MODELS OF PALLASITE FORMATION

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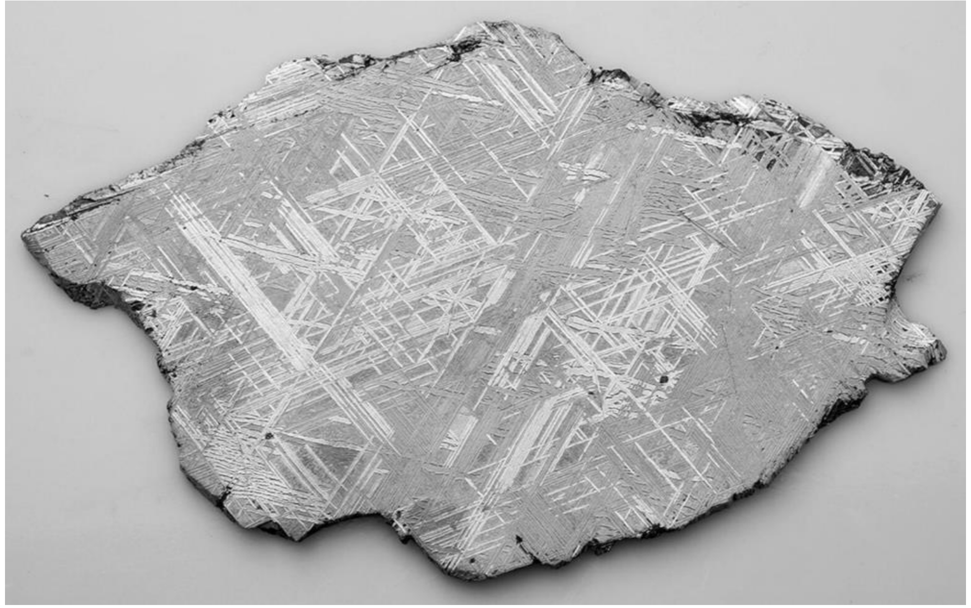
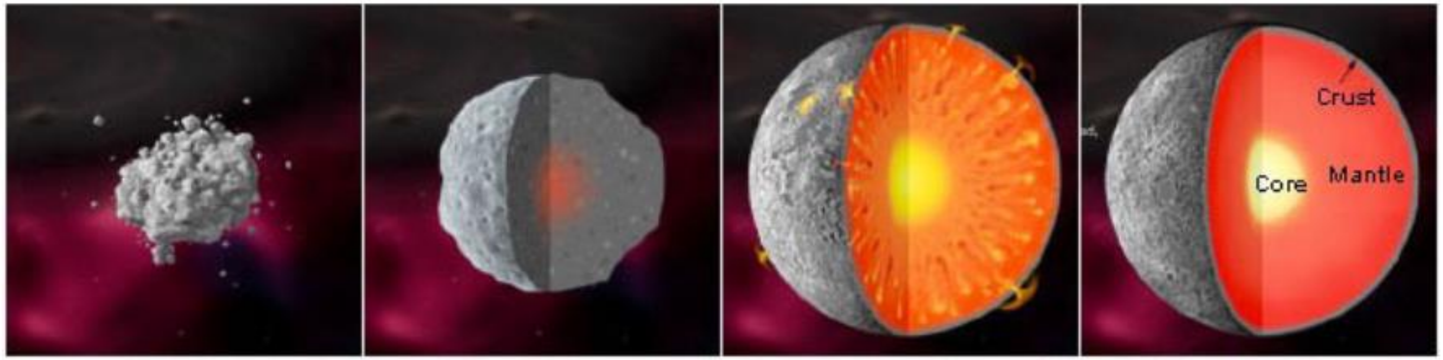
Atacama Desert, Chile

MARKERS OF PLANETESIMAL EVOLUTION

- Classification:
  - Primitive vs non-primitive, or undifferentiated vs differentiated
- Families:
  - Chondrites, achondrites, **stony-irons**, irons
- Differentiation – mantle-core segregation



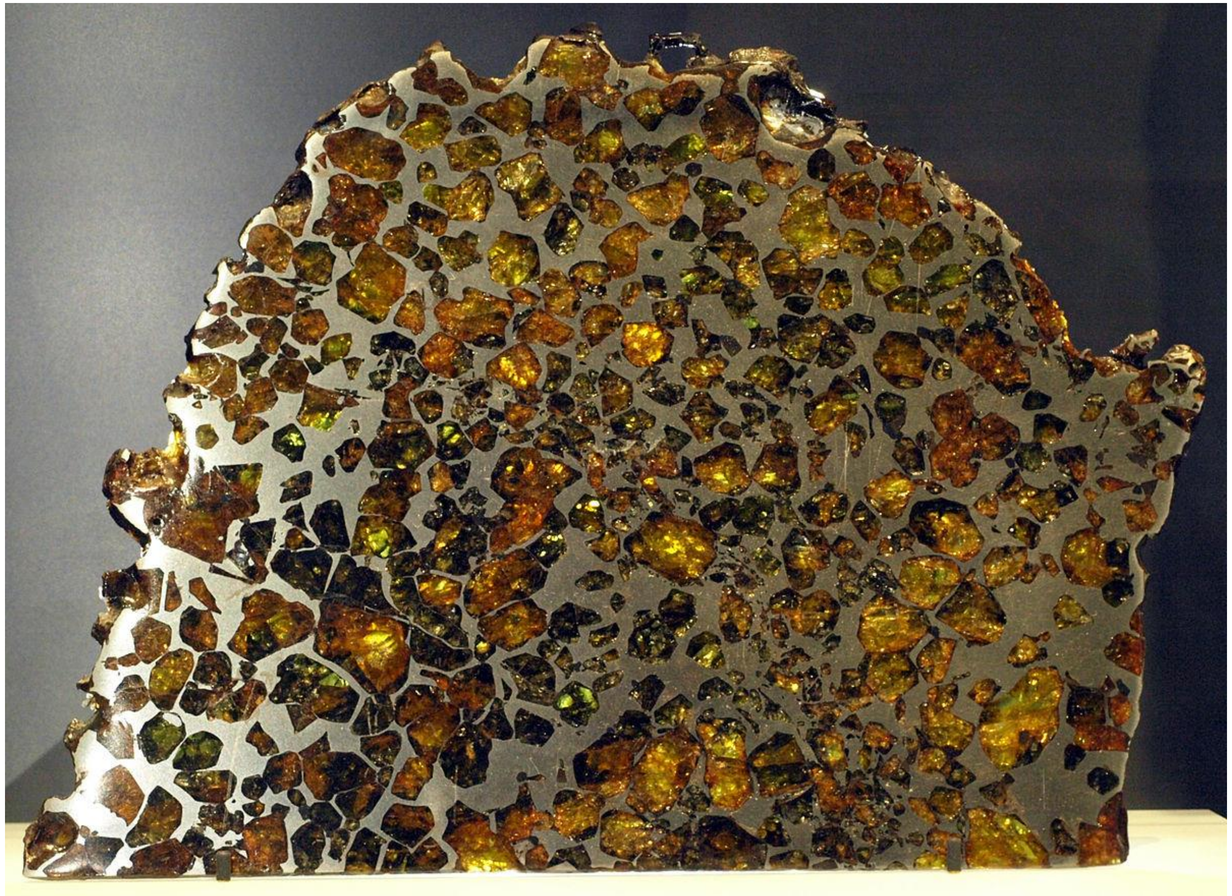
Widmanstätten pattern in iron meteorite ▲



(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

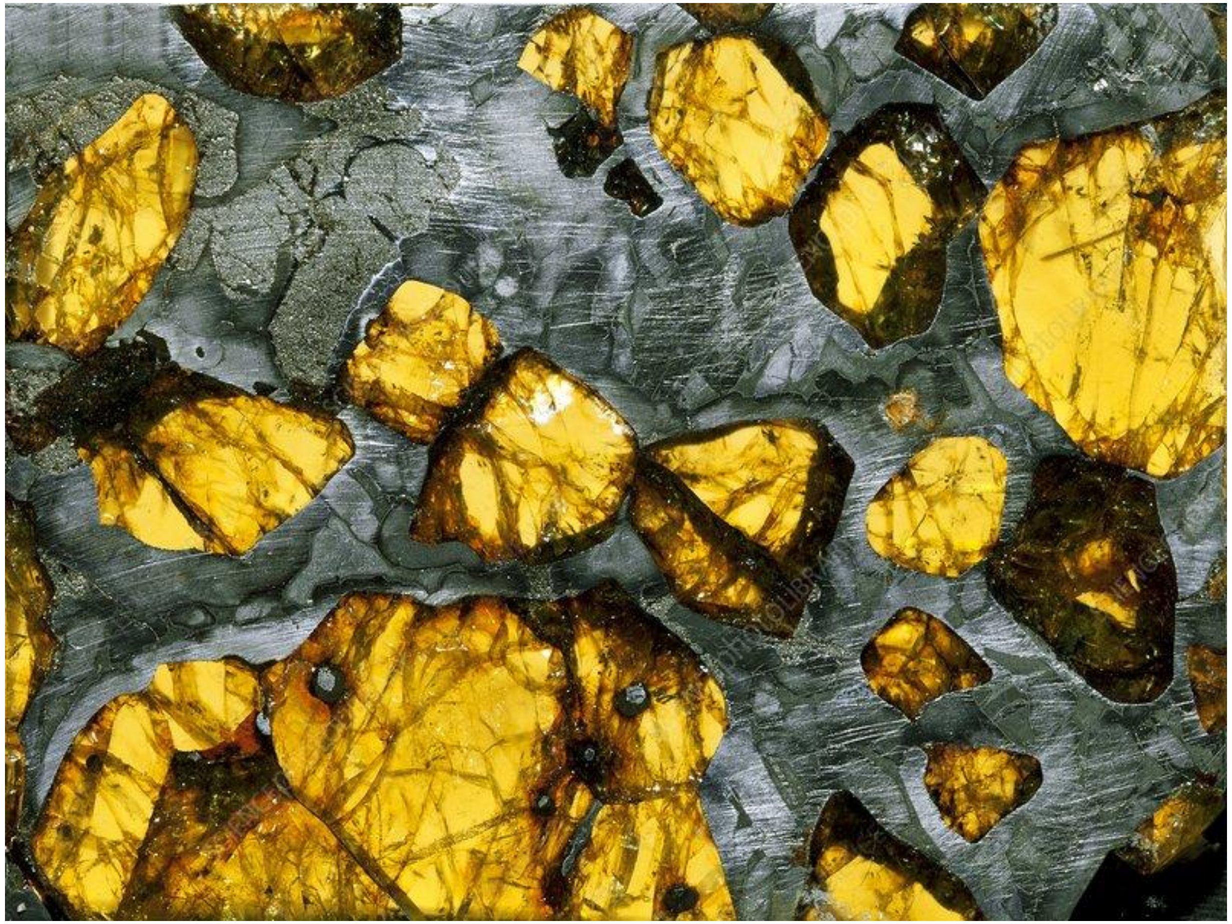
◄ Schematic of planetary differentiation

PALLASITES

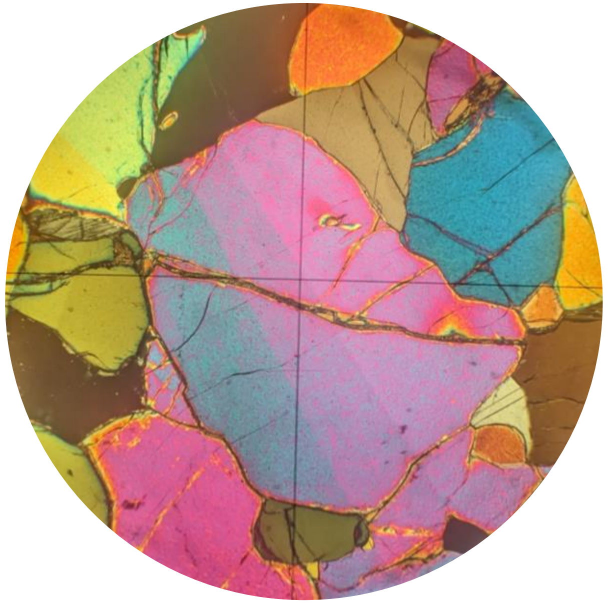


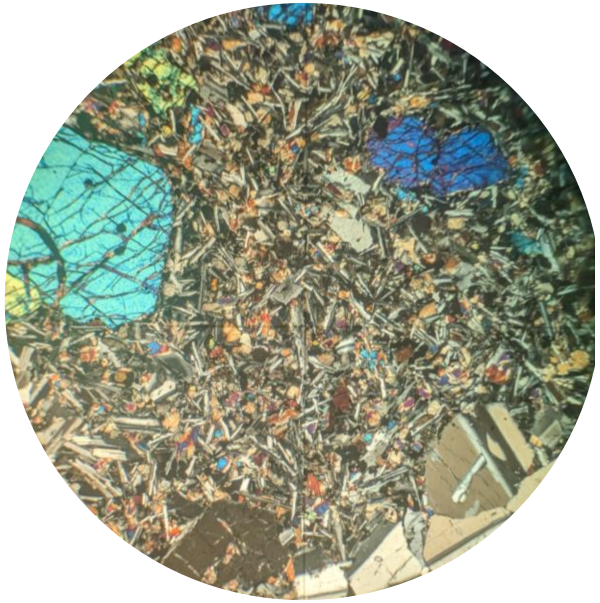
- Non-primitive stony-iron
- Secondary olivine $(Mg,Fe)_2SiO_4$ in a Fe-Ni matrix
- Thought to represent core-mantle boundaries (CMBs) of differentiated parent bodies
- Many models have been proposed!
- Let's take a look at some experimental evidence and theoretical predictions…

ANGULAR AND FRACTURED OLIVINE



▲ Pallasite



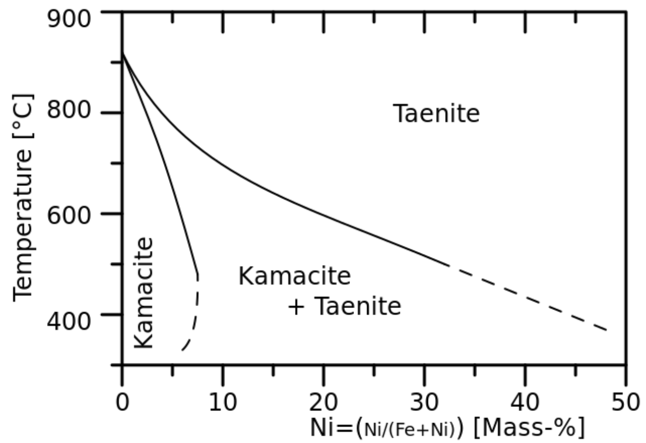


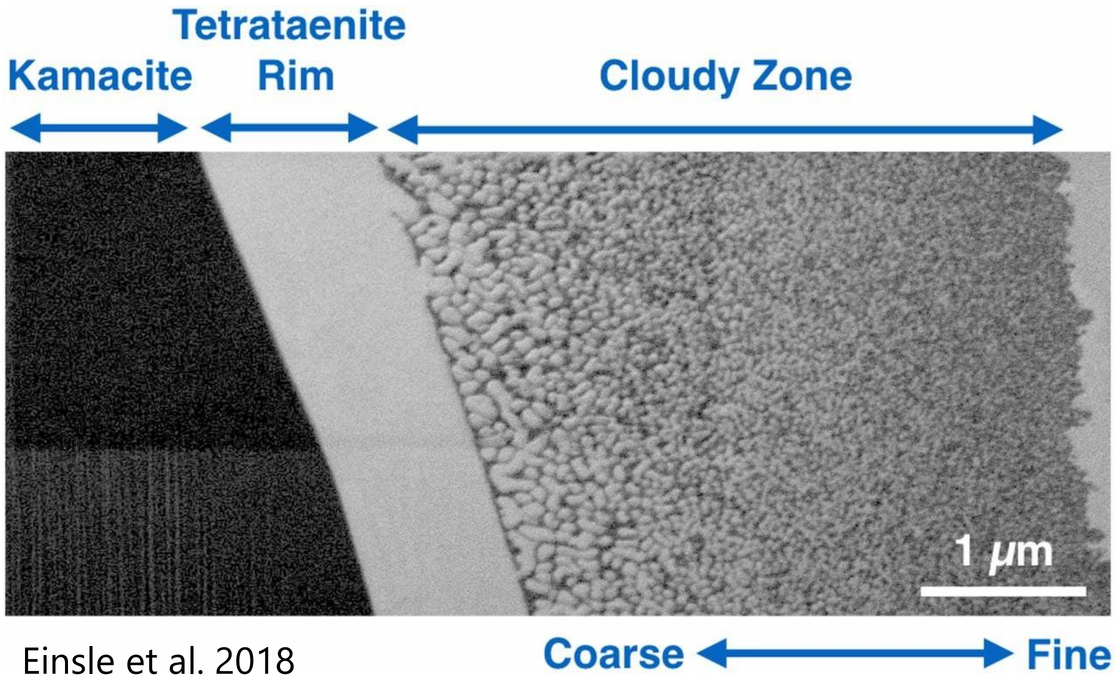
Peridotite HS (above)
Peridotite and basalt TS, XPL (below) ►

Fe-Ni MICROSTRUCTURE

- Widmanstätten patterns are intergrowths of kamacite (low Ni) and taenite (high Ni)
  - Impose low T constraint (<500°C)
- Cloudy zones are blobs of tetrataenite (ordered taenite) surrounded by Fe-rich matrix
- Existence of tetrataenite implies slow cooling
- Tetrataenite ordering occurs below 320°C
  - Acquires remanent magnetization

Phase diagram ►





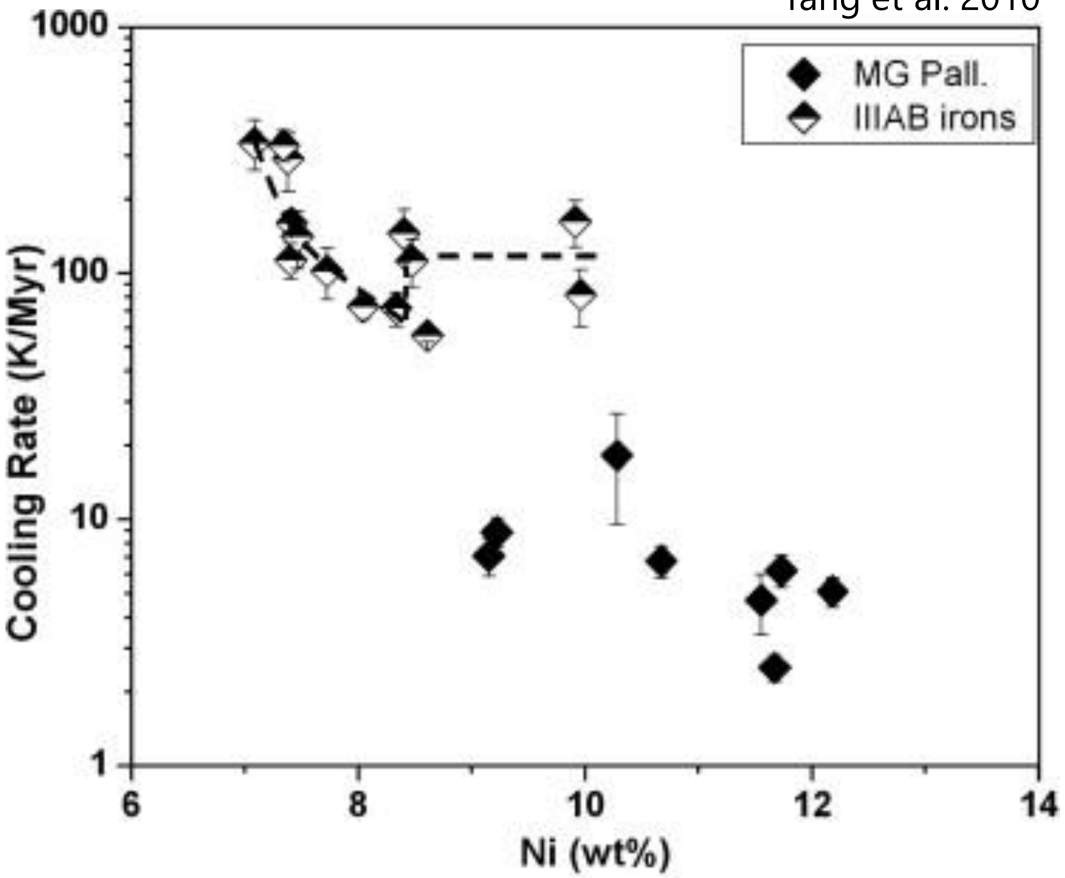
Einsle et al. 2018

COOLING RATE ESTIMATES

Samples from CMB should have the same cooling rates!

- Diffusion profiles, kamacite, tetrataenite bandwidth etc.
- Study by Yang et al. (2010) found significant variation in cooling rates across ~20 MG pallasites
- Concluded from the range of cooling rates that unlikely to have formed *at* the CMB, but at different depths within the mantle

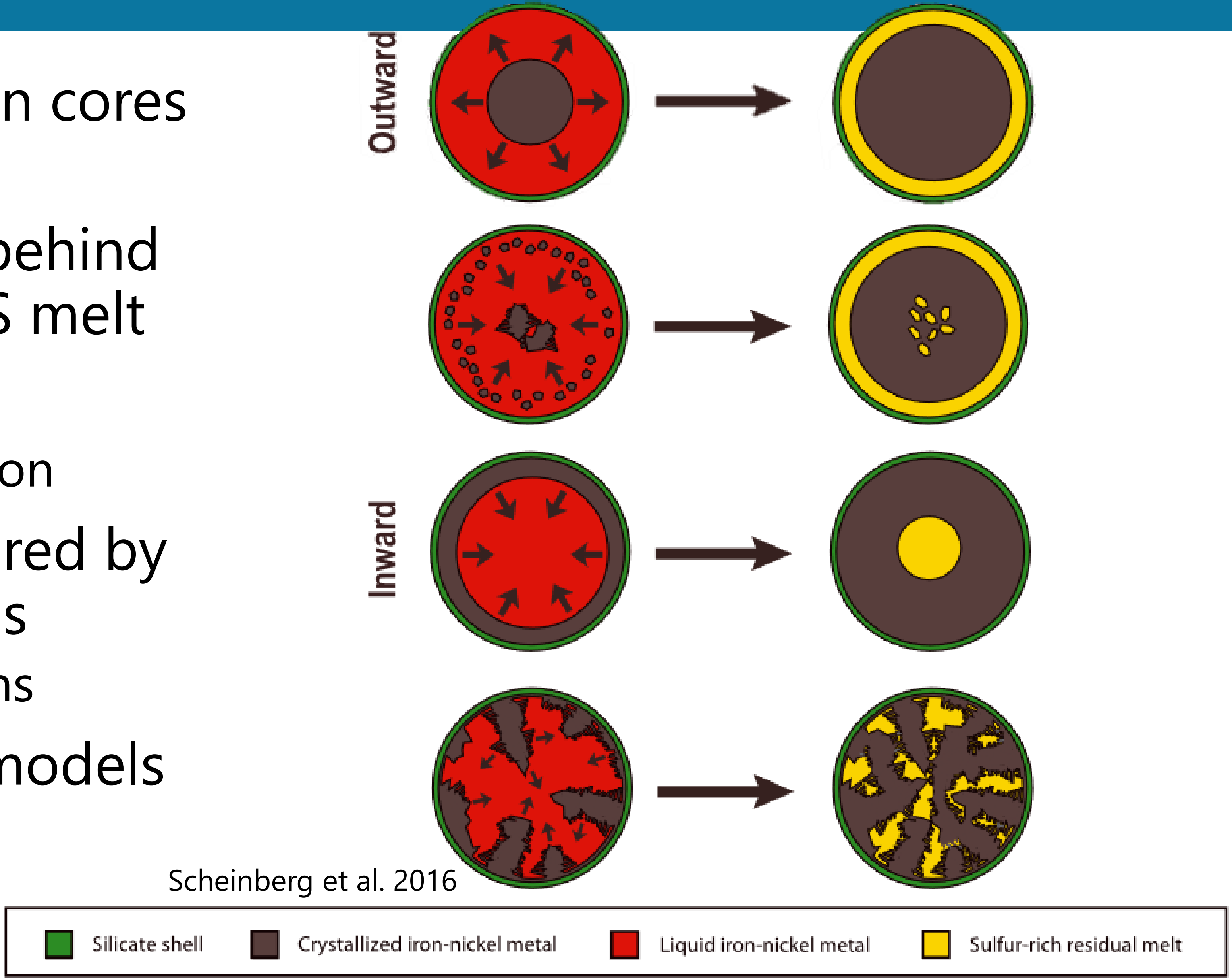
Yang et al. 2010



▲ Cooling rates inferred from Ni diffusion profiles of taenite bands

CORE SOLIDIFICATION

- Post-differentiation: molten cores cool and solidify
- Fe crystallises and leaves behind increasingly sulfur-rich FeS melt
- Can be inward or outward
  - Earth is outward solidification
- Inward solidification favoured by thin-mantled planetesimals
  - Mantle stripped by collisions
- Concentric and dendritic models proposed (Scheinberg et al. 2016)



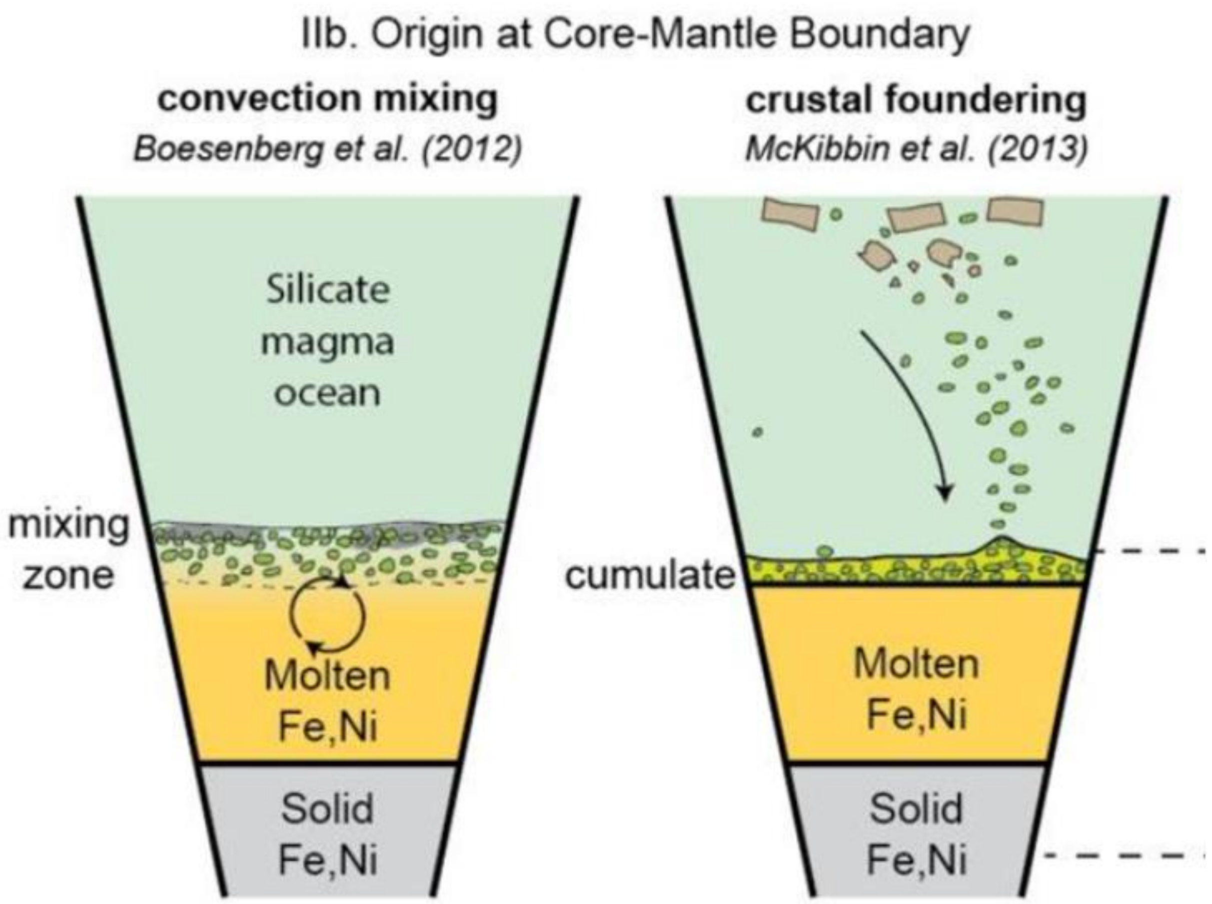
Scheinberg et al. 2016

A HISTORY OF FORMATION MODELS

Wasson and Wetherill (1968)	Collapse of mantle shell into molten upper core mixes solid olivine with molten metal.
Scott (1977a,b,c)	Metal intrudes overlying olivine layer, dispersing olivine masses through metal. Gravitational separation of olivine and metal prevented by metal crystallization. Pallasite metal resembles that calculated following 80% fractional crystallization of a IIIAB metallic melt.
Buseck (1977)	Pallasites form deep in multiple parent bodies by recurring processes. Pallasites could be either the residue of fractional fusion or cumulates produced by fractional crystallization. Metal and olivine form together. Pallasites contain close-packed olivine. Possible multiple immiscible melts present during formation.
Wood (1978a,b, 1981)	Olivine–molten metal assemblage accumulates stably with olivine in close-packed array. If only buoyancy is considered, only tiny fractions of olivine plus metal (pallasite) assemblages can exist in large parent bodies (>100 km) for long times. At molten metal temperatures, olivine would exclude metal and form a dunite by power-law creep. Molten iron from core replaces silicate liquid between olivine grains.
Mittlefehldt (1980)	External heat source partially melts a portion of chondritic parent body surface. Accretion buries zone of maximum temperature. Dunites form in hot zone, while basaltic melts move toward surface. Pallasites form when dunite roof collapses onto contracting and crystallizing metal pods.
Takahashi (1983)	A chondritic source partially melts. Silicate melt density-separates leaving behind residue of metal-sulfide and olivine.
Malvin et al. (1985)	Double impact. First impact makes layered magma body composed of cumulate olivine over metal over residual olivine. Second impact mixes olivine and metal.
Scott and Taylor (1990)	Pallasites with large rounded olivines form when cumulate olivine is submerged into molten core by buoyant forces. Pallasites with angular olivines form by mixing of fragments of olivine mantle with molten metal during impacts.
Ulff-Møller et al. (1998)	Pallasites form by intrusion of highly evolved (low Ir, high Ni, Au and S) molten melt into fragmented olivine. After intrusion, the degree of crystallization of molten melt varies with location. An FeS-rich liquid either escapes or forms underrepresented FeS-rich pallasites.
Wasson and Choi (2003)	Pallasite precursors may be required to interact with a gas phase to produce Ga and Ge concentrations in metal.
Scott (2007)	Pallasites are impact-generated core-mantle mixtures formed as chains of differentiated bodies with diverse metal–silicate ratios following glancing impacts between protoplanets (Asphaug et al., 2006). Following reassembly, the pallasite layer is emplaced shallowly, where fast cooling rates are recorded in angular olivine. Post-impact regolith buries layer deep, consistent with metal cooling rates.
Yang et al. (2010)	Differentiated asteroid or protoplanet with an olivine-rich mantle and a metallic core that is 80% solidified impacts larger body at a glancing angle. The differentiated body is torn apart forming the pallasite body from residual molten metal and fragments of olivine mantle. Solid core and remaining mantle do not accrete.

see Boesenberg et al. 2012, Table 4

MIXING AT THE CORE-MANTLE BOUNDARY



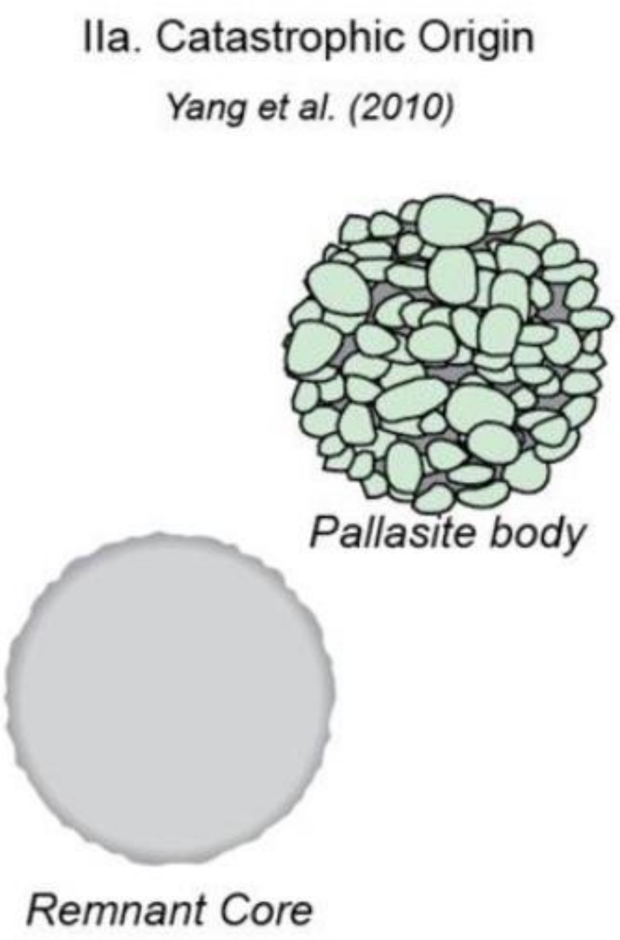
Donohue et al. 2018

- Outward core solidification and composition from single body

Convection mixing

- Start with fractional melting of primitive, olivine-rich body
- Olivine-rich melt segregates from other melt at CMB and clusters crystallise from supersaturation
- Mix molten metal with smaller olivine clusters
- Fractured olivines due to surface impacts

IMPACT MODELS



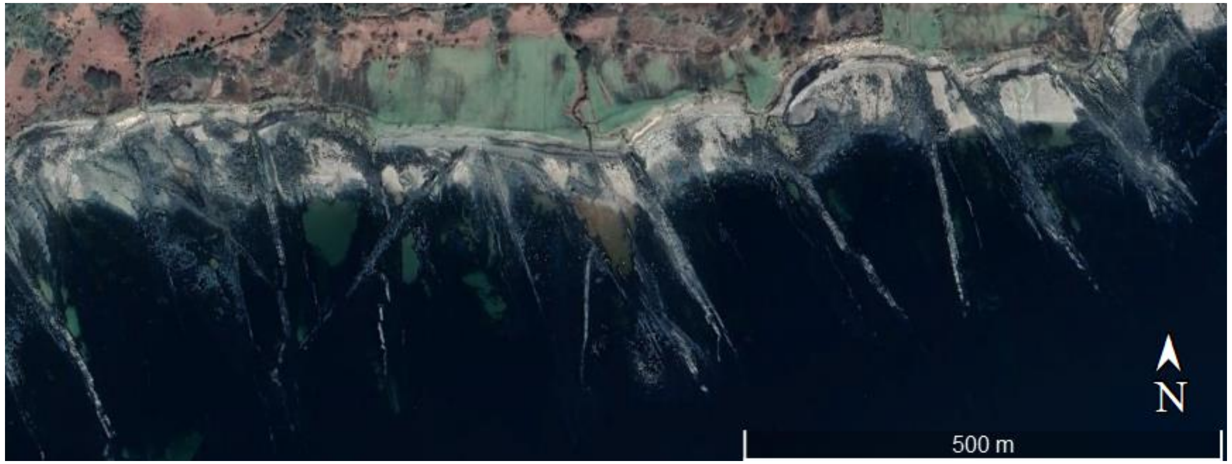
Catastrophic origin

- One parent body with olivine-rich mantle and outward solidification
- Impact with another body
- Forms pallasite body from residual molten metal and olivine mantle
- Removes solid Fe-Ni core, which fails to accrete

FERROVOLCANISM

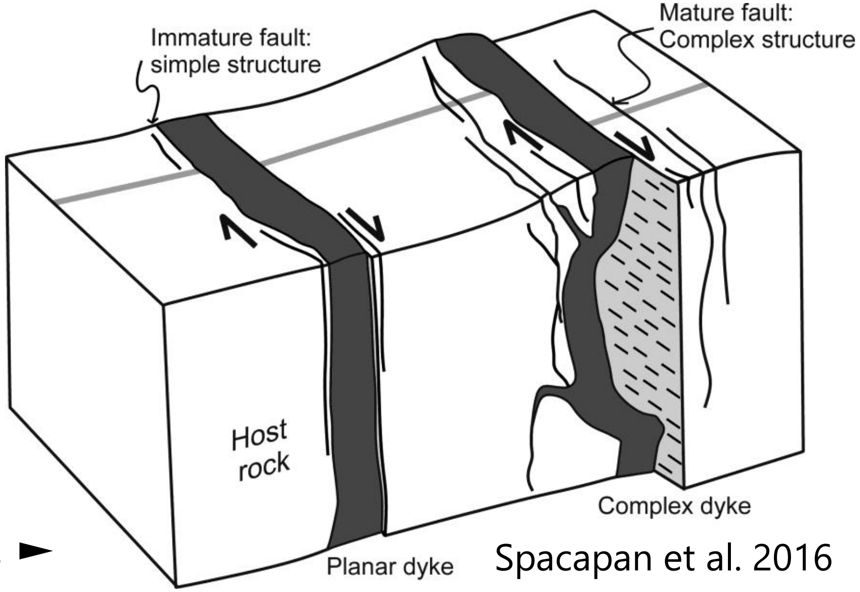
Why is this considered?

- Eruption of material on Earth's surface can occur via dykes
  - Weaknesses in the (brittle) rock are exploited by melt (less dense)
- Same process is proposed to happen at the CMB, via "metallic dykes"
- This mechanism can entrain the olivine crystals in the Fe-Ni melt
- Johnson et al. (2020)



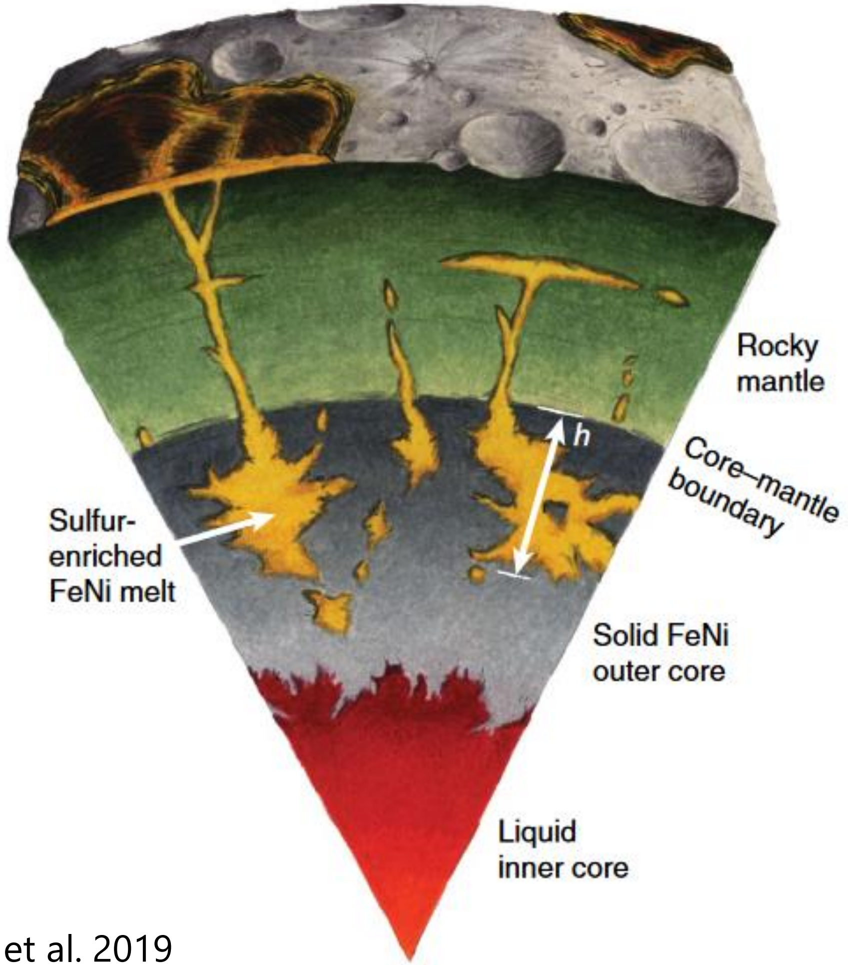
▲ Dykes on the south coast of Arran, Scotland

Geometry of dykes ►



Spacapan et al. 2016

FERROVOLCANISM



Johnson et al. 2019

Schematic diagram of ferrovolcanism ▲

- Inward solidification via dendrites
- Consider negatively buoyant core melt w.r.t. mantle rock
- If negatively buoyant then ascent is driven by excess pressure
- If excess pressure is greater than the tensile strength of the mantle then dykes can propagate
- … provided that the mantle is brittle at these temperatures and pressures

CONDITIONS FOR DYKE PROPAGATION

- Consider the excess pressure P_e due to residual core melt at the CMB

$$P_e = (\rho_{\mathrm{Fe}} - \rho_{\mathrm{FeS}})hg$$

- ρ_{FeS} is the density of the melt, ρ_{Fe} is the density of the solid iron
  - Assume no Ni composition; ρ_{FeS} is controlled by sulfur content
- h is the vertical extent of the partially molten layer, g is set by core size. Gravitational acceleration at the CMB
- This excess pressure acts on the mantle above
- Check if this exceeds the tensile strength of rock

CONDITIONS FOR DYKE PROPAGATION

Check if this exceeds the tensile strength of rock

- CMB temperature ~ Fe-FeS eutectic temperature (i.e. in equilibrium)
- This is ~1300 K – similar to terrestrial dykes

→ take tensile strength of mantle ~ terrestrial analogue (~1 MPa)

What about propagation through solid iron?

- MP of pure Fe (~1800 K) and sulfur-enriched material > eutectic temp
- Pure Fe tensile strength ~10 MPa at 1000 K, decreases to zero at MP
- Again take tensile strength of Fe ~1 MPa

DYKE PROPAGATION

How far into the mantle do the dykes propagate?

- Ignoring change in g with changing depth, mantle penetration height obtained by equating excess pressure with negative buoyancy of intrusion

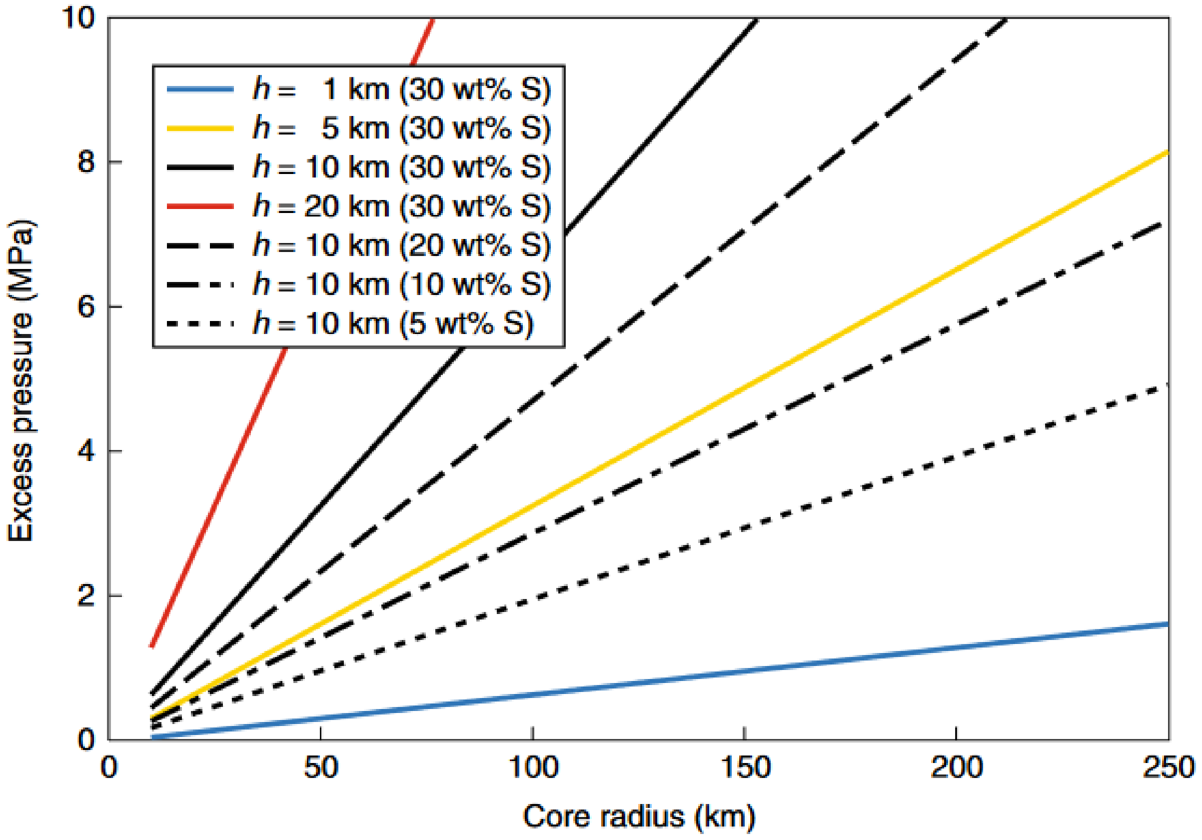
$$\underbrace{hg(\rho_{\mathrm{Fe}} - \rho_{\mathrm{FeS}})}_{\text{excess pressure}} = \underbrace{tg(\rho_{\mathrm{FeS}} - \rho_{\mathrm{mantle}})}_{\text{intrusion}}$$

- t is independent of g and hence core size

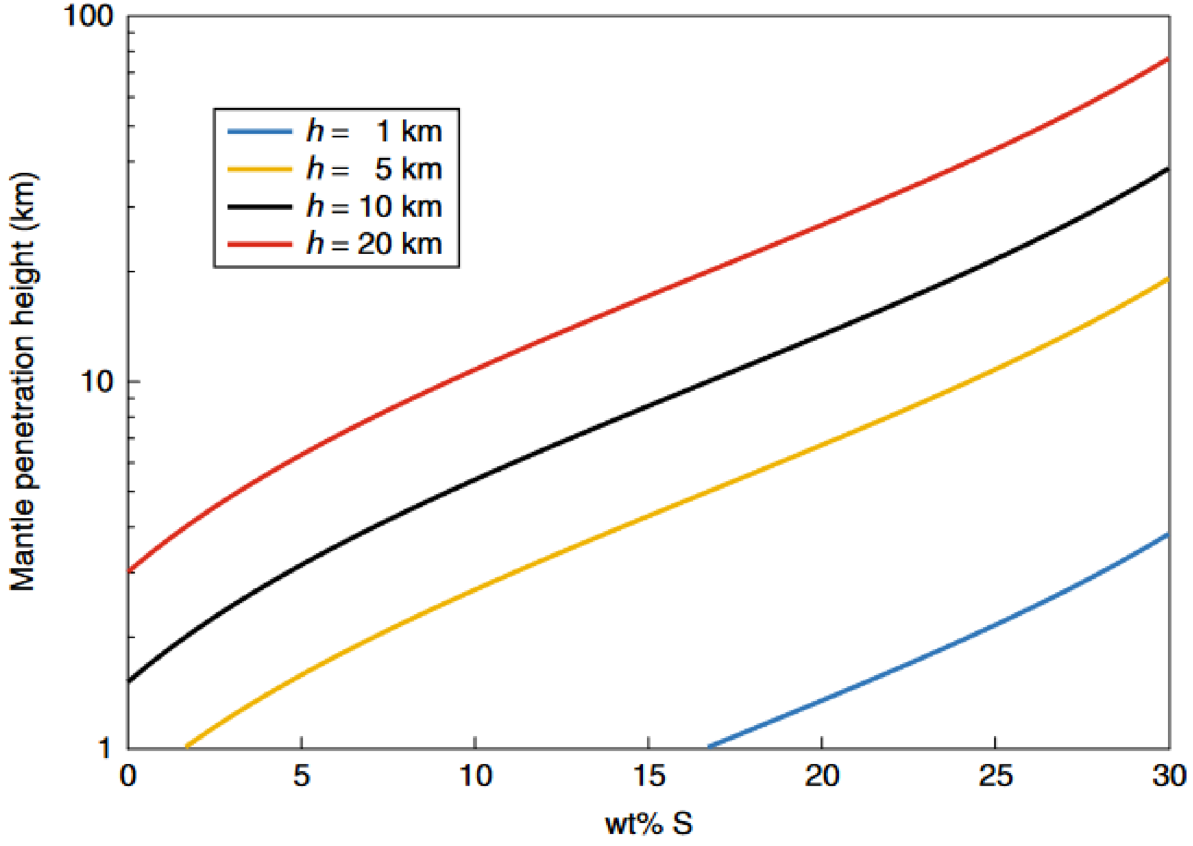
What if the top of the melt is depth D from the CMB?

$$t_D = (h + D)\frac{\rho_{\mathrm{Fe}} - \rho_{\mathrm{FeS}}}{\rho_{\mathrm{FeS}} - \rho_{\mathrm{mantle}}} > t$$

DYKE PROPAGATION



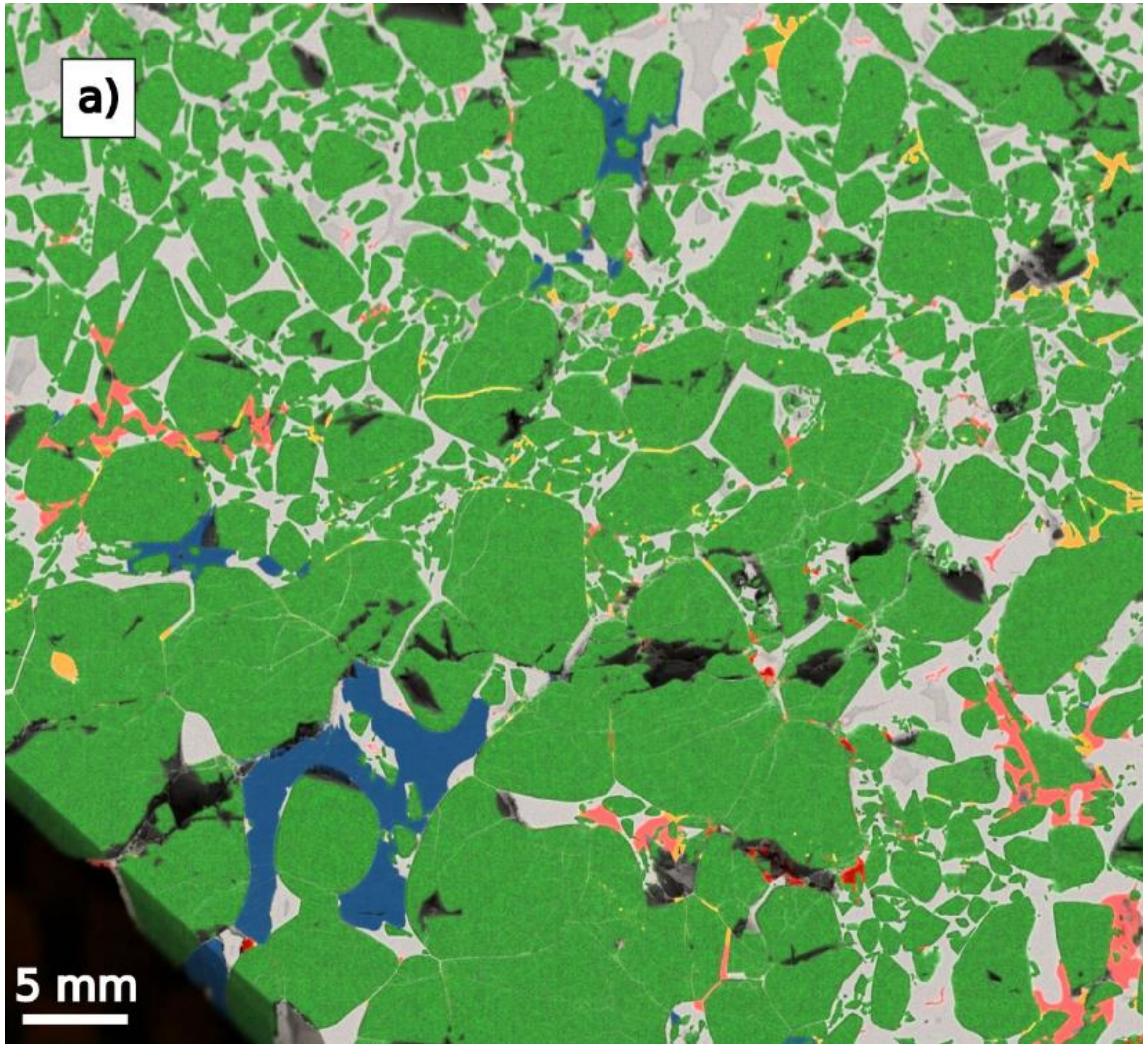
▲ Excess pressure, varying R, h and sulfur content. Estimated tensile strengths <6 MPa



▲ Mantle penetration height, varying sulfur content and h.

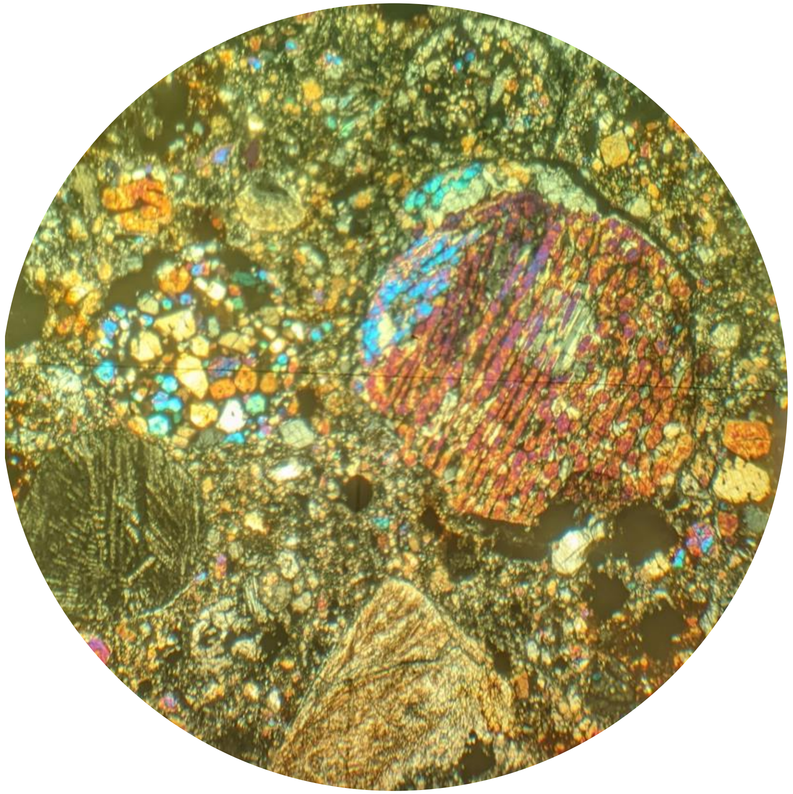
CONCLUSIONS

- Ferrovolcanism possible in large-cored, thin-mantled bodies, with high sulfur content
- Variation in dyke propagation accounts for cooling at different depths
- Pressure induced by dykes could cause fractures observed in olivine
- For supporting palaeomagnetic evidence see Nichols et al. (2021)

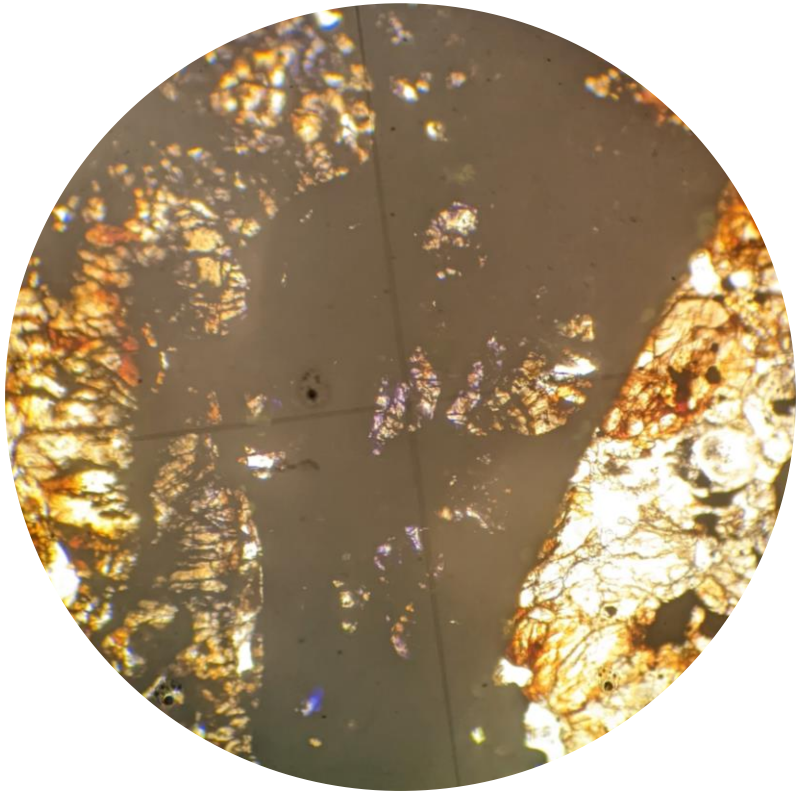


▲ XRF phase map of Brahin (McKibbin et al. 2019)

SHOCK METAMORPHISM IN THIN SECTION



L4 Bjurböle (XPL)



L6 Tenham (XPL)