^{40}Ar retention in the terrestrial planets

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Noble gas

- He, Ne, Ar, Kr, Xe, Rn

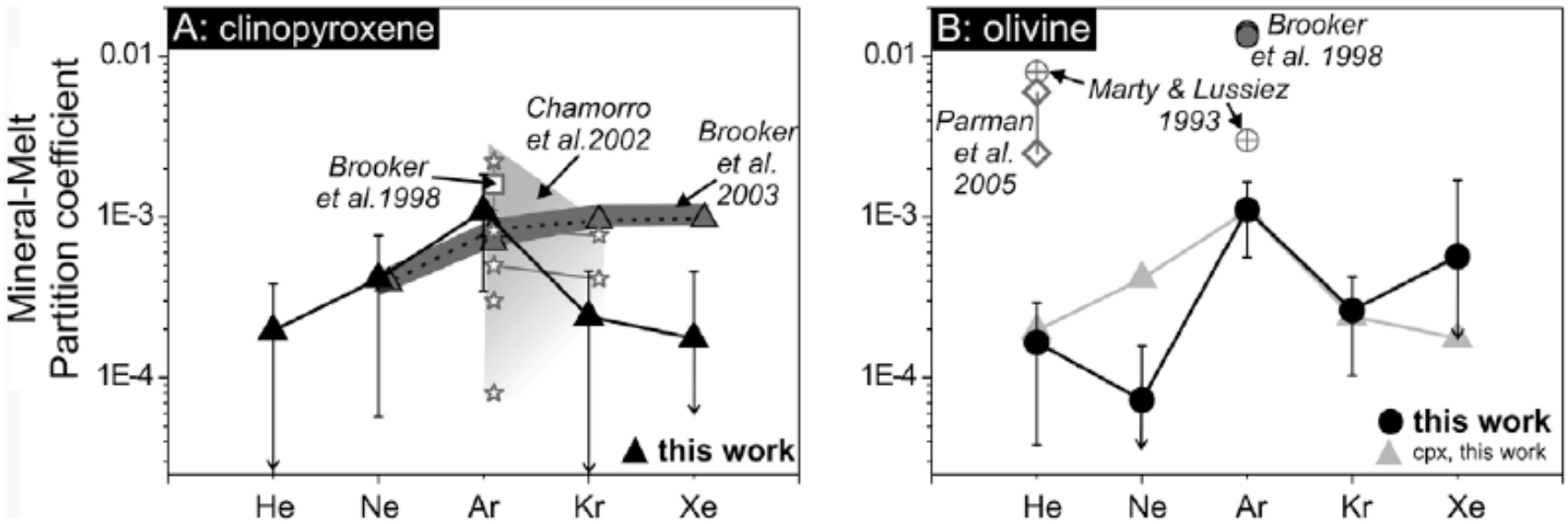
Inert (no reaction with Earth's materials)

Information on timing (degassing event)

Implicit understanding

1. Degassing during melting (incompatible)
2. Not recycled back into the mantle

Noble gases are incompatible??



Heber et al. (2007)

Crystal-growth procedure

Radiogenic noble gas isotope

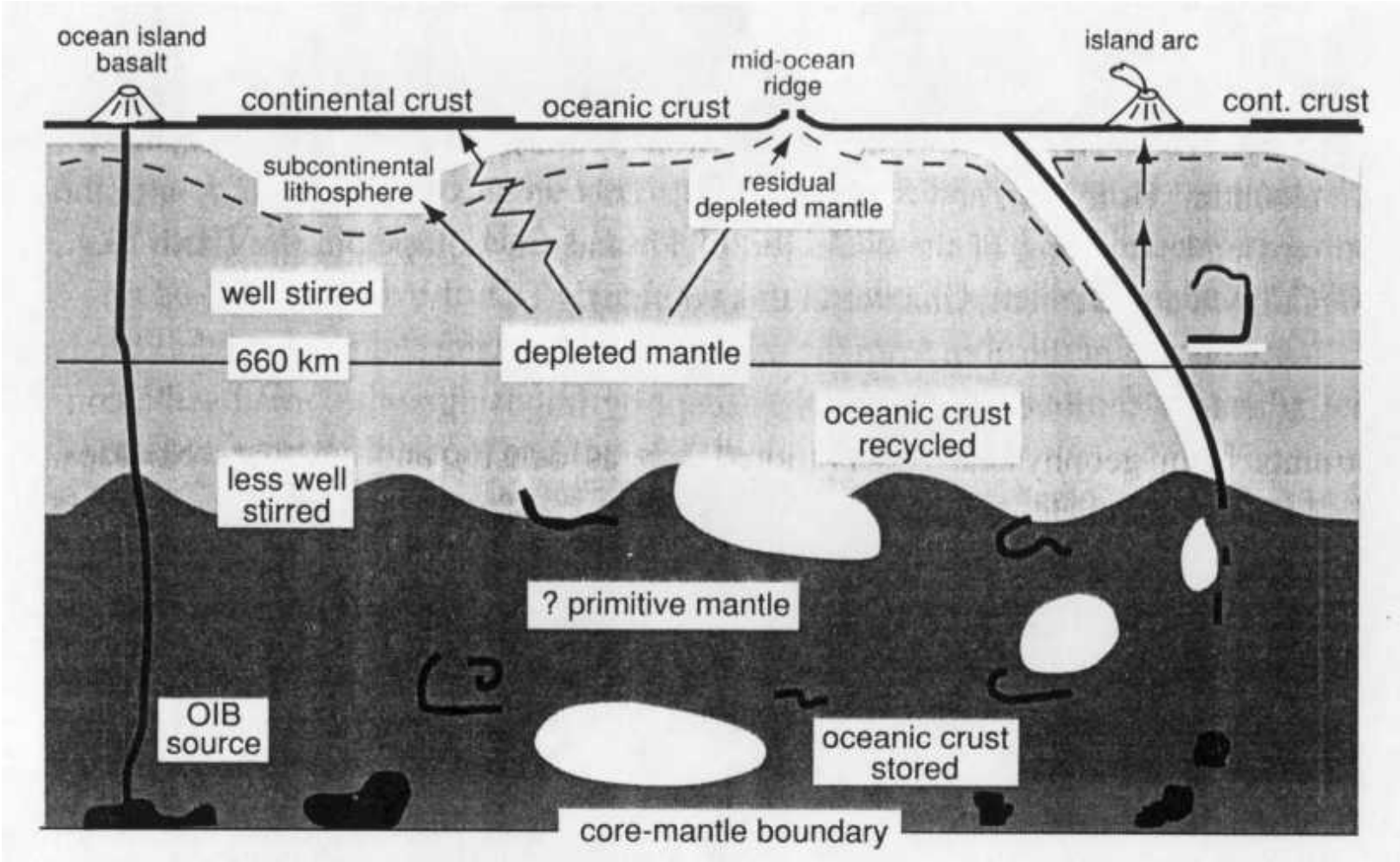
$^{129}Xe/\ ^{130}Xe$ ($^{129}I \rightarrow\ ^{129}Xe$: 15.7Myr)

The first 50-100myr of the Earth's history

$^{3}He/\ ^{4}He$

The early degassing of the Earth is incomplete

2 geochemical reservoirs



$^{40}Ar/\ ^{36}Ar$

- ^{40}Ar (radiogenic: $^{40}K \rightarrow\ ^{40}Ar$: 1.251 Gyr)
- ^{36}Ar and ^{38}Ar (stable) are primordial

Knowledge of accurate K content of the bulk Earth
→ time-integrated extent of terrestrial degassing estimated from the abundance of ^{40}Ar in the atmosphere (295.5)

The present estimate: ~50% degassing

What they did and proposed

Determination of the solubility and diffusivity of Ar in olivine and enstatite

Deny the simple magma degassing scenario

The upper mantle of the Earth is not essentially degassed during melting and can store ^{40}Ar in olivine and orthopyroxene.

Experimental procedure

Starting material

1. Mg_2SiO_4 single crystal (synthetic)
2. Natural enstatite $MgSiO_3$ single crystal from Sri Lanka (FeO~0.9wt.%)

Apparatus

Cold seal pressure vessel

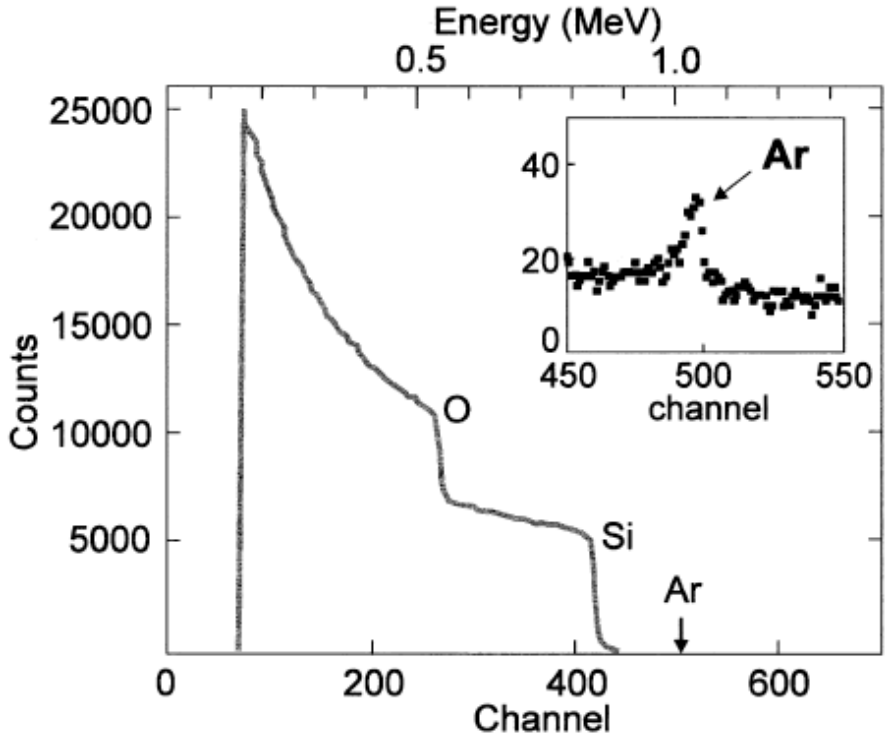
Run condition

690~1340K, Ni-NiO and Mo-MoO_2 buffers, 120-716 hrs

Analytical

- Rutherford backscattering spectroscopy (RBS)

Ar diffusion in quartz



Watson & Cherniak (2003)

$^4He^+$ ion (1~3 MeV)

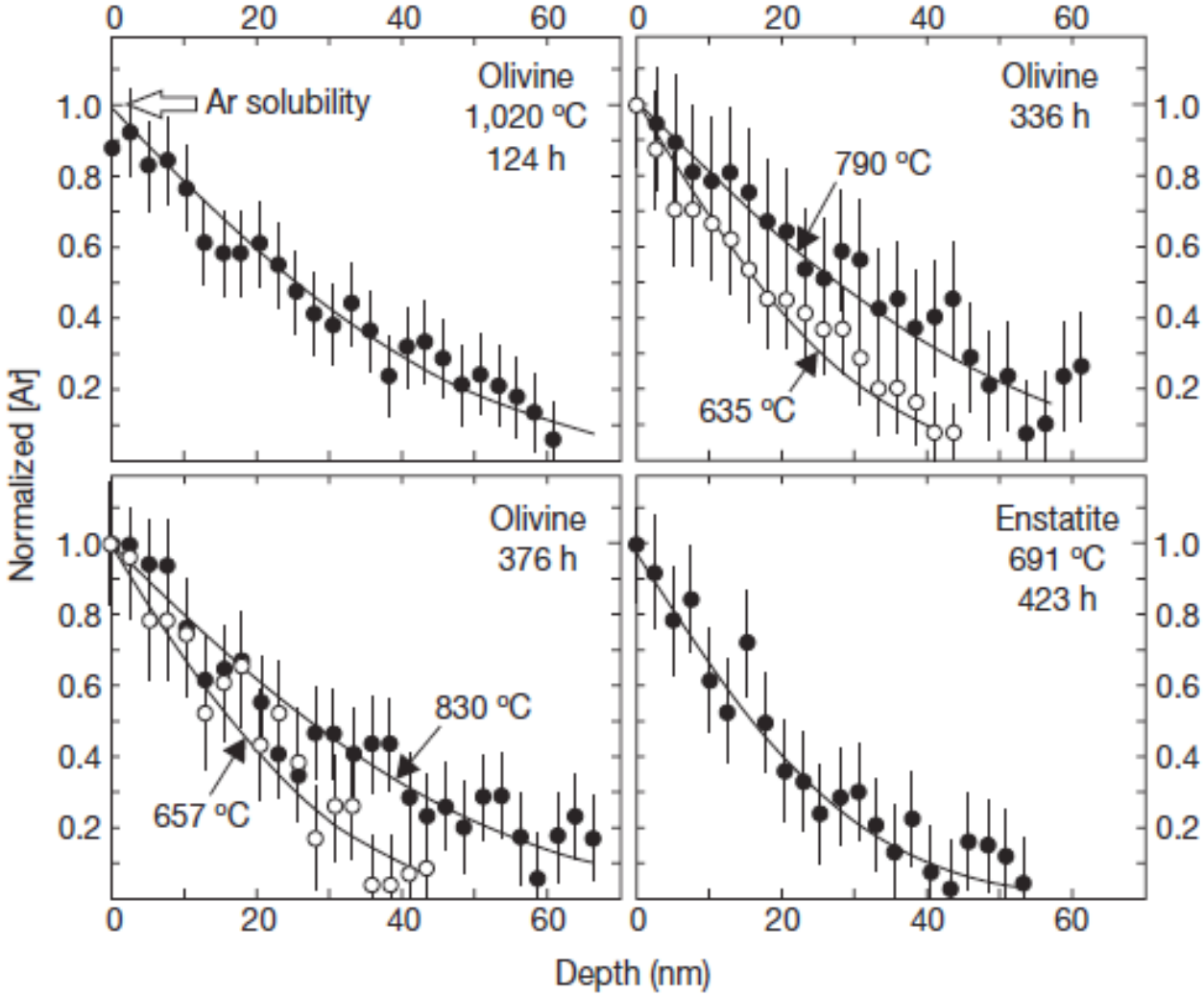
Principle

Energy of back scattered $^4He^+$ ion depends on

1) The mass of the nucleus (element)
2) The depth in the sample at which collision occurred (depth profile)

$^4He^+$ ion lose energy through inelastic process as they travel back through the sample

Ar diffusion



$$C_x/C_o = 1 - \mathrm{erf}[x/(Dt)^{1/2}]$$

Evaluation of the surface absorption

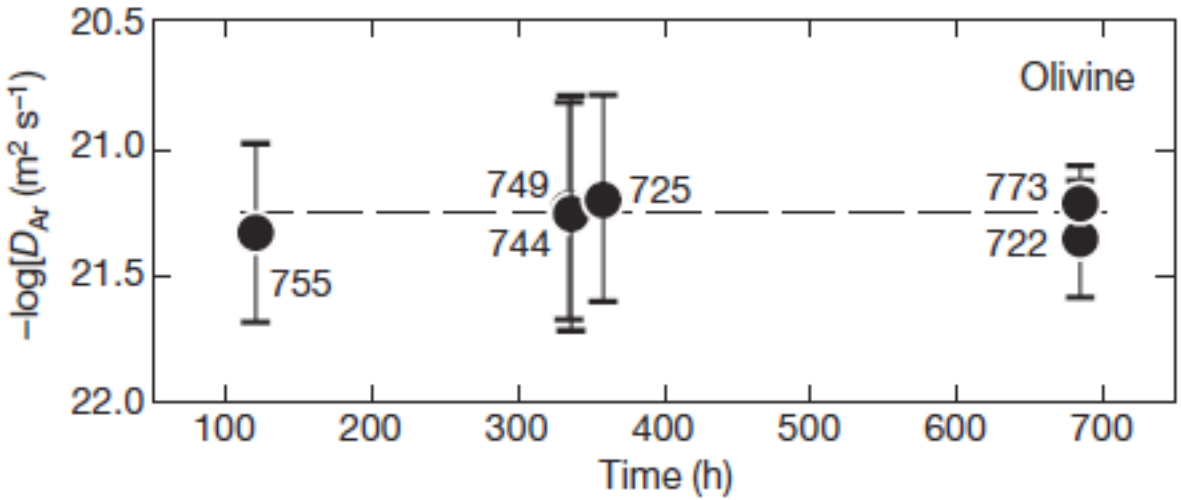
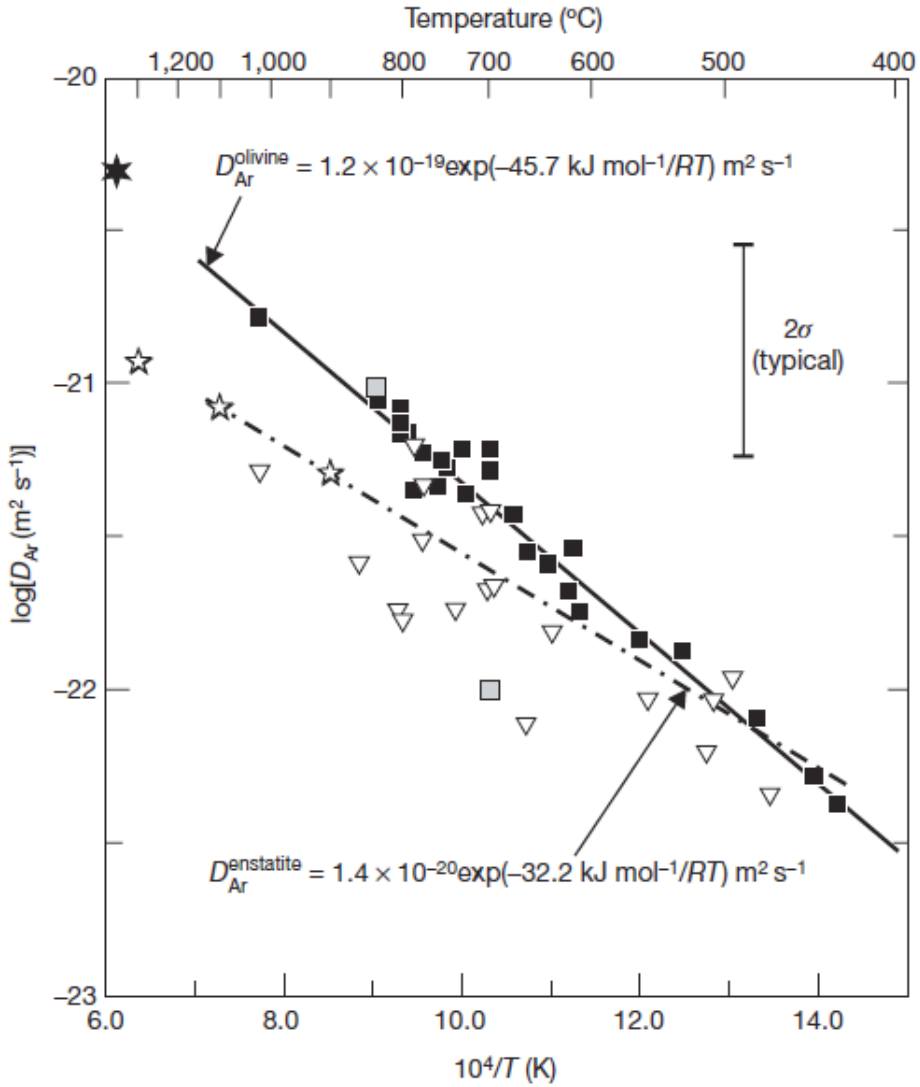


Figure 2 | Diffusivities of Ar in olivine at $T \approx 750$ °C from experiments of differing duration. The similarity of D values extracted from experiments of markedly different duration eliminates surface control as a factor in the diffusive uptake of Ar. Error bars as in Fig. 1.

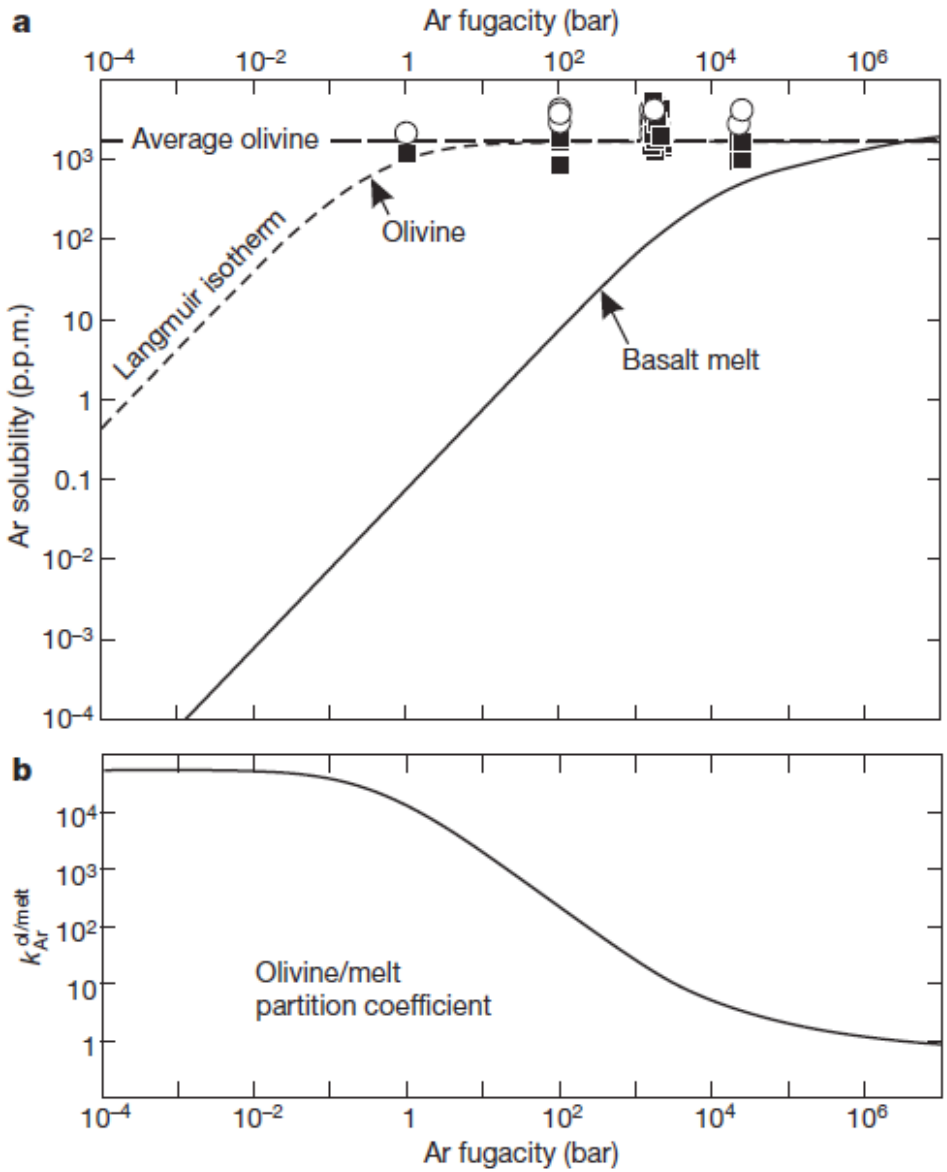
Arrhenius plot



Ar diffusivity

1. Very low
2. Weak temperature dependence (Ol: 46 kJ/mol and En: 32 kJ/mol)

Ar solubility



Olivine: 1830 ppm
Enstatite: 3230 ppm

No dependence on temperature or Ar fugacity (1~10^4 bar)

Langmuir isotherm*

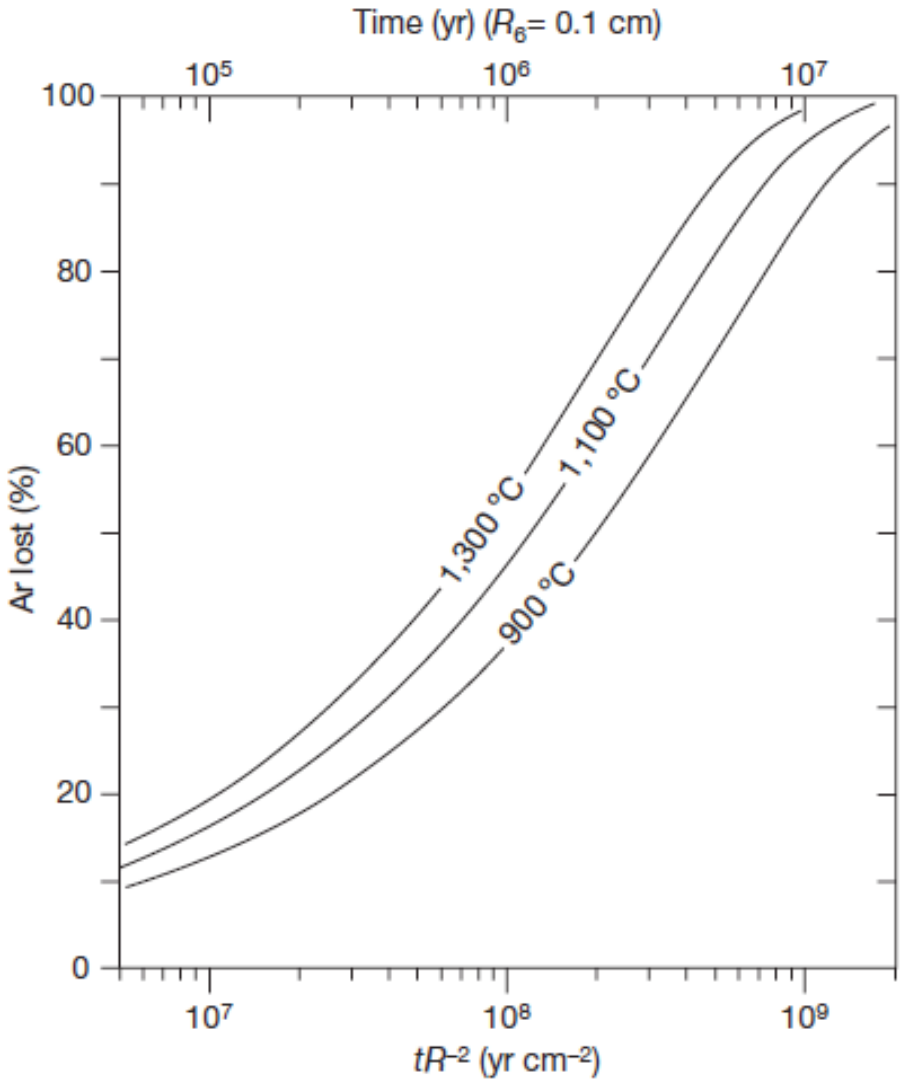
The Langmuir isotherm relates the absorption of molecules on a solid surface to gas pressure or concentration of a medium above the solid surface at a fixed temperature.

$$k_L = [n/(M-n)]/f_{Ar}$$

Ar is compatible

$$k_{Ar}^{min/melt} \gg 1$$

Diffusive loss of Ar from spherical grains



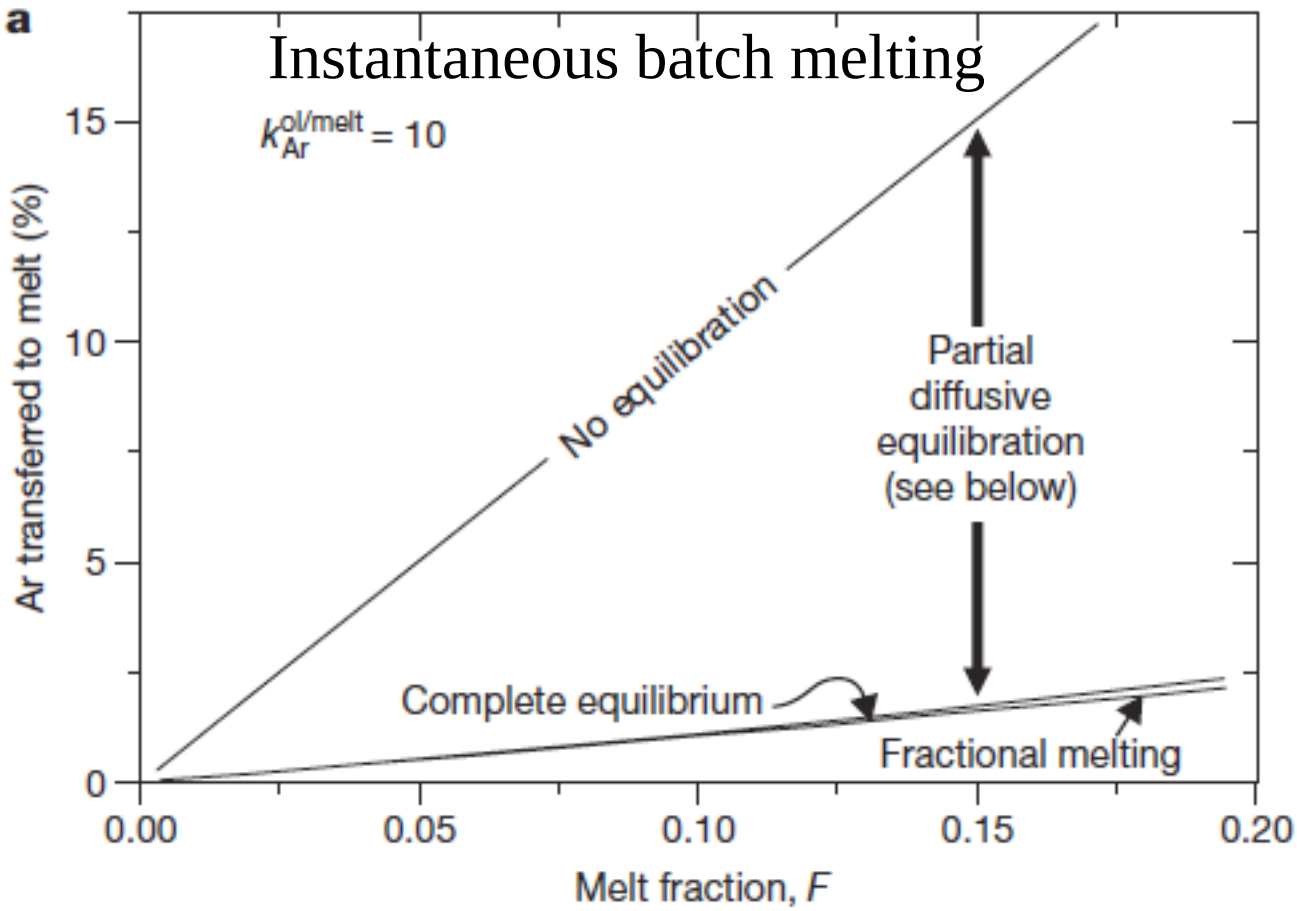
K sink: clinopyroxene (generation of ^{40}Ar)
Diffusive loss of ^{40}Ar

↓

Ar uptake in olivine and opx

Ar can disperse throughout all phases on geodynamically short time scale

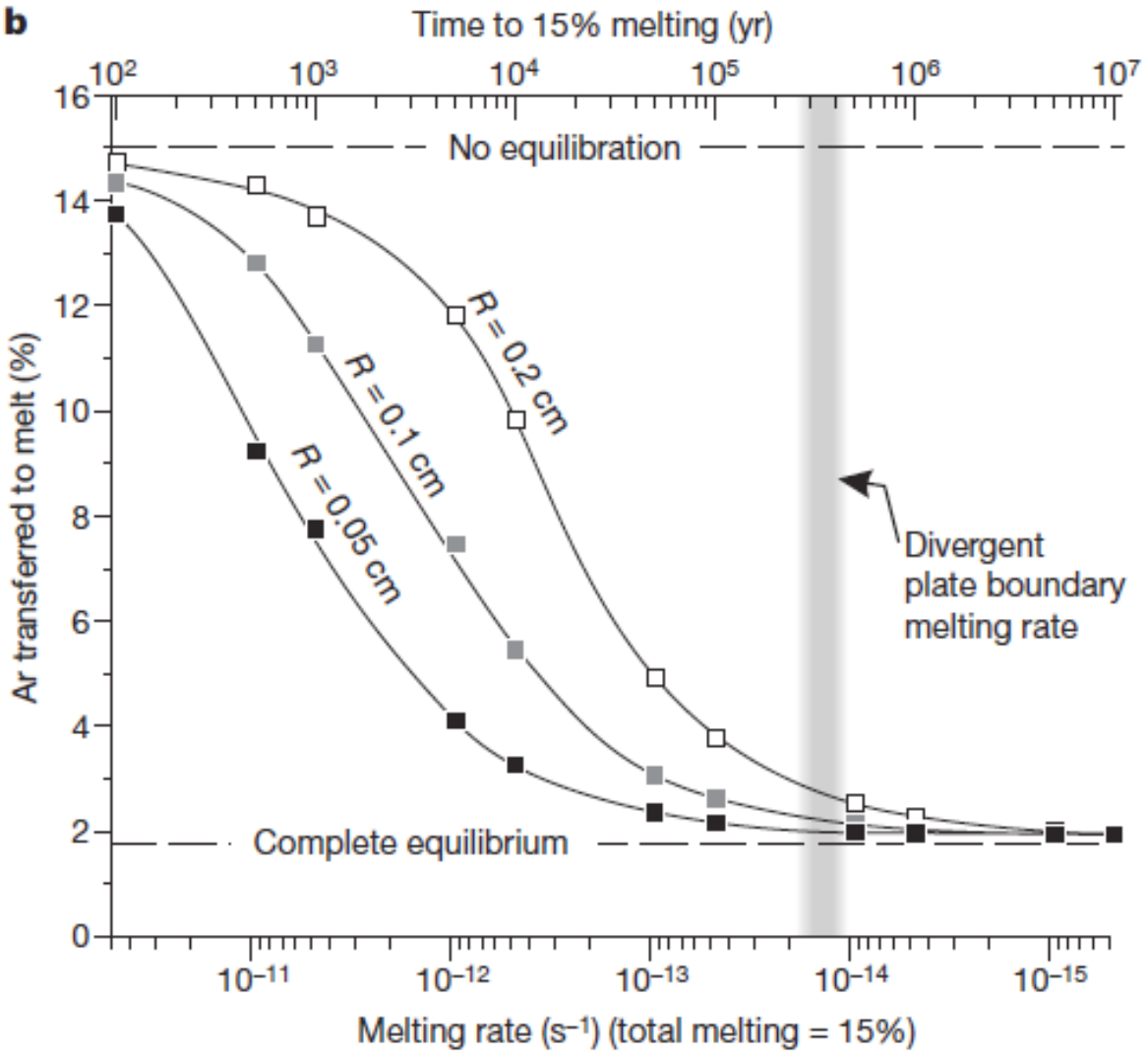
The behavior of Ar between the onset of melting and the removal of melt from the solid residue



Mantle Ar degassing is not effective

Partial equilibration scenario

At 1300˚C



Near-equilibrium (reasonable grain size)

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Mantle Ar degassing efficiencies ~2%

Alternative possibilities of Ar degassing

- Hydration of oceanic lithosphere
- Alteration of olivine and orthopyroxene to serpentine and the other hydrous minerals
- Weathering, metamorphism and partial melting of crustal materials (K-rich)

Applications

- Mars $^{40}Ar/ ^{36}Ar$ =~3000 (Earth 295.5)

Degassing of the near-surface through weathering process (most of primordial Ar remaining deep in the planet)

- No significant contamination of low $^{40}Ar/ ^{36}Ar$ mantle plume (400-4000) and high $^{40}Ar/ ^{36}Ar$ MORB (40000)

Conclusions

- Ar is between 10,000 and 10 million times more compatible than was previously thought.
- Ultra slow Ar diffusion rates even at mantle temperature