2023 Fall High-Temperature Geochemistry and Cosmochemistry

Oral Presentation

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Outline

1. Introduction

1. Basic Information
   1. Earth's missing argon paradox resolved by recycling of oceanic crust
2. Why Choose this article?

Basic Information

- Argon Isotope/Missing Argon Paradox:

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Earth's missing argon paradox resolved by recycling of oceanic crust

Jonathan M. Tucker[1,2]✉, Peter E. van Keken[1] and Chris J. Ballentine[3]

Figure 1: Basic Information

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- JCR: Q1
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- Published: 13 January, 2022

Why Choose this article?

1. Radioactive Isotope
2. Interesting Topic
3. High-quality and Multidiscipline
4. At the Forefront of Academic Research
5. The Newest Perspective
6. To Improve Critical Thinking

2. Missing Argon

1. Background
2. Controversial

Background

- Phenomenon: All terrestrial ^{40}Ar is produced from ^{40}K decay, but the current concentration of ^{40}Ar on Earth does not align with theoretical calculations based on ^{40}K.

  Half of Earth's ^{40}Ar is missing from the atmosphere

- Missing ^{40}Ar: The substantial portion of Earth's ^{40}Ar not accounted for by the atmosphere, crust and upper mantle.
- Research Purpose: To find where's the Missing ^{40}Ar?

  Mantle or Ancient Oceanic Crust or Core

  or Lost from the earth entirely?

Literature Review

Davies, 1999:

1. The earth might contain less potassium than is usually estimated.
2. Some of the ^{40}Ar, and its parent ^{40}K, might be in the core.
   1. Imply that the K/U ratio of the silicate earth is lower than 10,000
   2. Other elements would also be expected to have partitioned into the core

   The least attractive
3. Some of the ^{40}Ar might have been lost from the earth entirely.
   1. Difficult to evaluate, but there are plausible arguments that some amount might have been lost

   More Consideration

Controversial

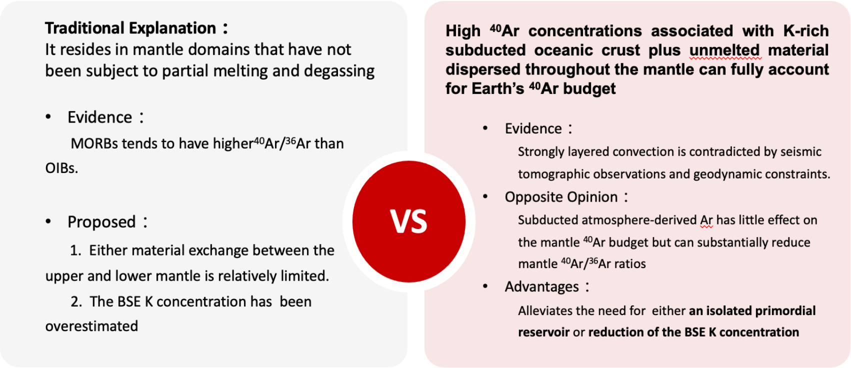

Figure 2: Controversial about Missing ^{40}Ar

Controversial

- Geochemistry State: Depleted, Outgassing, BSE K Concentration (Traditional Explanation)
- Geophysics State: Mantle Convection Model (In this Paper)
- Theoretical Basis: **Mantle Convection and Plates tectonic continually modify the chemistry of the Earth's mantle, crust, atmosphere.**
- Seismology Evidence: **Oceanic crust has subducted to the depths of the lower mantle.** (Grand, 1997)

Controversial

Whole-mantle Convection

VS.

Layered Mantle Convection

3. Two Traditional Paradoxes

1. Are large isolated primordial domains necessary?
2. Is Earth's K concentration overestimated?

Are large isolated primordial domains necessary

- Method: Thermochemical mantle convection in a cylindrical geometry.
- Purpose: Track ^{40}K, ^{40}Ar and ^{36}Ar compositions.
- Basis: K is strongly concentrated into the oceanic crust during partial melting.
- Key Elements: Modeling Earth's convective vigor, including effects of oceanic crust subduction on the K–Ar system.

Are large isolated primordial domains necessary

Table 1 | Parameters optimized by MCMC sampling

Parameter	Prior distribution	Posterior distribution (median and middle 95%)					
		dlnρ26	**dlnρ38**	**dlnρ45**	**dlnρ51**	**dlnρ64**	**dlnρ64ts**
$\phi_{\mathrm{Ar}}^{\mathrm{mantle}}$	0–1	$0.014^{+0.027}_{-0.013}$	$0.015^{+0.03}_{-0.014}$	$0.016^{+0.03}_{-0.015}$	$0.016^{+0.03}_{-0.015}$	$0.014^{+0.035}_{-0.014}$	$0.018^{+0.041}_{-0.017}$
E_{K}^{1}	0–1	$0.45^{+0.47}_{-0.43}$	$0.44^{+0.51}_{-0.42}$	$0.43^{+0.52}_{-0.42}$	$0.42^{+0.55}_{-0.4}$	$0.39^{+0.56}_{-0.38}$	$0.46^{+0.5}_{-0.42}$
E_{K}^{2}	0–1	$0.76^{+0.23}_{-0.54}$	$0.75^{+0.23}_{-0.56}$	$0.77^{+0.22}_{-0.6}$	$0.82^{+0.17}_{-0.57}$	$0.79^{+0.2}_{-0.6}$	$0.76^{+0.23}_{-0.68}$
R_{K}	0–10	$2.5^{+5.3}_{-2.4}$	$2.5^{+5.4}_{-2.4}$	$2.5^{+5.6}_{-2.3}$	$3.7^{+5.2}_{-3.5}$	$3.2^{+5.8}_{-3.1}$	$3.5^{+5.9}_{-3.3}$
R_{Ar}	0–2	$0.011^{+0.022}_{-0.01}$	$0.013^{+0.025}_{-0.012}$	$0.015^{+0.031}_{-0.014}$	$0.019^{+0.043}_{-0.018}$	$0.03^{+0.052}_{-0.028}$	$0.03^{+0.06}_{-0.028}$
K_{BSE} (ppm)	150–300	160^{+10}_{-9}	168^{+13}_{-14}	176^{+16}_{-18}	188^{+18}_{-22}	206^{+26}_{-30}	221^{+48}_{-41}

Prior distributions are the uniform ranges from which MCMC samples are drawn. The median and middle 95% of the posterior distributions are considered the 'best-fit' values and a measure of their uncertainties.

Figure 3: Parameters optimized by MCMC Sampling (Tucker et al., 2022)

Are large isolated primordial domains necessary

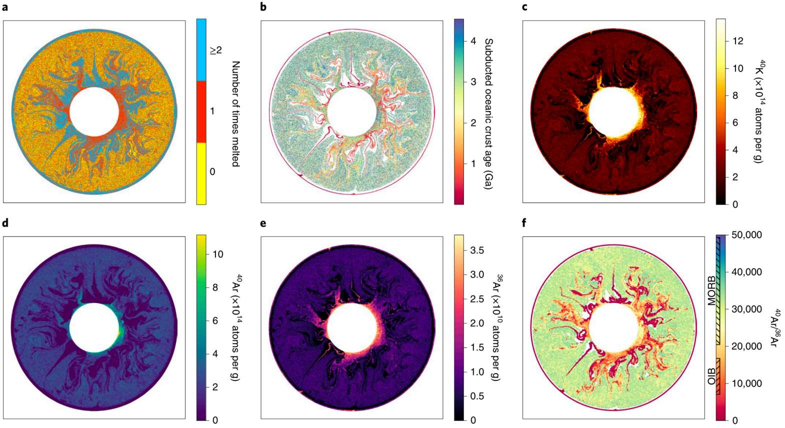

Figure 4: Tracer distribution and compositions in the final model time step (4.55 Gyr, $dln\rho 64$ mode) (Tucker et al., 2022)

Missing Ar in ancient oceanic crust

- New Perspective: ^{40}Ar may be associated with ancient oceanic crust, not just primordial material.
- Basis: During mid-ocean-ridge melting, K is efficiently transferred from residual mantle lithosphere to the oceanic crust.
- Mechanism: Accumulation of ^{40}Ar in ancient oceanic crust through subduction, retaining some K.
- Result: Substantial ^{40}Ar in ancient oceanic crust, reducing the need for large isolated primordial domains.

Missing Ar in ancient oceanic crust

- Basic Concept:
  - E_K^1: The Archaean (0-2 Gyr) efficiency of K extraction from subducting oceanic crust to the continental crust.
  - E_K^2: The post-Archaean (2-4.55 Gyr) efficiency of K extraction from subducting oceanic crust to the continental crust (where 0 Gyr is the model start and 4.55Gyr is the present day).
- Phenomenon: $E_K^2 > E_K^1$
- Indication: More K elements are preserved in the oceanic crust in Archean (Ancient Oceanic Crust).
- Proposed: ^{40}K remaining in acient oceanic crust **through subduction creats a reservoir** of mantle ^{40}Ar independent of primordial material.

Missing Ar in ancient oceanic crust

In the $dln\rho 64$ model, almost half of Earth's ^{40}Ar is in the mantle, yet **only a quarter of the mantle mass is unmelted**.

Proposed:

In optimal model, almost 40% of the mantle ^{40}Ar resides **in ancient oceanic crust rather than unmelted mantle**.

Unmelted material in our models is **not concentrated in the lower mantle**, but rather distributed **throughout the mantle** (Fig. 4a).

Proposed:

Slabs quickly penetrate vertically to the lower mantle, displacing older material upwards.

Are large isolated primordial domains necessary

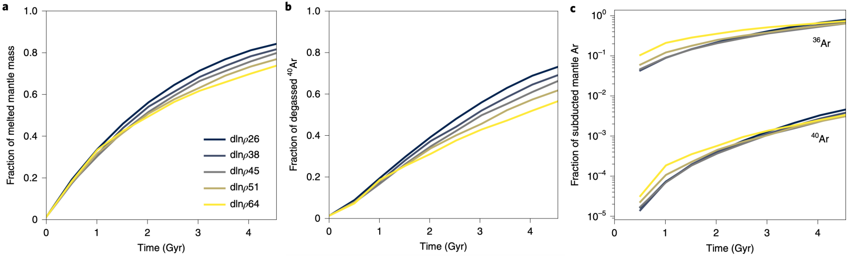

Figure 5: Fraction of melted mantle mass, degassed ^{40}Ar and subducted mantle Ar in the five best-fit models (Tucker et al., 2022)

Models of K-Ar

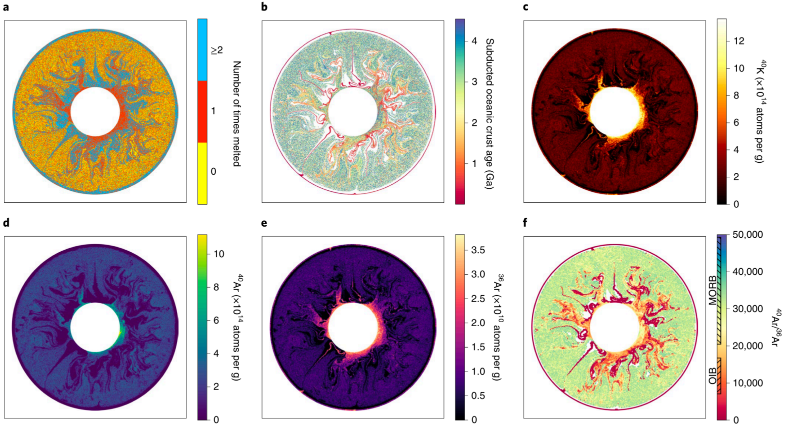

Figure 6: Tracer distribution and compositions in the final model time step (4.55 Gyr) (Tucker et al., 2022)

Conclusion

1. Production and storage of ^{40}Ar from ^{40}K in ancient oceanic crust **Alleviates** the requirement for all mantle ^{40}Ar to reside in **large isolated primordial domains.**

   (Refutation of Traditional Assumption 1)

Is Earth's K concentration overestimated?

- Key: The BSE K concentration directly determines Earth's ^{40}Ar content and consequently the amount of missing ^{40}Ar.
- BSE K/U: Inferred from the MORB by assuming that K and U do not fractionate during the tectonic process.
- Subducted Ocean Crust K/U: Dehydration during subduction causes it to carry particularly low K/U ratio and that the BSE K/U ratio is lower than that estimated from MORBs alone. (Lassiter, 2004).

Is Earth's K concentration overestimated?

- Finding: Continental crust has **similar K/U to the MORB average** (**not** have a **complementary** high K/U ratio).
- Propose:
  1. K/U fractionation during subduction is unlikely to strongly affect the global K and U budgets.
  2. There is no strong evidence for a BSE K/U ratio substantially lower than the MORB value.

(Refutation of Traditional Assumption 2)

Is Earth's K concentration overestimated?

- Highlight:
  1. Discussing which BSE K value fits better through MCMC test, rather than assuming a BSE K value to prove it.
- Conclusion:
  1. High BSE K values are permissible with higher oceanic crust density and lower E_k^1.

Table 1 | Parameters optimized by MCMC sampling

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E^2_K	0–1	$0.76^{+0.23}_{-0.54}$	$0.75^{+0.23}_{-0.56}$	$0.77^{+0.22}_{-0.6}$	$0.82^{+0.17}_{-0.57}$	$0.79^{+0.2}_{-0.6}$	$0.76^{+0.23}_{-0.68}$
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Figure 7: Parameters optimized by MCMC Sampling (Tucker et al., 2022)

Conclusion of Two Traditional Paradoxes

- The missing Ar paradox can be reconciled **without a convectively isolated lower mantle** and **without a particularly low BSE K concentration** as long as subducted oceanic crust is dense enough to sequester K (and ^{40}Ar) from the rest of the silicate Earth.

4. About New Perspectives

1. Ar subduction
2. Atmospheric $^{40}Ar/^{36}Ar$ evolution

Ar subduction explains mantle $^{40}Ar/^{36}Ar$ variability

1. Layered Convection:
   - OIB: lower mantle ⇒Fewer degassed ⇒ Enrich ^{36}Ar and ^{3}He
   - MORB: upper mantle ⇒ More degassed⇒ ^{36}Ar and ^{3}He loss, enrich Radiogenic isotope such as ^{40}Ar
2. Whole-mantle Convection:
   - Seismological Evidence: Oceanic crust has subducted to the depth of the lower mantle (Grand, 1997)
   - Geochemical Evidence: Subducted oceanic crust material has been added to the mantle plume (OIB).
3. Parai., 2019:
   - OIBs $^{40}Ar/^{36}Ar$: around 10,000–20,000
   - MORBs $^{40}Ar/^{36}Ar$: around 20,000–50,000

Ar subduction explains mantle $^{40}Ar/^{36}Ar$ variability

- Atmosphere $^{40}Ar/^{36}Ar$: 298.6
  (**Significantly lower than that of mantle**)

Purpose:

1. Exploring whether low $^{40}Ar/^{36}Ar$ ratios are due to primordial material or subducted atmosphere?
2. Exploring whether atmospheric Ar subduction is another possible solution to the missing Ar paradox?

Ar subduction explains mantle $^{40}Ar/^{36}Ar$ variability

- Proposed:
  1. Subduction of atmosphere-derived Ar $\Rightarrow$ High ^{36}Ar concentrations near the core–mantle boundary (Fig. 4d).
  2. ^{40}K decay within ancient oceanic crust $\Rightarrow$ High ^{40}Ar concentrations
  3. The spatial distribution of $^{40}Ar/^{36}Ar$ ratios strongly mirrors that of ^{36}Ar (Fig. 4f) $\Rightarrow$ $^{40}Ar/^{36}Ar$ ratios are modulated by subducted atmosphere-derived.
  4. Subduction much more strongly affects mantle ^{36}Ar than ^{40}Ar.
- Weakness:
  1. Models do not explicitly consider previous events:
     - late accretion
     - giant impact-induced catastrophic outgassing

Models of K-Ar

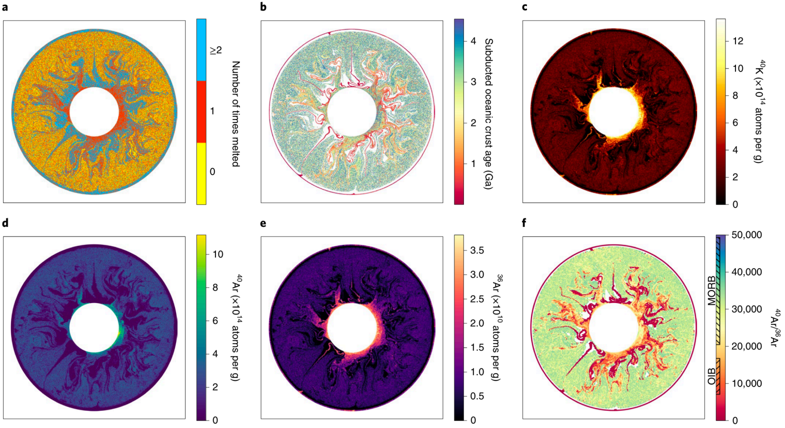

Figure 8: Tracer distribution and compositions in the final model time step (4.55 Gyr) (Tucker et al., 2022)

Ar subduction explains mantle $^{40}Ar/^{36}Ar$ variability

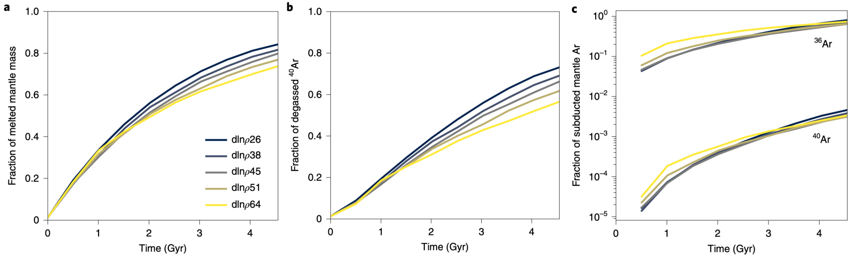

Figure 9: Fraction of melted mantle mass, degassed ^{40}Ar and subducted mantle Ar in the five best-fit models (Tucker et al., 2022)

Ar subduction explains mantle $^{40}Ar/^{36}Ar$ variability

Purpose:

1. Exploring whether low $^{40}Ar/^{36}Ar$ ratios are due to primordial material or subducted atmosphere?

   Subducted Atmospherer

2. Exploring whether atmospheric Ar subduction is another possible solution to the missing Ar paradox?

   Due to ^{40}K decay within ancient oceanic crust

Atmospheric $^{40}Ar/^{36}Ar$ evolution

1. Method:
   - Rescaling time in $dln\rho 64$ model to predict the time evolution of the atmospheric $^{40}Ar/^{36}Ar$ ratio.
2. Result:
   - Models with faster convective vigour early in Earth history tend to match these observations from ancient samples better.
3. Conclusion:
   - Although due to limitations in the timescaling methodology, the plausibility of enhanced early convective vigour explaining the data within the context of a fully dynamic model.

Atmospheric $^{40}Ar/^{36}Ar$ evolution

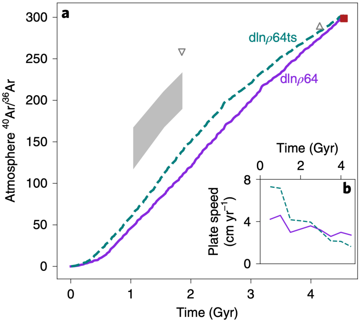

Figure 10: Comparison of models with constant convective vigour and enhanced early convective vigour (Tucker et al., 2022)

- Modern atmospheric composition (red square):
  1. Both Match
- Ancient atmosphere:
  1. $^{40}Ar/^{36}Ar$ rises faster in the $dln\rho64ts$ model, more approaching.
- Average plate speeds:
  1. Nearly constant with time
  2. Decrease by a factor of 4

5. Conclusion

Conclusion

1. Missing Argon: Ancient Subducted Oceaniec Crust
   (plus unmelted material dispersed throughout the mantle can fully account for Earth's ^{40}Ar budget)
2. BSE K Concentration: Explainable
3. Atmosphere-derived Ar Subduction:
   1. Little effect on the mantle ^{40}Ar budget
   2. Substantially reduce mantle $^{40}Ar/^{36}Ar$ ratios

6. Implications

Implications

1. Understanding of Earth's Interior Processes and Mantle Structure
   - Enhances understanding of the material cycles and mantle convection processes inside the Earth
   - Provides a new perspective on the chemical and physical properties of Earth's mantle.
2. Geological History Studies
   - Introduces a new approach (Geochemistry + Geophysics model) to studying Earth's early convective vigour and geological processes.
3. Geological Resource Exploration
   - Guides the exploration of mineral resources, especially those closely related to mantle processes, like K or noble gas.

Reference I

Albarède, F. (1998). Time-dependent models of u–th–he and k–ar evolution and the layering of mantle convection. *Chemical Geology*, *145*(3-4), 413–429.

Allègre, C. J., Hofmann, A., & O'Nions, K. (1996). The argon constraints on mantle structure. *Geophysical Research Letters*, *23*(24), 3555–3557.

Coltice, N., Gérault, M., & Ulvrová, M. (2017). A mantle convection perspective on global tectonics. *Earth-science reviews*, *165*, 120–150.

Davies, G. F. (1999). Geophysically constrained mantle mass flows and the 40ar budget: A degassed lower mantle? *Earth and Planetary Science Letters*, *166*(3-4), 149–162.

Grand, S. P., Van der Hilst, R. D., & Widiyantoro, S. (1997). High resolution global tomography: A snapshot of convection in the earth. *Geological Society of America Today*, *7*(4).

Reference II

Hanes, J., York, D., & Hall, C. (1985). An 40ar/39ar geochronological and electron microprobe investigation of an archean pyroxenite and its bearing on ancient atmospheric compositions. *Canadian Journal of Earth Sciences*, *22*(7), 947–958.

Lassiter, J. C. (2004). Role of recycled oceanic crust in the potassium and argon budget of the earth: Toward a resolution of the "missing argon" problem. *Geochemistry, Geophysics, Geosystems*, *5*(11).

Parai, R., Mukhopadhyay, S., Tucker, J. M., & Pető, M. K. (2019). The emerging portrait of an ancient, heterogeneous and continuously evolving mantle plume source. *Lithos*, *346*, 105153.

Staudacher, T., & Allègre, C. J. (1988). Recycling of oceanic crust and sediments: The noble gas subduction barrier. *Earth and Planetary Science Letters*, *89*(2), 173–183.

Reference III

Tucker, J. M., van Keken, P. E., & Ballentine, C. J. (2022).Earth’s missing argon paradox resolved by recycling of oceanic crust. *Nature Geoscience, 15*(1), 85–90.

van Keken, P. E., & Ballentine, C. J. (1998).Whole-mantle versus layered mantle convection and the role of a high-viscosity lower mantle in terrestrial volatile evolution. *Earth and Planetary Science Letters, 156*(1-2), 19–32.

Xie, S., & Tackley, P. J. (2004).Evolution of helium and argon isotopes in a convecting mantle. *Physics of the Earth and Planetary Interiors, 146*(3-4), 417–439.

Thanks for your listening!

Please feel free to ask me any questions you like,

I 'd be pleased to answer them.

December 28, 2023