In situ Dating Experiments of Igneous Rocks using the KArLE Instrument: A Case Study for ~380 Ma Basaltic Rocks

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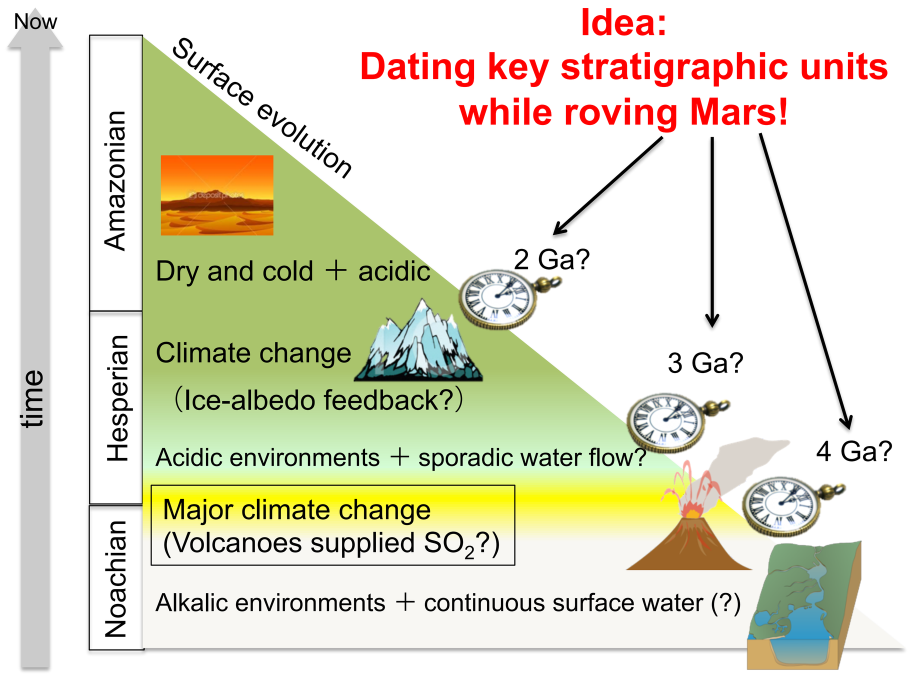
1. Why in situ Geochronology?

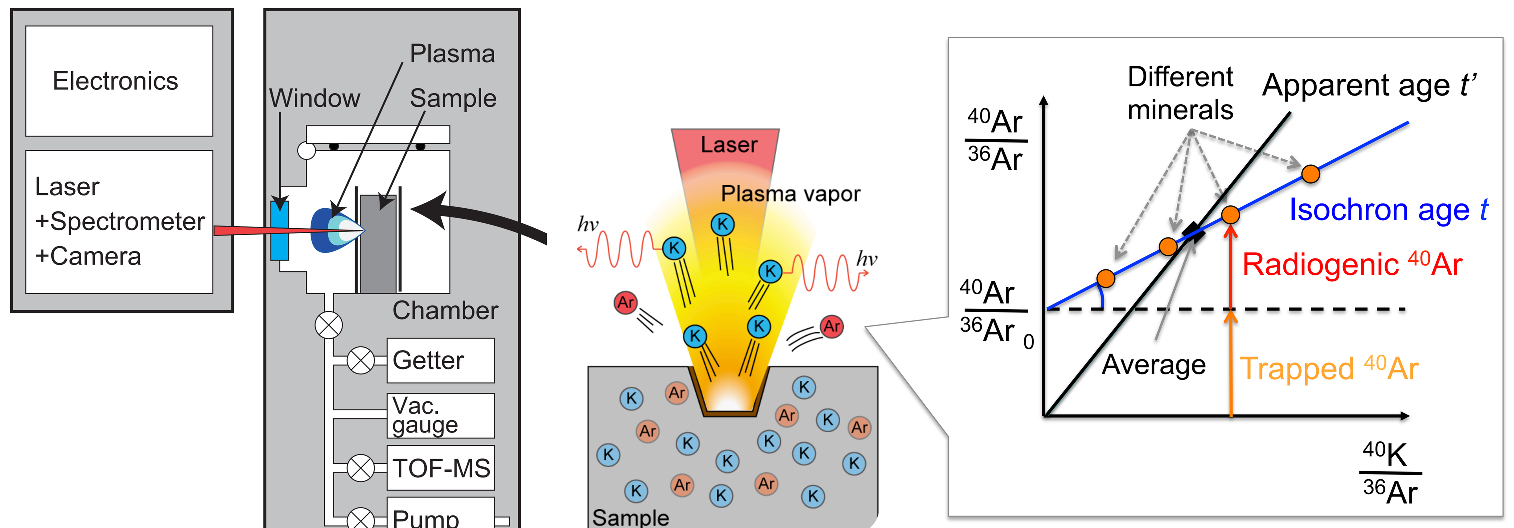
◆When were they formed?

▲Beautiful stratigraphy observed by *Curiosity* on Mars. Nobody knows exactly when these layers were formed. Knowing their absolute ages is important to understand the processes that emplaced these deposits.



▲An important goal of the science community is to measure the age of various key geologic units to reconstruct Martian history and correlate it with other Solar System events (e.g., Earth history).

2. K–Ar Laser Experiment (KArLE) Concept



▲Schematics of KArLE measurements. Spot-by-spot analyses yield the isochron age of target rocks, enhancing the reliability and accuracy of the K–Ar age measurement.

◆ K–Ar dating with LIBS–MS approach

[Cho+ 2016, PSS; Cohen+ 2014, GGR; Devismes+ 2016, GGR]

K–Ar age $t = \frac{1}{\lambda}\ln\left(\frac{\lambda}{\lambda_e}\frac{[^{40}\mathrm{Ar}]_{\mathrm{rad}}}{[^{40}\mathrm{K}]}+1\right)$

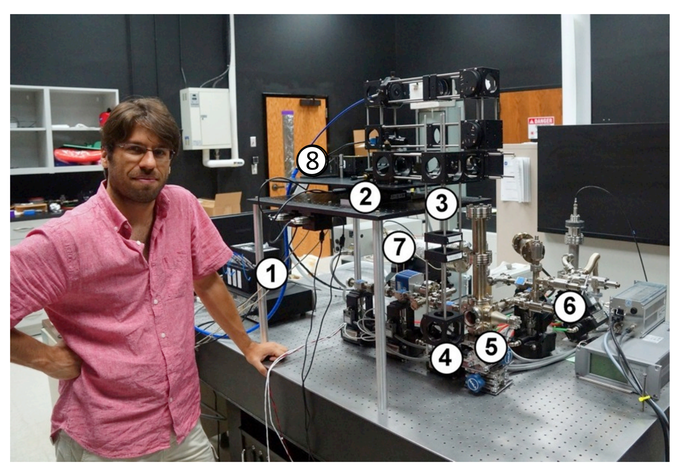
1. Laser ablates a target rock in vacuum chamber
2. K contents measured with LIBS (e.g., ChemCam)
3. Released Ar measured using mass spectrometry (e.g., SAM)
4. K and Ar related by volume of the ablated pit using optical measurement (e.g., MAHLI)

◆ Use TRL 9 components to achieve new science

1. Payload synergy
2. Reasonable cost
3. Low risk
4. Near-term implementation

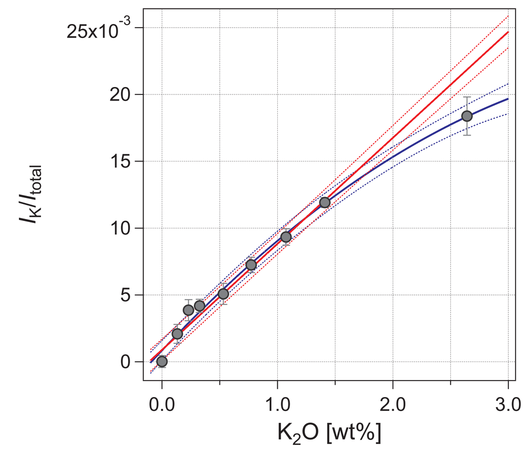
See Cohen+ #1029 this meeting, for our mission Curie!

3. Experimental



▲KArLE breadboard

1- HR2500+ Ocean Optics spectrometer
2- Optical setup
3- Column for a camera recording the sideview of the plasma
4- Mirror
5- Ablation cell
6- Vacuum line including getter, pneumatic valves, turbomolecular pump
7- Mass Spectrometer (Hiden Analytics QMS)
8- Nd:YAG laser 1064 nm, 30 mJ, 3 Hz



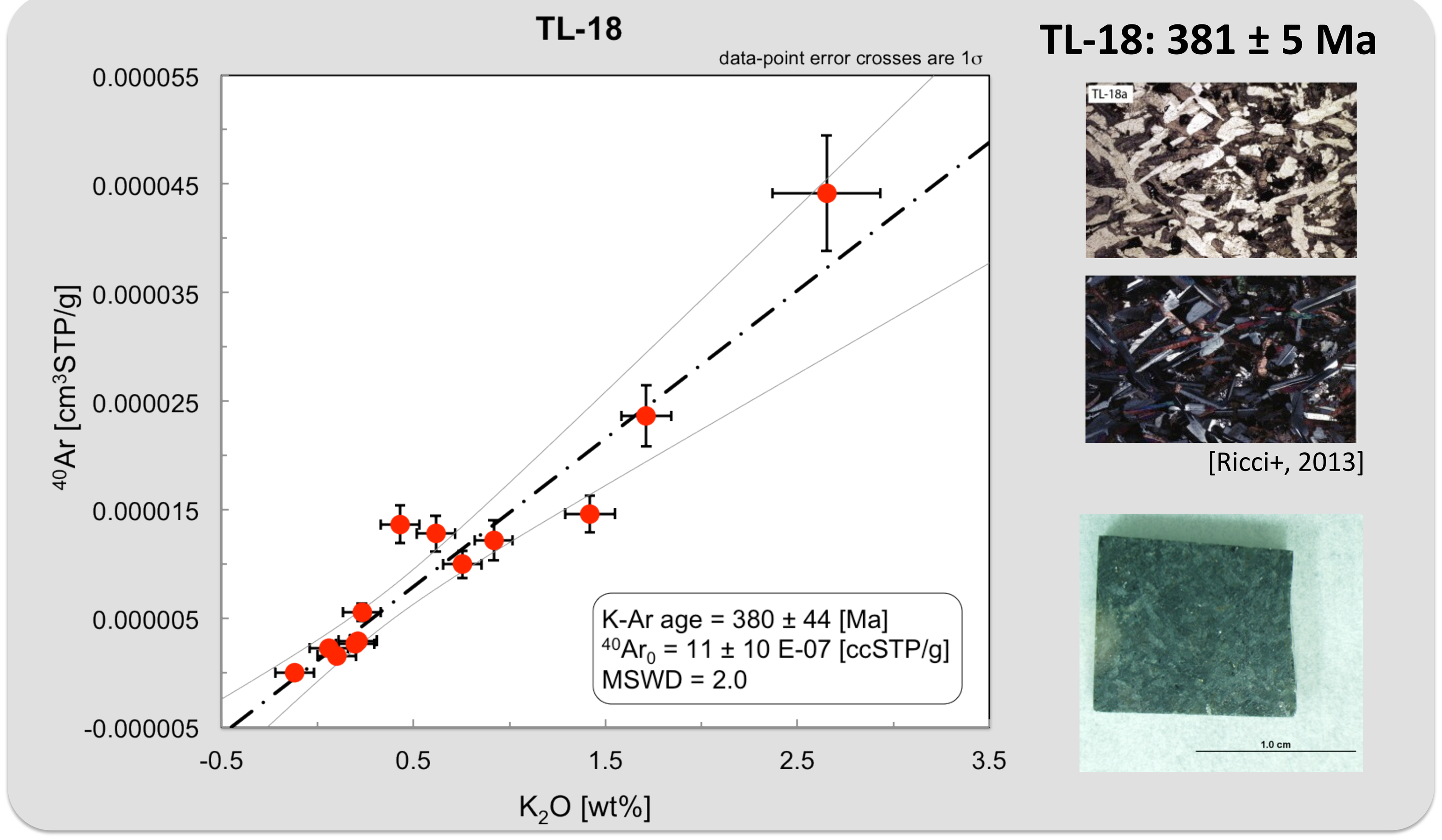
▲Potassium calibration models using standard samples. A linear regression was applied at K2O < 1.1 wt% and a quadratic curve was used at K2O > 1.1 wt% to address potential self-absorption effect.

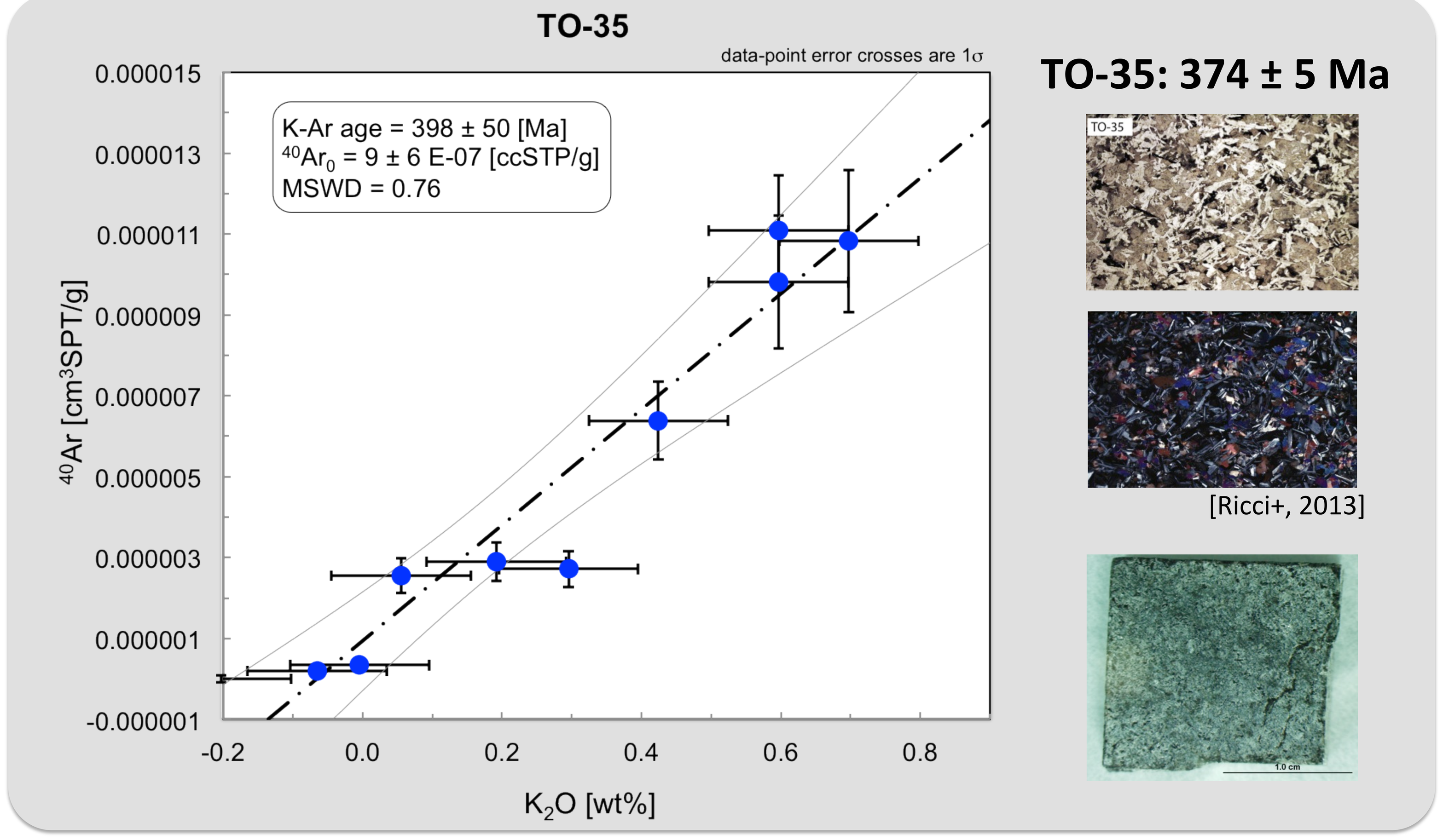
4. Summary

- We report new K–Ar isochron data for two ~380 Ma basaltic rocks, using an updated version of the Potassium–Argon Laser Experiment (KArLE).
- These basalts have K contents comparable to lunar KREEP basalts or igneous lithologies found by Mars rovers, whereas previous proof-of-concept studies focused primarily on more K-rich rocks.
- We continue to measure these analogue samples to show the advancing capability of in situ K–Ar geochronology.
- KArLE is applicable to other bodies including the Moon or asteroids.

5. KArLE results & Isochrons

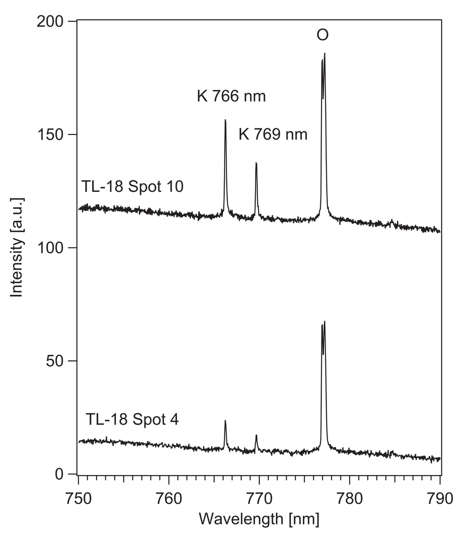
◆ **Obtained isochron ages consistent with published K-Ar ages**





◆ **How actual data look like**

K contents [wt%]

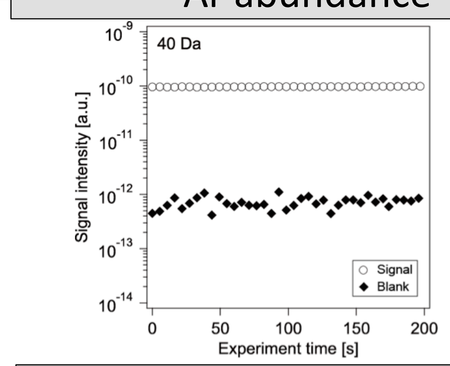


▲LIBS spectra for TL–18 spots #4 and #10 (offset by 100). Two K emission lines are present.

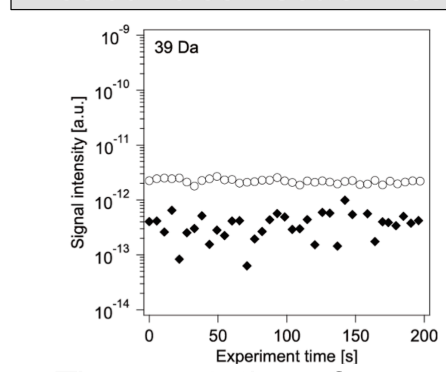
Volume of laser pits

Sample density

^{40}Ar abundance

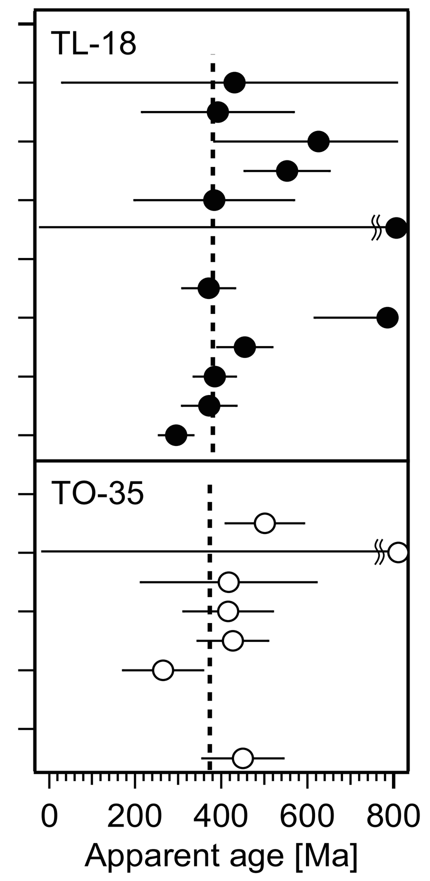


Isobaric correction for C_3H_4



▲Time evolution of gases and corresponding blanks for TL–18 spot #10.

6. Spot-by-Spot K–Ar ages



Weighted average age:
TL-18: 380 ± 22 Ma
TO-35: 414 ± 40 Ma

◂Apparent K–Ar ages for individual laser spots. TL–18 spot #1 to TO–35 spot #10 to from the top to the bottom. Vertical dashed lines indicate the published K–Ar ages of each sample. Negative apparent ages (spot #7 of TL–18, spots #1, 8, and 9 of TO–35) are not shown. Two samples with >1000 Ma with large error bars are shown with wavy lines.
◂ Broad overestimation was observed for TO–35, which is likely due to trapped ^{40}Ar.

7. To achieve ± 100 Myr error with a 4000 Ma rock

$$\Delta t = \frac{1-e^{-\lambda t}}{\lambda}\sqrt{\left(\frac{\Delta[\mathrm{K_2O}]}{[\mathrm{K_2O}]}\right)^2+\left(\frac{\Delta[^{40}\mathrm{Ar}]}{[^{40}\mathrm{Ar}]}\right)^2}$$

$$= \frac{1-e^{-\lambda t}}{\lambda}\sqrt{\left(\frac{\Delta[\mathrm{K_2O}]}{[\mathrm{K_2O}]}\right)^2+\left(\frac{\Delta\rho}{\rho}\right)^2+\left(\frac{\Delta V}{V}\right)^2+\left(\frac{\Delta^{40}\mathrm{Ar}}{^{40}\mathrm{Ar}}\right)^2}$$

◂ Expression of age error. The error sources include those in K concentration, ^{40}Ar amount, sample density, laser pit volume, as well as the age value itself.

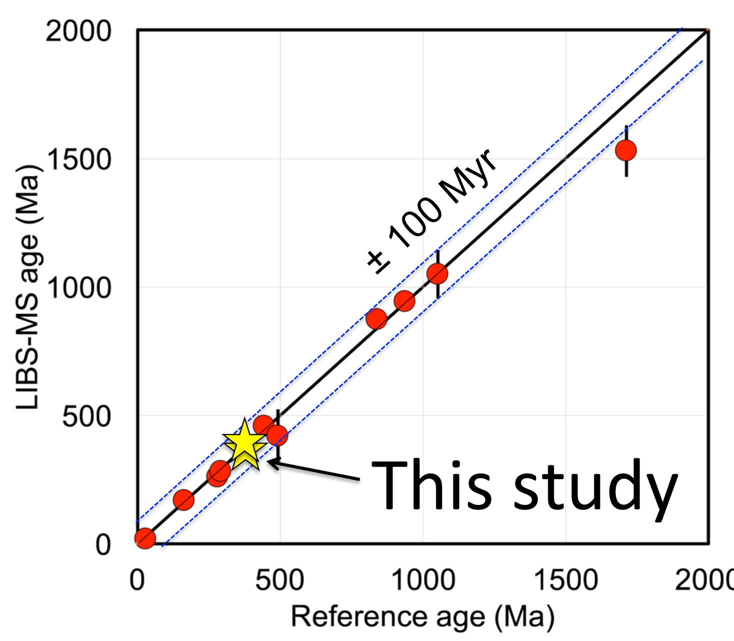
	Method	Dominant sources of uncertainty	Improvements	Error budget
Ar	Mass spectrometry	Sensitivity of the system, background	Precise knowledge of system's volume, smaller volume (higher partial pressure), lunar vacuum	5%
K	LIBS	Calibration curve, low K abundance	Better calibration set, PLS data reduction, high-QE detector	10%
Volume	Optical metrology	Vertical resolution of stereo pair	Higher-resolution imaging, by optics or distance	10%
Density	Computed	Mineralogy, porosity	PLS data reduction, higher-resolution imaging	5%
RSS error				16%

◂ Target error budgets and potential improvements to achieve them. The uncertainty of K concentration is the single dominant source of age uncertainty. Eight meaningful isochron data would lead to an error of ± 100 Myr when a 4000 Ma rock is measured.

8. Performance of K–Ar dating with LIBS–MS

▸Compiled K–Ar dating results published from multiple labs. Results from multiple laboratories yield whole-rock ages within error of accepted ages and precision close to theoretical.
= TRL 4 (validation in the laboratory)

Data sources: Solé 2014 Chemical Geol.; Cohen+ 2014 GGR Devismes+ 2016 GGR; Cho+ 2016 PSS.



9. Work in progress

- Using the laboratory breadboard to measure Mars and Moon analog materials
- Implementing PLS to improve K measurement capability
- Pursuing funding for construction and test of the flight concepts

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