From Radiogenic Source or Sink? — Simple and Complex ^{4}He Outgassing Behaviors and Diffusion Systematics Observed During Continuous Ramped Heating of Apatite

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Summary and Conclusions

- We performed continuous ramped heating (CRH) and found different types of ^{4}He outgassing behavior: simple unimodal gas-release and complex bimodal or multimodal ± spikes.
- Apatites with simple and unimodal gas-release under CRH show less age dispersion. Dispersion in these simple samples can be explained by intra-sample kinetic variations beyond effects of grain size and eU.
- Sink-like crystal imperfections may explain the observed secondary gas-release peaks.
- CRH analysis with different heating rates, combined with CRH of PRZ samples, confirms that the proposed sinks show a kinetic response and may offer a way to get expanded thermal-history information.

Motivation and Background

PROBLEM: age dispersion

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Existing and ongoing efforts:
grain size, radiation damage, grains chemistry, inclusions, etc

Dispersion still exsits...

↓

Development of CRH

Rapid characterization of gas release via CRH shows promise as a useful sample screening tool for AHe thermochronology. Idleman et al. (2018)

First trial of CRH

McDannell et al. (2018) applied CRH analysis to apatites from various geologic settings, confirmed the CRH's ability to identify if studied apatites obey volume diffusion, and proposed a CRH-based correction of dispersed ages.

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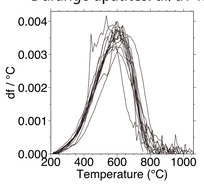
CRH of a well-studied sample suite:
Transantarctic Mountains This poster & Guo et al. (2021)

Ongoing: PRZ CRH and more
This poster

1. Simple vs complex ^{4}He outgassing behaviors

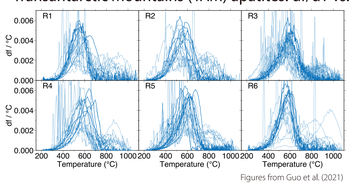
Durango apatites: df/dT vs. T



Left & Right figures: Incremental ^{4}He-release curves (i.e., df/dT) of Durango (left) and TAM (right) apatites via 30 °C/min CRH.

Simple df/dT curves (Durango)
Simple df/dT curves (TAM)
Complex df/dT curves (TAM)

Transantarctic Mountains (TAM) apatites: df/dT vs. T



Figures from Guo et al. (2021)

Simple He-release means less dispered ages

Apatites with simple and unimodal incremental gas-release curves that are similar to those predicted by volume diffusion show good (U–Th)/He age reproducibility, whereas samples exhibiting greater age dispersion have complex gas-release curves that feature ^{4}He 'spikes' and secondary gas-release peaks deferred to higher temperatures.

TAM apatites: He ages

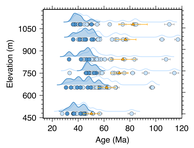


Figure on left: Age-elevation plot of six apatites from Cathedral Rocks profile of TAM.

Single-grain He ages with simple df/dT curves
Single-grain He ages with complex df/dT curves
Kernel densitie of He ages
AFT ages

Dispersion within grains showing simple outgassing?

Dispersion still exists after CRH screening. For those apatites with simple ^{4}He outgassing behavior, we found first-order variabilities in ^{4}He diffusion kinetics, and for some samples the ages correlates well with their apparent diffusivities.

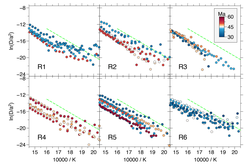
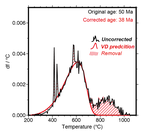


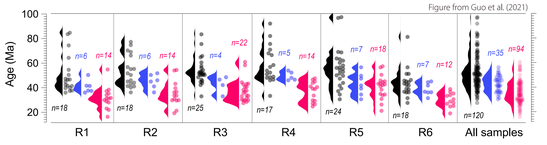
Figure above: Arrhenius plots made from CRH data. The plots only include results from apatite grains showing simple ^{4}He outgassing behavior. All grain sizes were corrected to 80 μm. Green line: kinetics from step heating by Farley (2000)

2. From attempt at CRH- age correction to ^{4}He diffusion systematics



Age correction was done by volume diffusion (VD) curve fitting, gas removal, and re-calculation of ^{4}He and ages.

Figure from Guo et al. (2021)

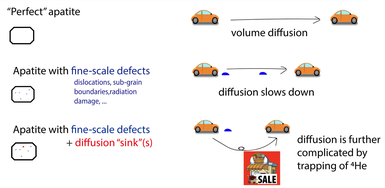


• All measured ages • Ages with simple gas-release • CRH-corrected ages

The CRH-corrected ages seem to have two problems: age correction does not greatly reduce dispersion; in some cases corrected ages appear to be too young based on previous thermochronological results from this part of the TAM.

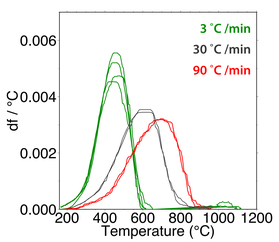
Existence of sink-like crystal imperfections

The observed high-temperature gas component (section 1) and the resulting "too-old" AHe ages, combined with the "over-correction" issue, seem to indicate the existence of sink-like crystal imperfections that can trap ^{4}He both in nature and during laboratory heating.



3. Kinetically responsive "gas sink": insights from CRH at various heating rates

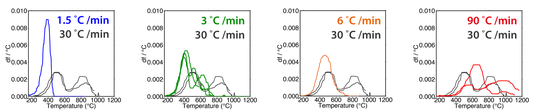
Durango apatites: df/dT vs. T



Slower and faster CRH should shift gas-release peaks representing volume diffusion to lower and higher temperatures.

We conducted CRH under heating rates of 3 °C/min and 90 °C/min on Durango apatite. Compared to our typical 30 °C/min experiments, all the observed peaks did relocate.

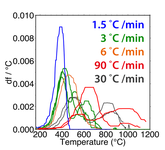
TAM apatites: df/dT vs. T



Secondary gas-release peaks are responsive to CRH rates

We also performed CRH under different heating rates on TAM apatites (figures above and right).

Not only do the main gas-release peaks shift their location on the plots as the heating rate varies, the secondary peaks are also sensitive to the varying heating rates, demonstrating that the proposed release from sinks has a kinetic response. This suggest that rather than representing an obstacle to dating, this higher-temperature release might be exploited to gain additional thermal-history information.



4. CRH of PRZ samples comfirms ^{4}He trapping in"gas sink"

Only high-temperature release from PRZ samples

Samples from the ^{4}He partial retention zone should be excellent candidates to examine the existence of reversible sinks as we would predict that little or no "conventional " ^{4}He would be present to be released at low CRH temperatures.

Below are CRH (30 °C/ min) results from the German Continental Deep Drilling Program (KTB) pilot borehole that have significant ^{4}He present at temperatures well above the expected closure temperature. In line with the prediction of our trapping model, almost all ^{4}He was released at the higher temperatures we found typical for the secondary gas-release peaks in the TAM sample suite.

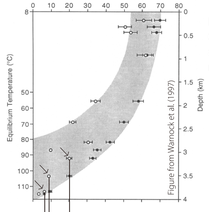
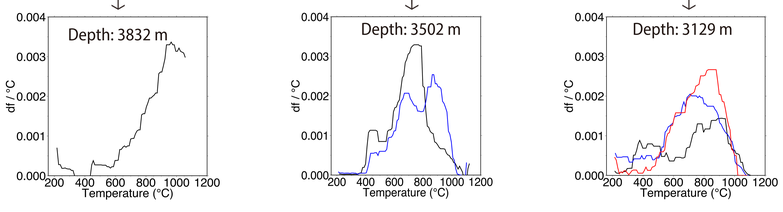


Figure left: KTB borehole age-depth plot. Open circles: AHe ages. Closed circles: AFT ages. These are not single-grain ages but mean ages dated by Warnock et al. (1997)

3129 m, ~20 Ma

3502 m, ~8.5 Ma

3832 m, ~6.1 Ma



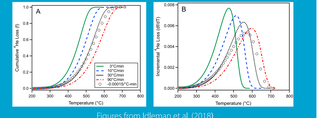
Potentially useful extra info

TAM apatites background

Location of the TAM apatite sample suites (Cathedral Rocks) and Fitzgerald et al (2006)'s original study

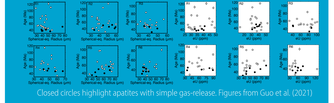
Figure from Guo et al. (2021)
Map and data from Guo et al. (2021)

Crank-Nicolson volume diffusion models: Theoretical CRH gas-release curves



Figures from Idleman et al. (2018)

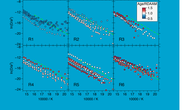
TAM apatites: age-size & age-eU



Closed circles highlight apatites with simple gas-release. Figures from Guo et al. (2021)

TAM apatites: intra-sample kinetic variability after correction of both grain size and eU

Measured ages were normalized to their "RDAAM-modeled age" counterparts (figure on right, from Guo et al., 2021). T-t inputs from Fitzgerald et al. (2006).



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Idleman et al. (2018), Chem Geol, 476, 223-232
McDannell et al. (2018), Geochim Cosmochim Acta, 223, 90-106
Warnock et al. (1997), Geochim Cosmochim Acta, 61, 5371-5377

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