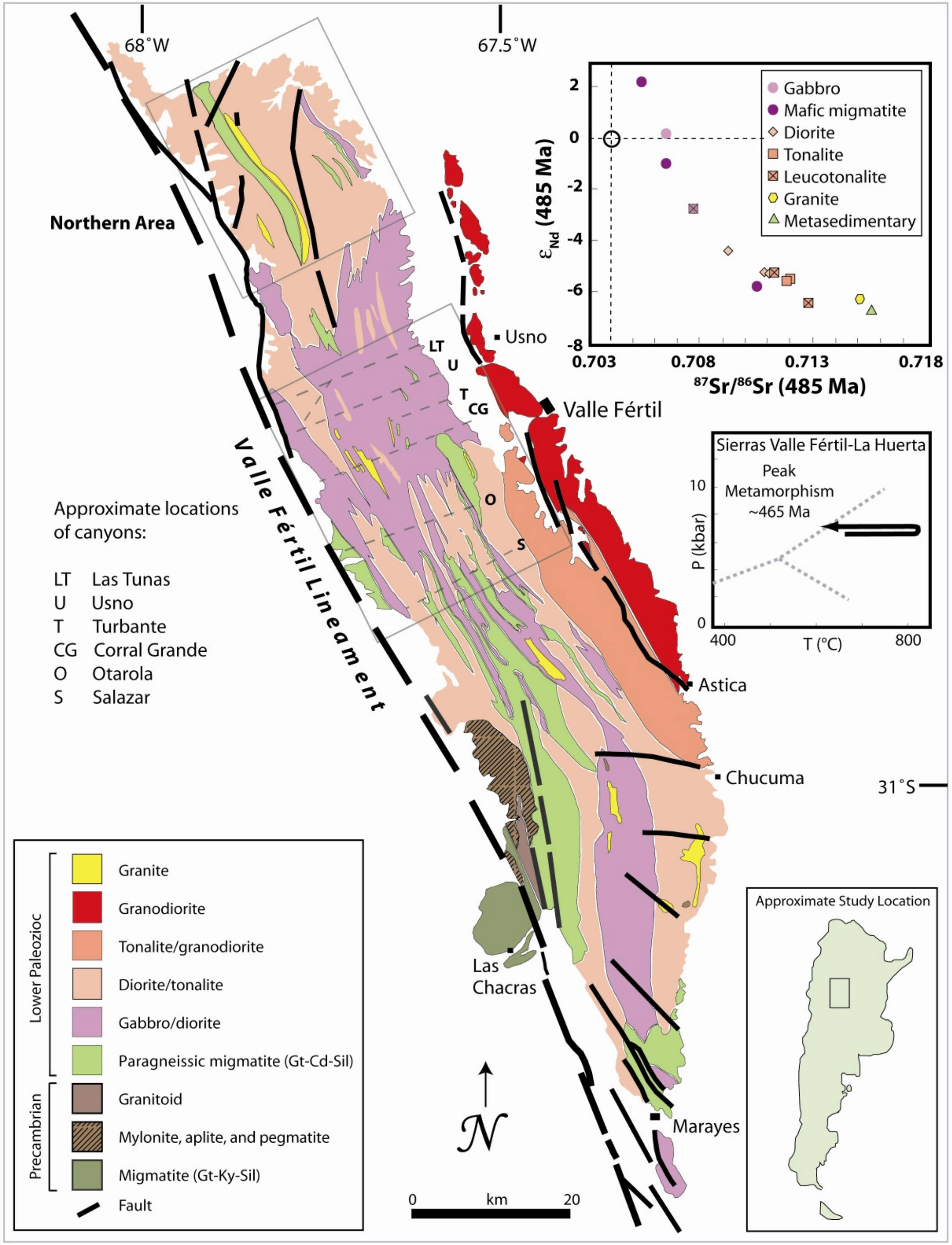
Calvert, 2015 AGU Fall meeting V23C-06

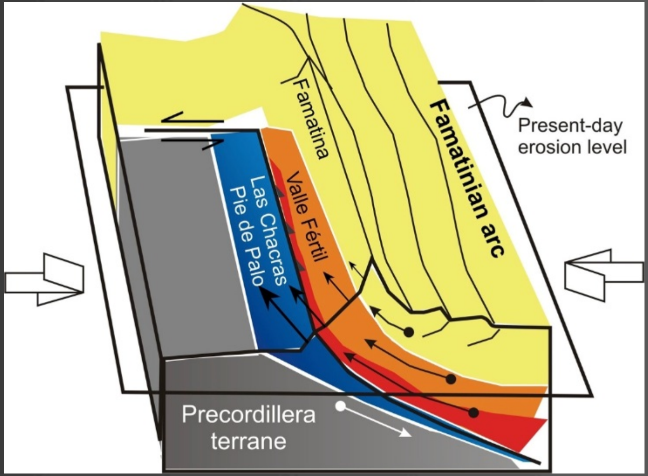


What is the significance of the 4-5 m.y. trigger?

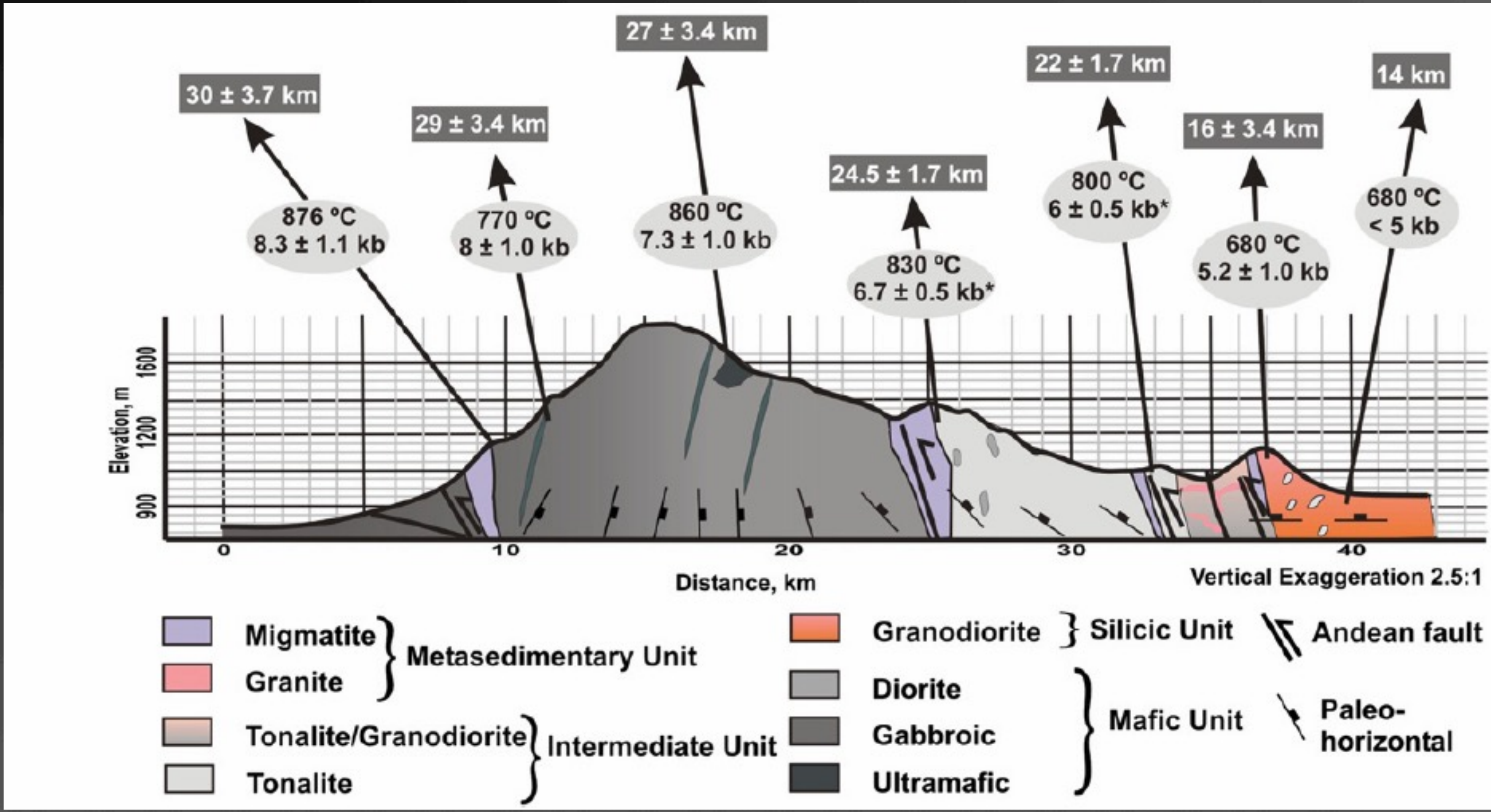
(Grunder et al., 2008, Trans. Roy. Soc. Edin.)

Sierra Valle Fertil

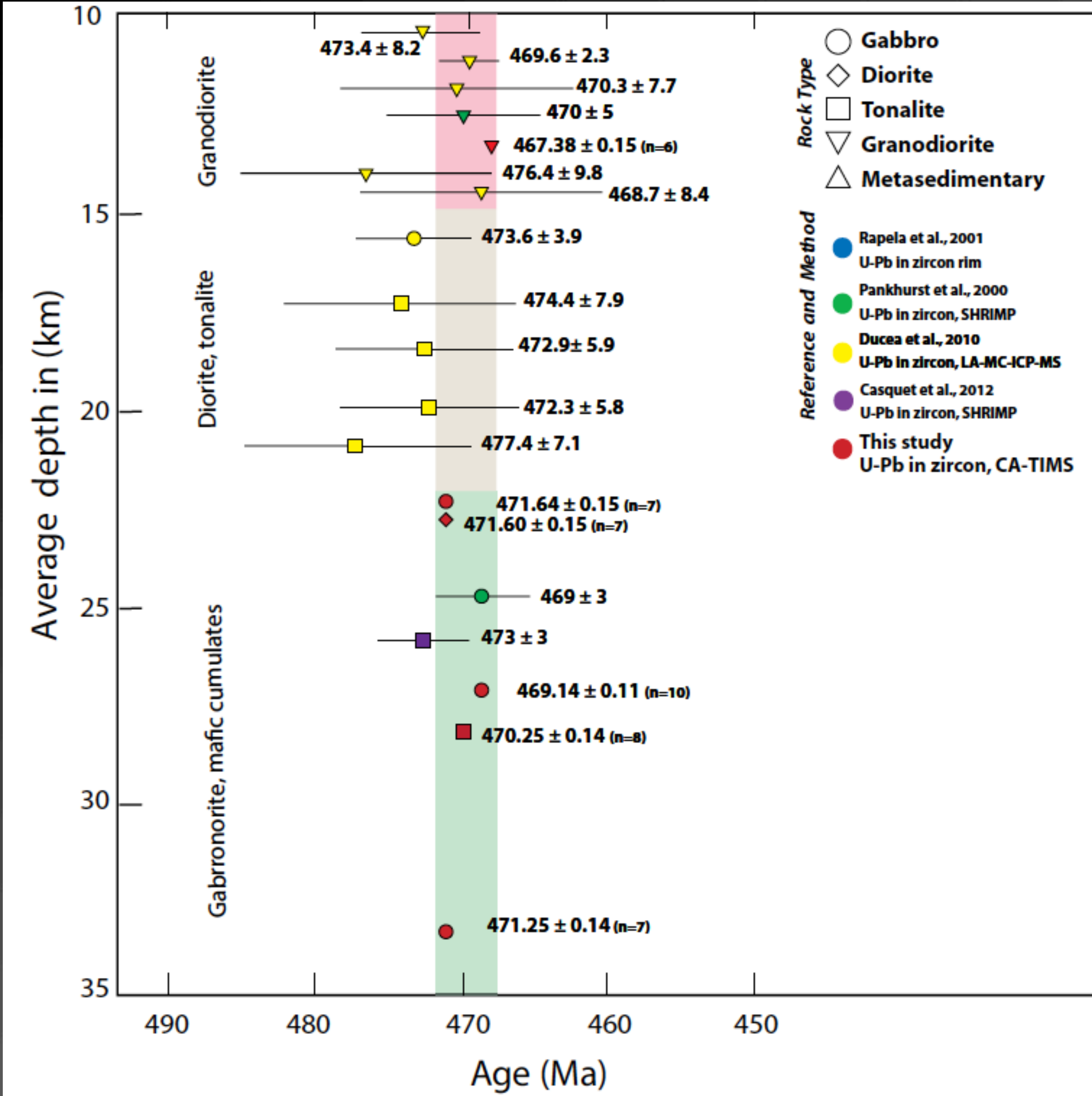




Sierra Valle Fertil Cross section



Tibaldi et al. Tectonophysics, 2013



Crustal section built in ~ 4 million years

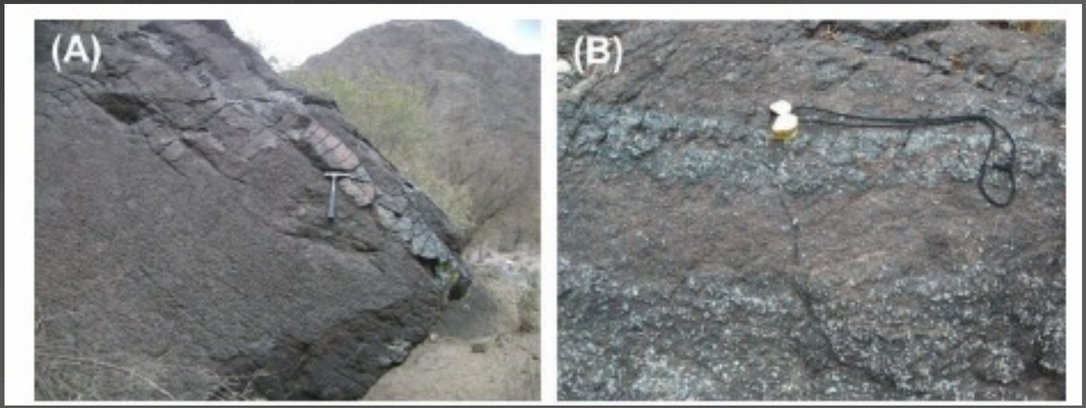
Assembly was not a simple bottom-up process

Ducea et al., 2017, Geology

Massive ultra-mafic cumulate pods

Amp-olv webesterite, small dunites, anorthosites elsewhere

Modal and compositional layering in gabbro



Tonalite (daughter) domains in gabbro

Contacts gradational and hyper-solidus

Amp oikocrysts in gabbro

Heterogeneous tonalite with enclaves

Many scales of melt channels

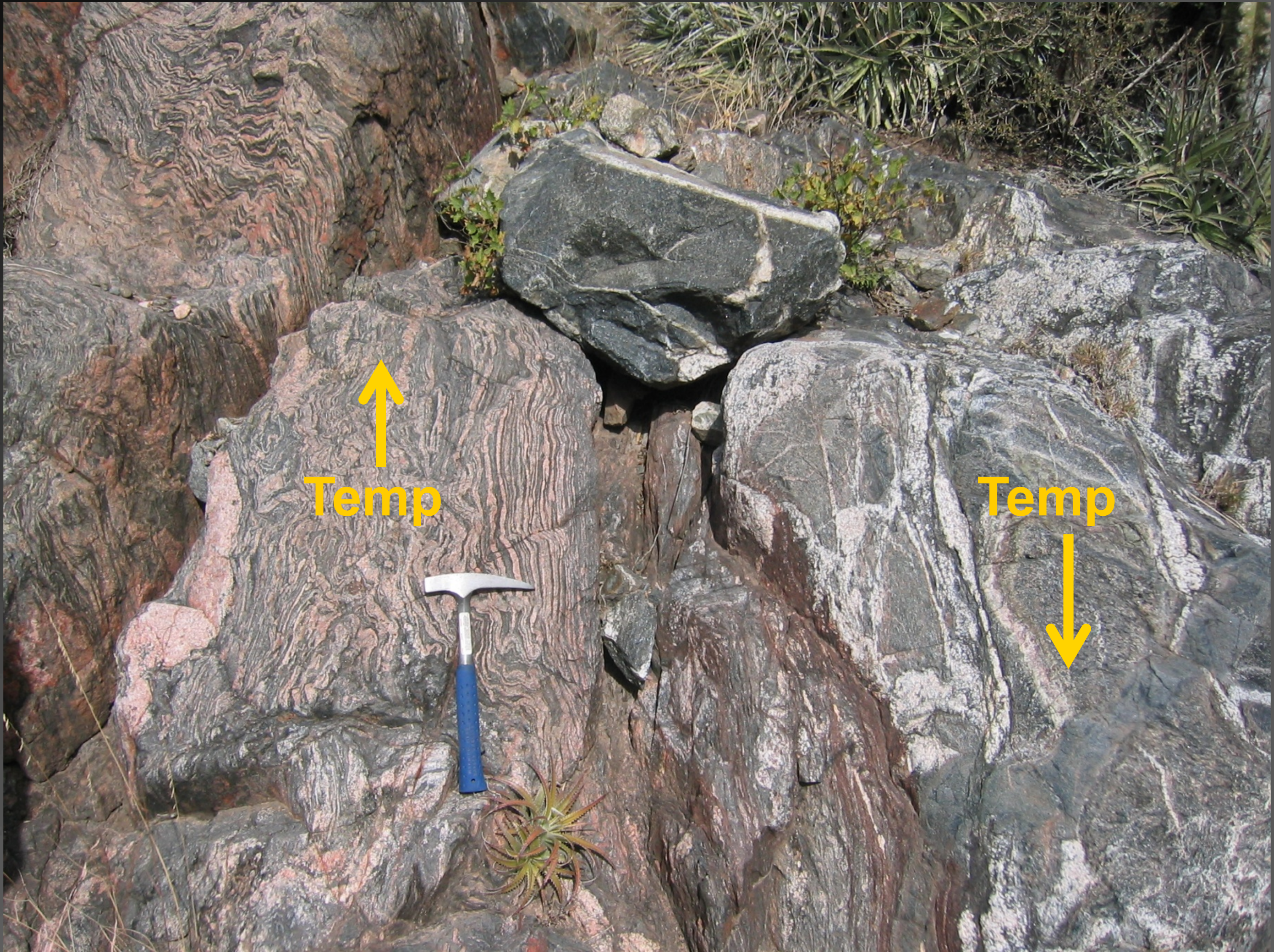
Melt drainage networks: what controls length scales and porosity reduction?

prograde path

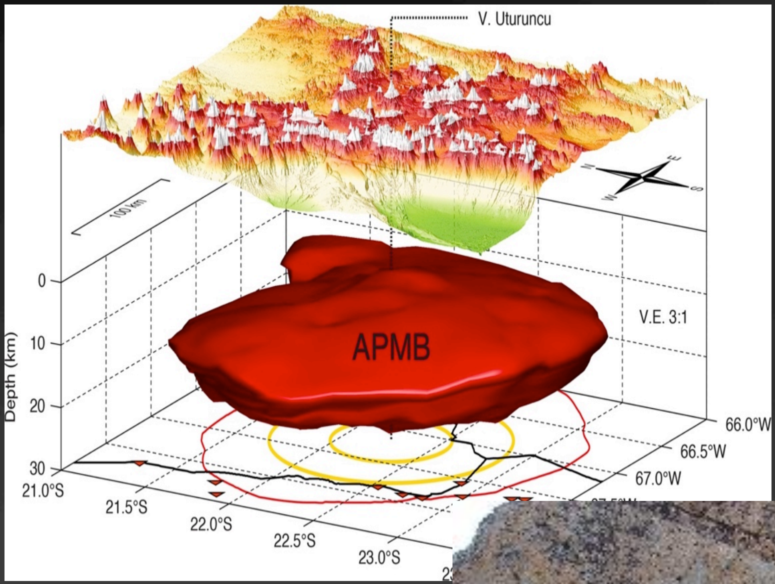
Stromatic migmatite ⟶ Diatexite

Pl+ Qtz+ Bt+Sil = melt+Kfs+Grt+Crd+Ilm/Mt

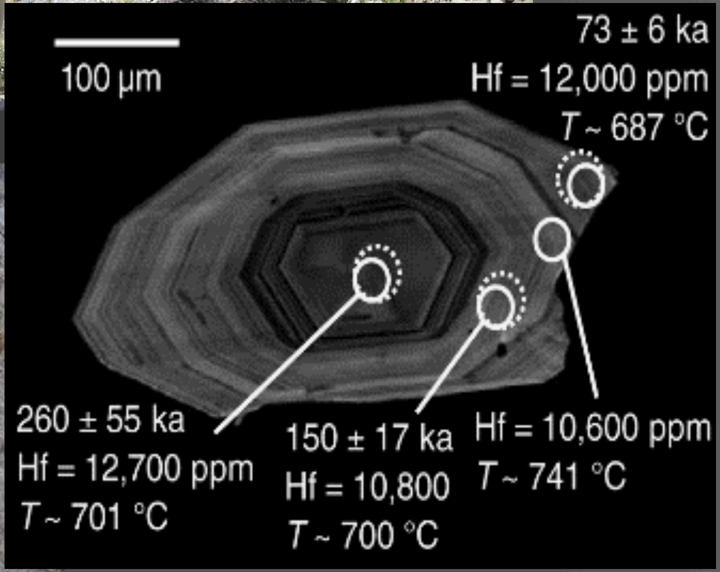
Differing expressions of melt organization and migration



What observations motivate an interest in mush?

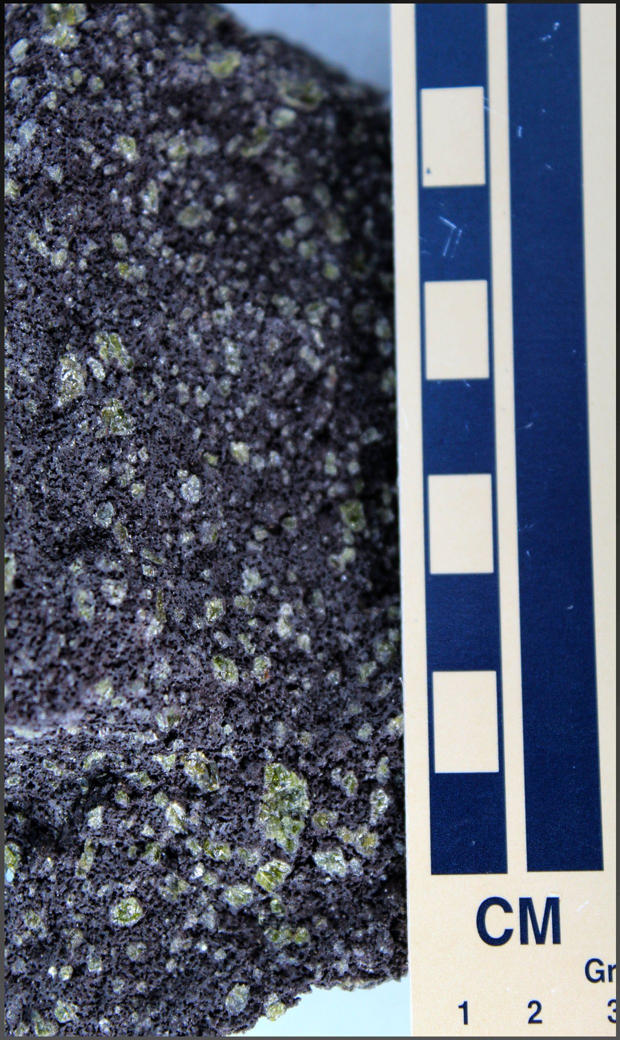


Ward et al., EPSL 2014

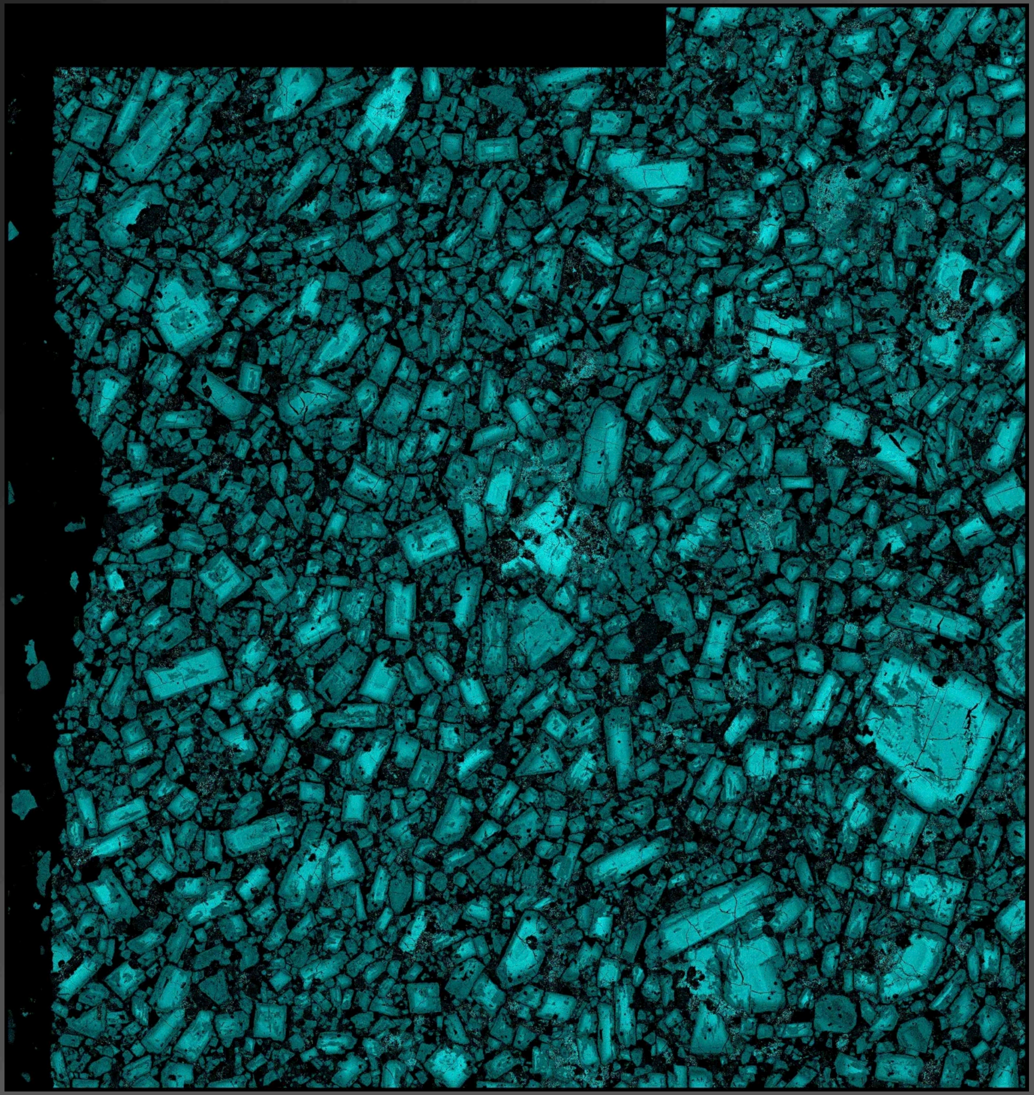


Claiborne et al., 2010, Geology

What does a “living” mush look like?



Mauna Loa 1868 picrite



Rabida, Galapagos plag-rich xenolith

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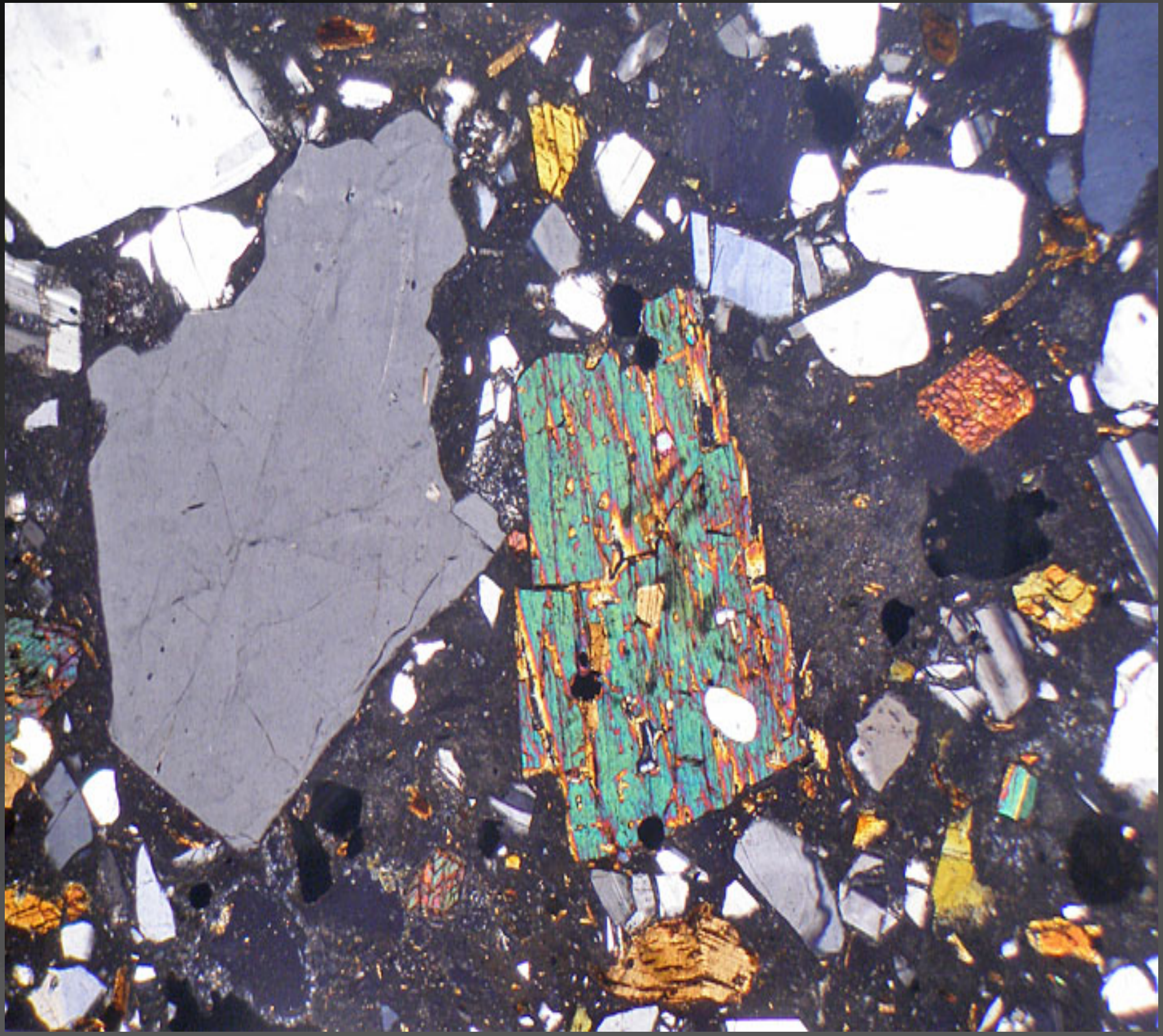

Fish Canyon Tuff

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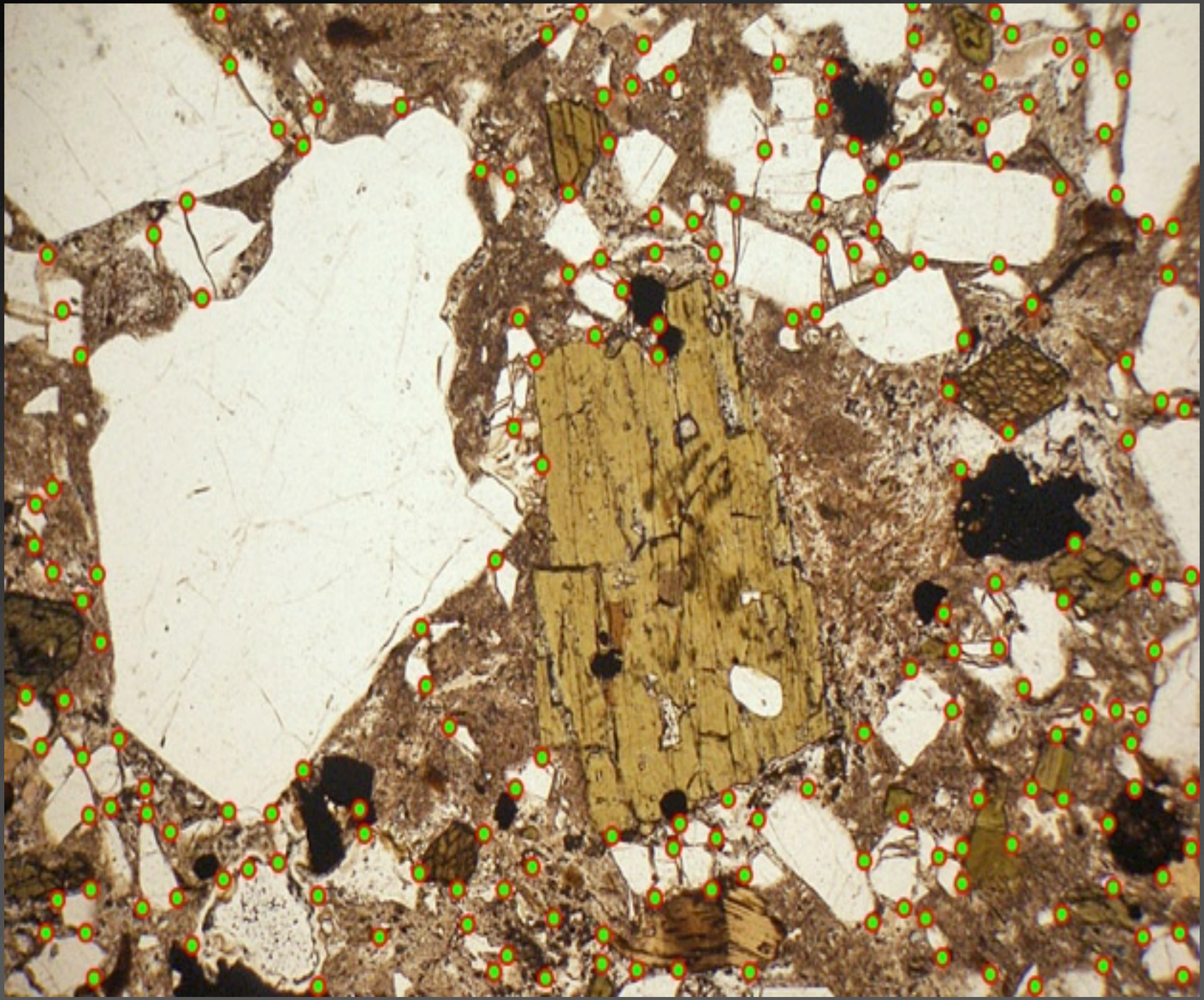
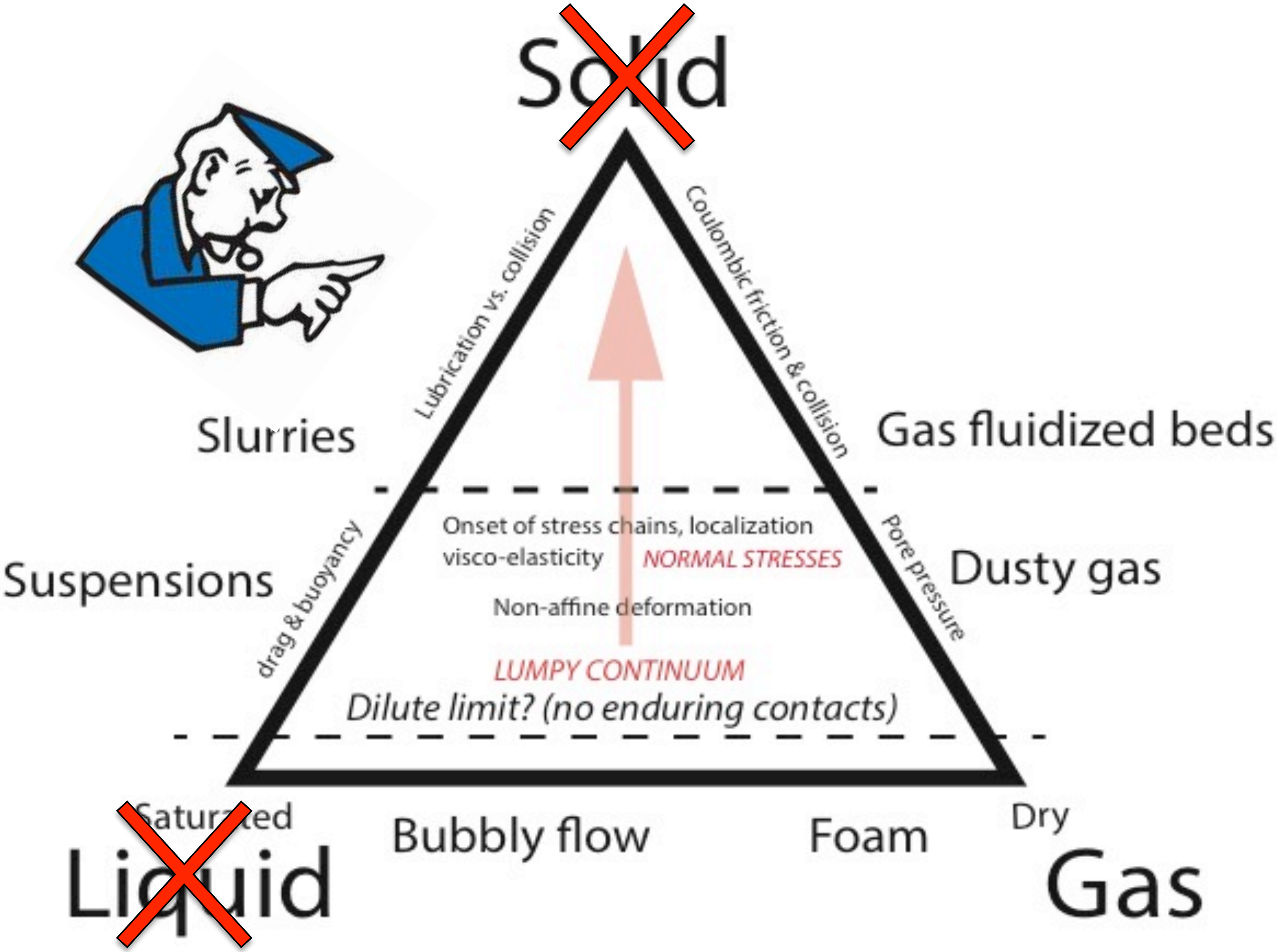


Fish Canyon Tuff

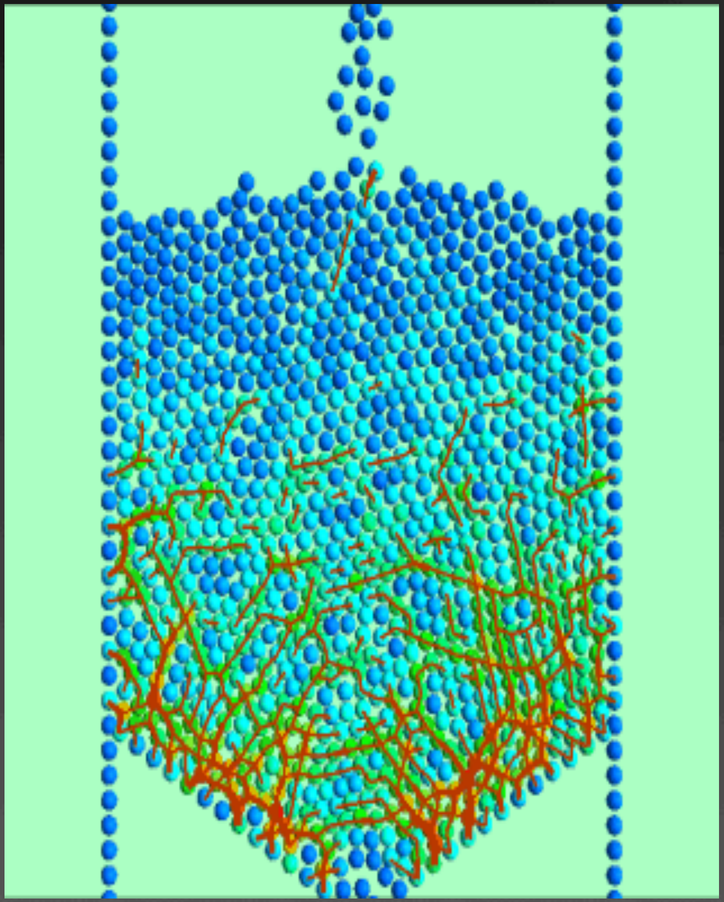
“Textural analysis in the time of mush…”

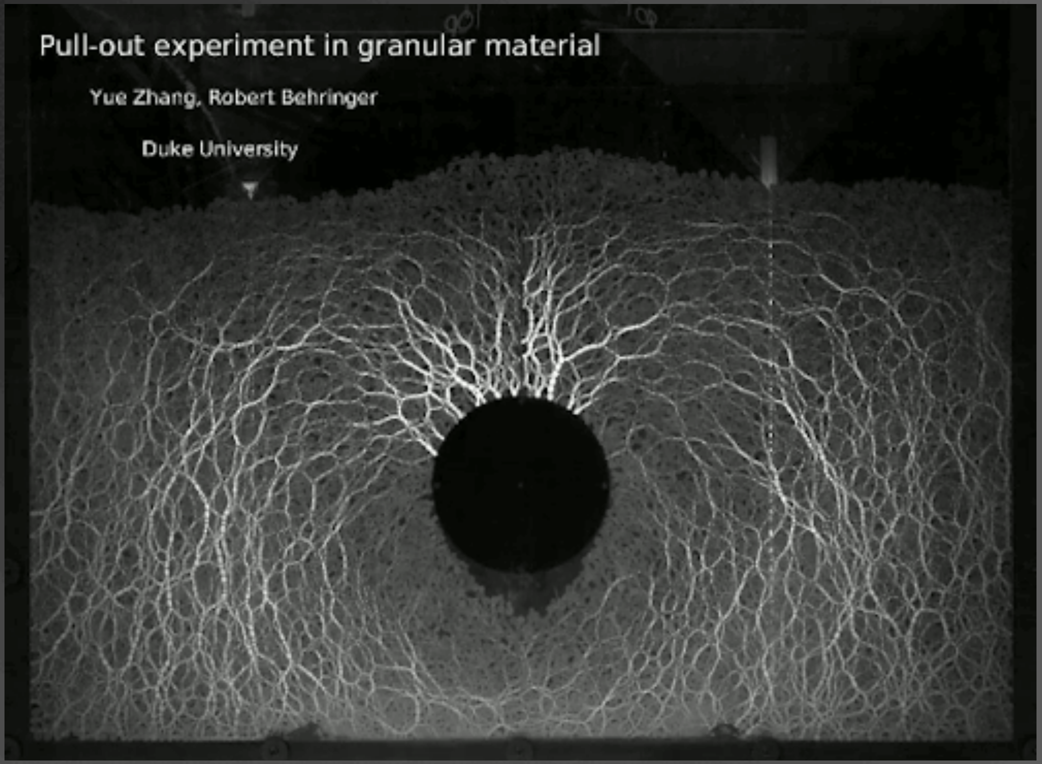
- Kathy Cashman, Laguna del Maule, Chile, 2018



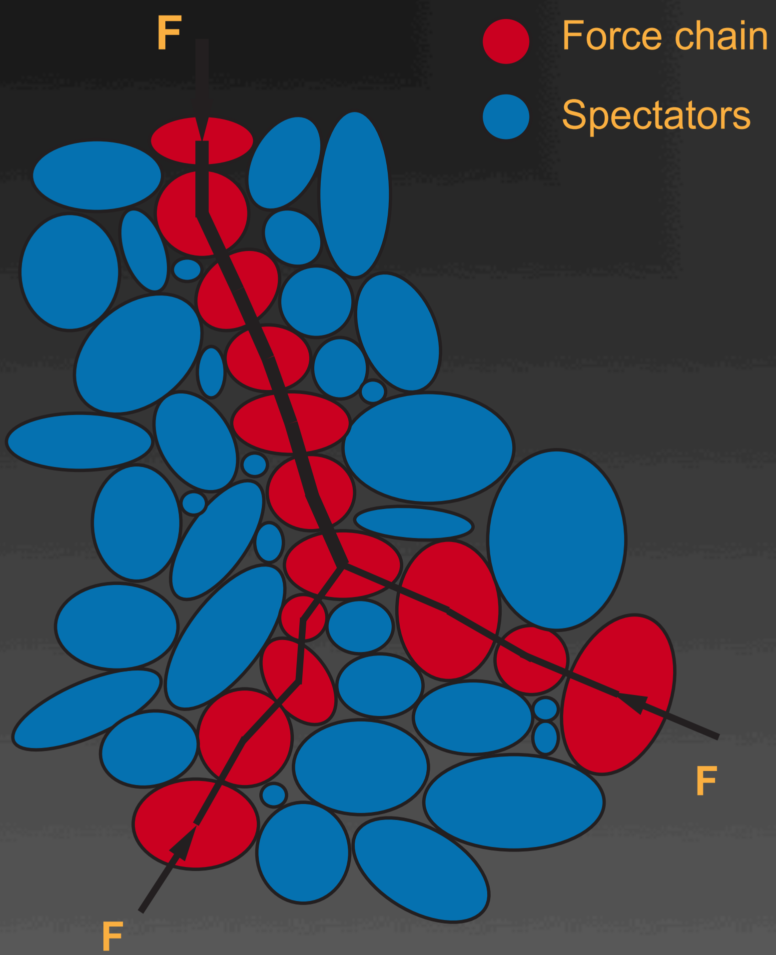
Many and diverse sources of dissipation

Statics: Force chains





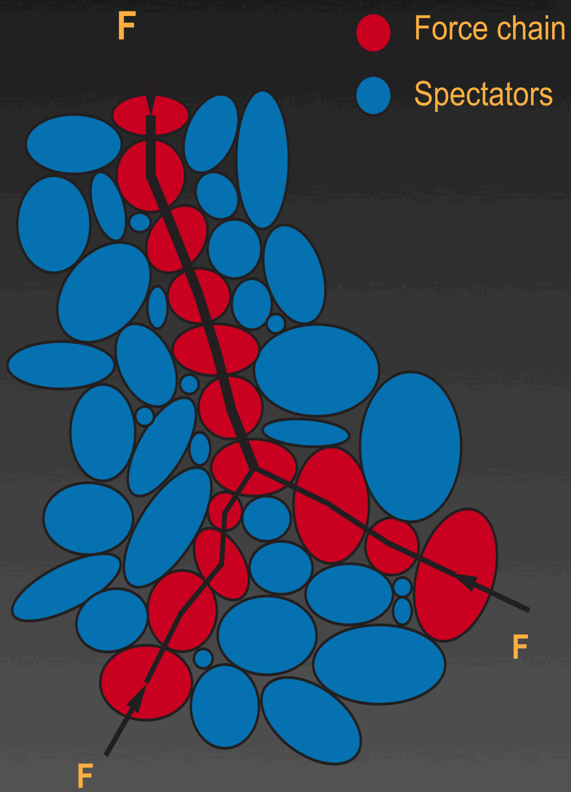
Stress transmission in hydrogranular media: Force chains and arches

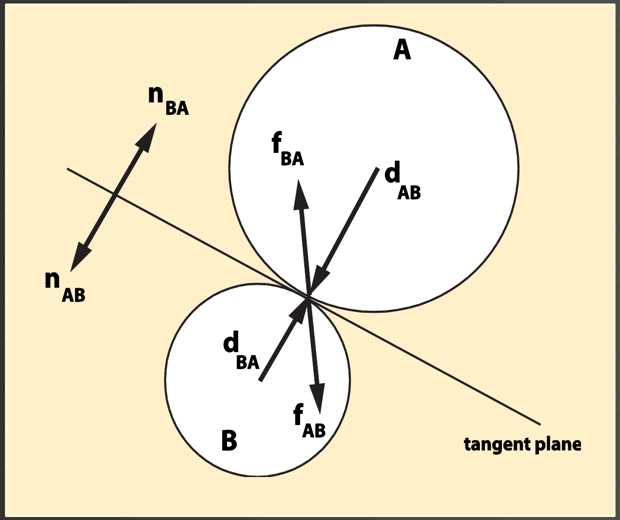


Coordination number Z: average number particle-particle contacts per particle

$$Z = \sum_{c} c\xi(c)$$

Kinematics: Elements of description





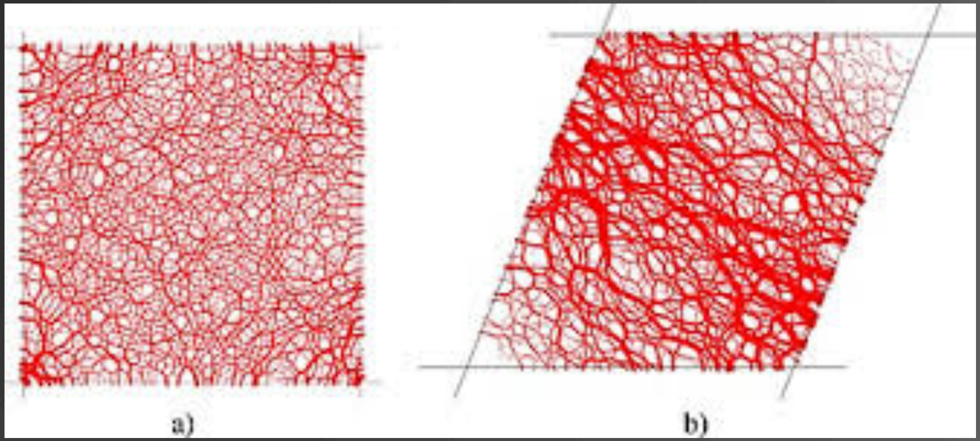
$$\mathbf{F}_c = \oint_\Omega E(\mathbf{n})\mathbf{n} \otimes \mathbf{n} d\Omega = \frac{1}{N}\sum_{k=1}^{N} n^k \otimes n^k$$

$$F_{ij} = \frac{1}{N}\begin{bmatrix} \sum_{k=1}^{N} \cos\theta^k \cos\theta^k & \sum_{k=1}^{N} \cos\theta^k \sin\theta^k \\ \sum_{k=1}^{N} \sin\theta^k \cos\theta^k & \sum_{k=1}^{N} \sin\theta^k \sin\theta^k \end{bmatrix}$$

Robustness: redundancy in particle network

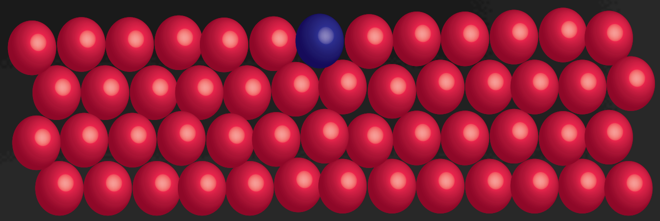
weak

strong

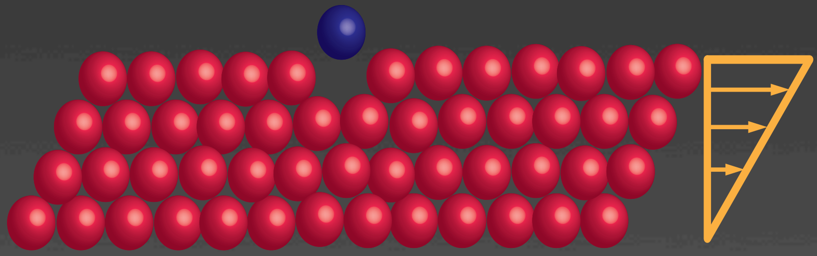


Strength: a network property

How to initiate cluster or melt channel formation?



Two competing time scales:



Separate particle response time from granular ‘continuum’ response time

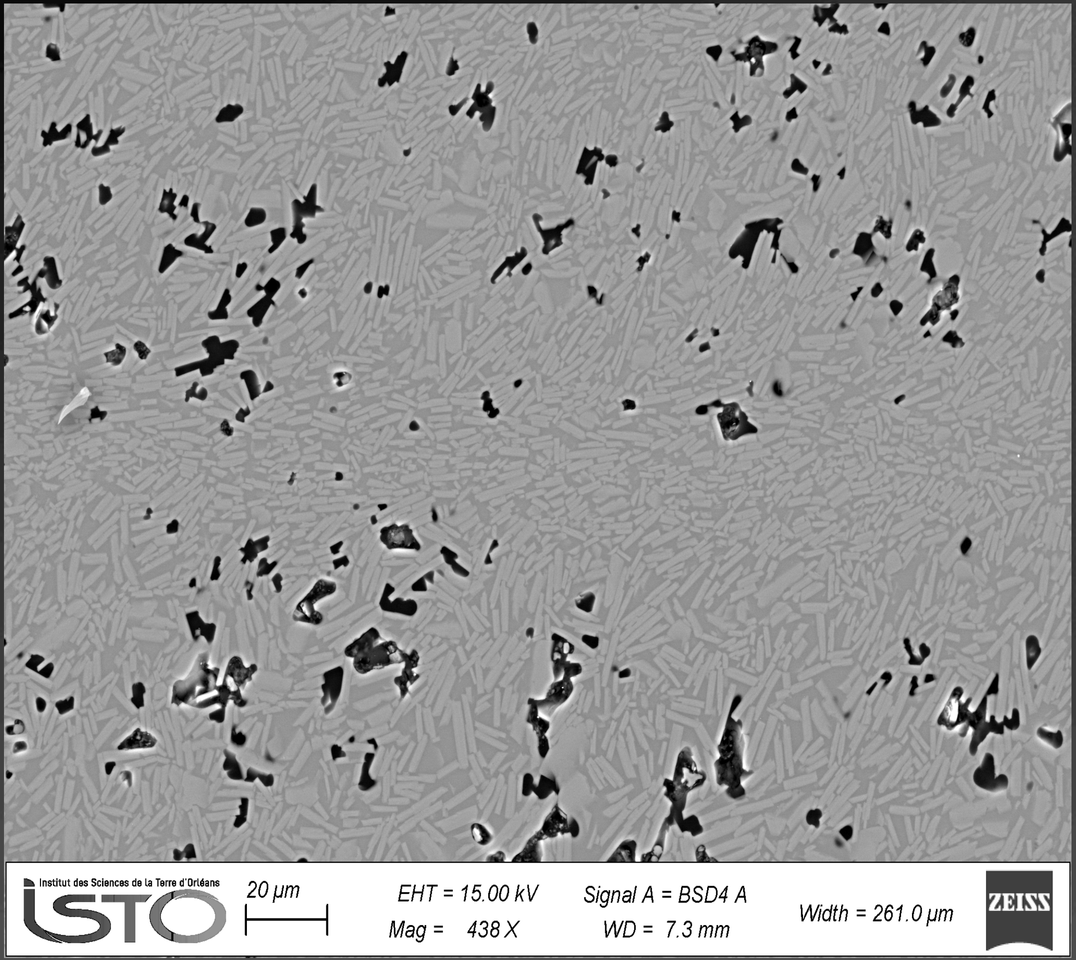
The Viscous number: ratio of the particle response time to the far field shear rate, controls granular behavior

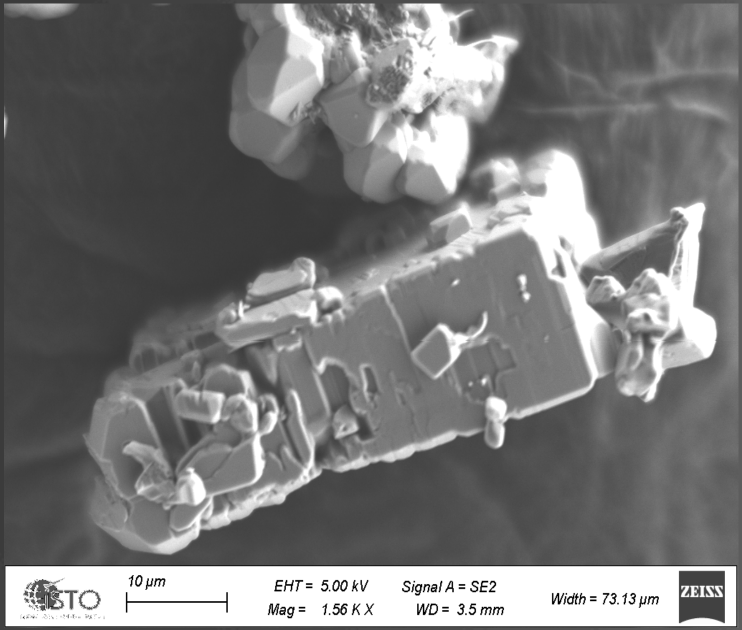
$$I_{vg} = \frac{3\eta_f \dot{\gamma}}{2\Delta\rho g \alpha d}$$

← *solid* *fluid* →

Dynamic Unlocking →

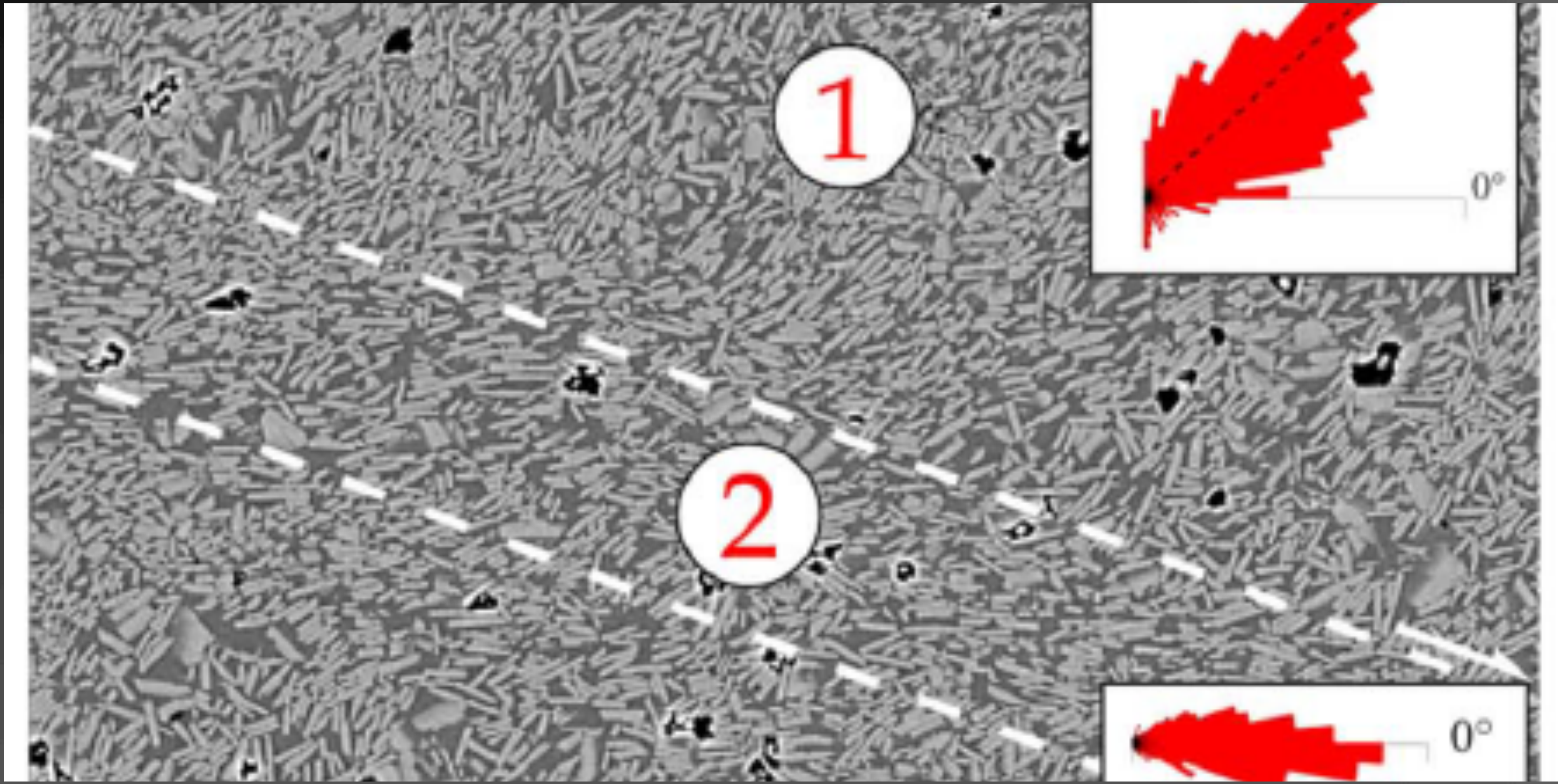
Next steps: Real mushes are paranematic





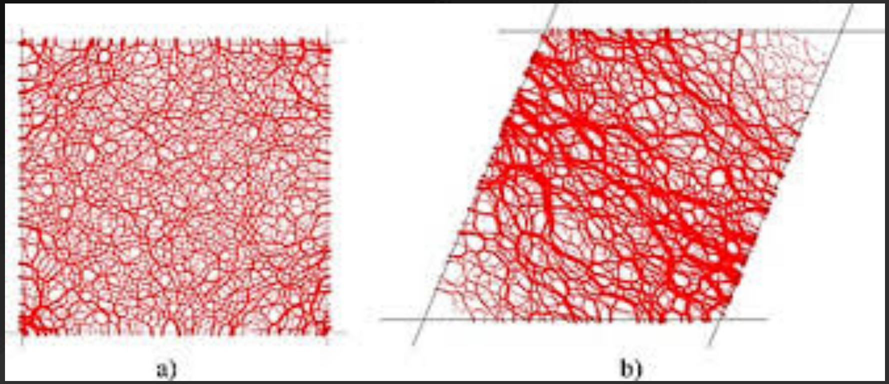
Picard et al., JGR, 2013

Strain partitioning and grain size reduction, 52% crystals



Paterson rig experiments *Picard et al., JGR, 2013*

Dynamics: Friction activated by the appearance of normal forces, the “*f* factor”



$$f_n^* = \frac{f_n}{\langle f_n \rangle}$$

fragile states

jamming

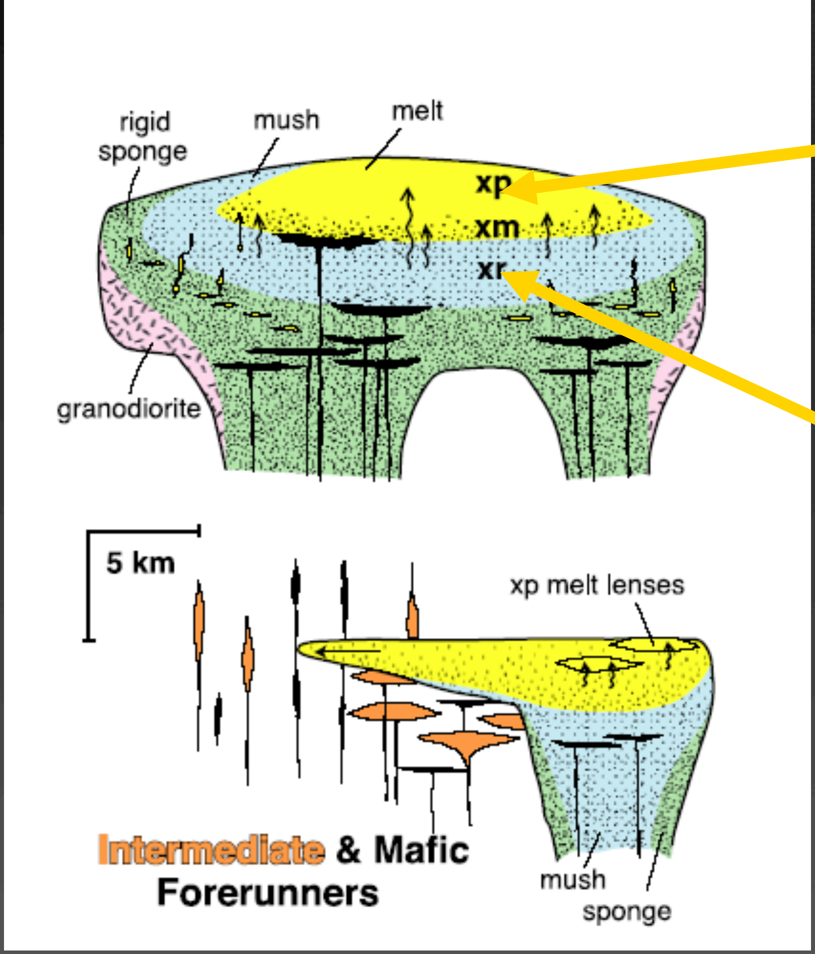
Ansatz: $PDF_{f_n^*} = \exp(C(1 - f_n^*))$

Kinematics: Discrete displacements, how to define strain (plastic deformation)?

- Steric effects yield particle trajectories that deviate from imposed flow $\longrightarrow$ symmetry breaking
- Decompose displacement field into an affine and fluctuating part $\longrightarrow$ *granulence* (after Radjai & Roux, 2002)
- Dissipation is governed by particle friction and drag not controlled by a single length scale

Silicic Mushes?

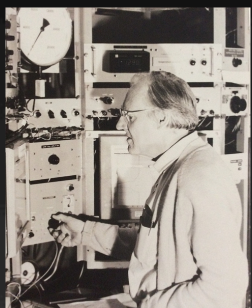
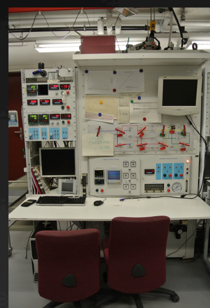
Bishop Tuff



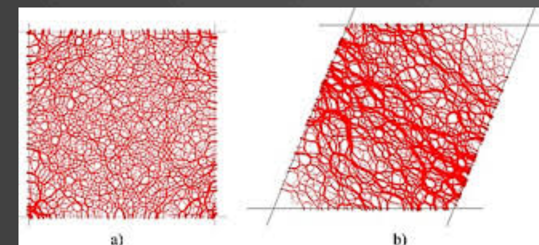
(Hildreth, 2004, J. Volc. Geotherm. Res., v. 136, p. 169)

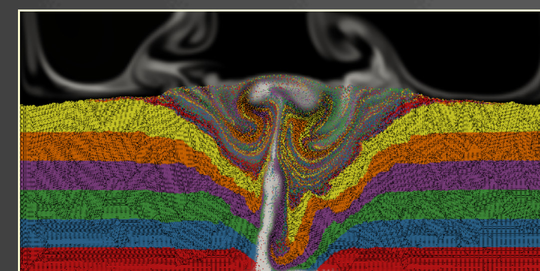
Understanding Magmaic to Volcanic Behavior

Lab experiments


Numerical experiments





Field examples