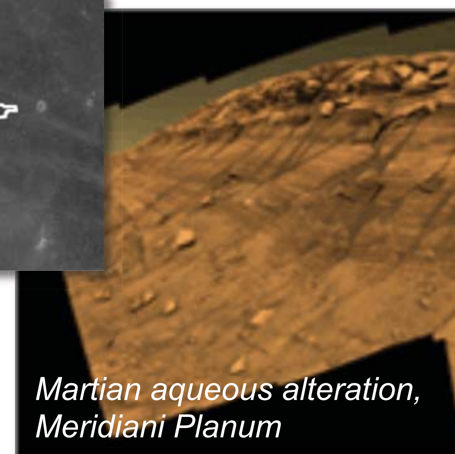
The Potassium-Argon Laser Experiment (KArLE): *In Situ* Geochronology for Planetary Robotic Missions


Ancient Martian Crust, Syrtis Major
Image: NASA/JPL/University of Arizona


Youngest lunar basalt, Oceanis Procellarum


Martian aqueous alteration, Meridiani Planum

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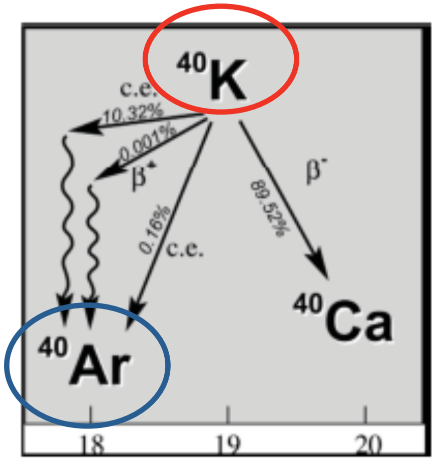
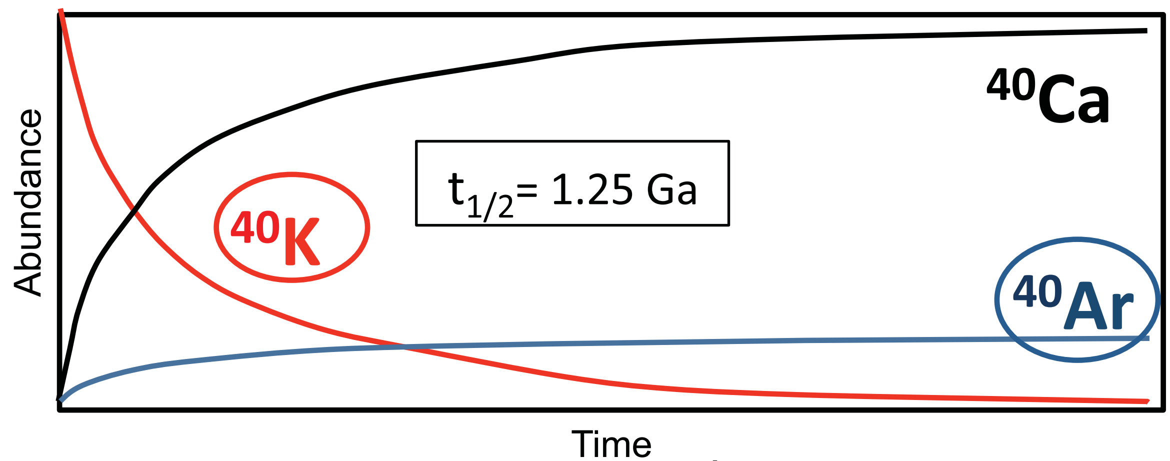
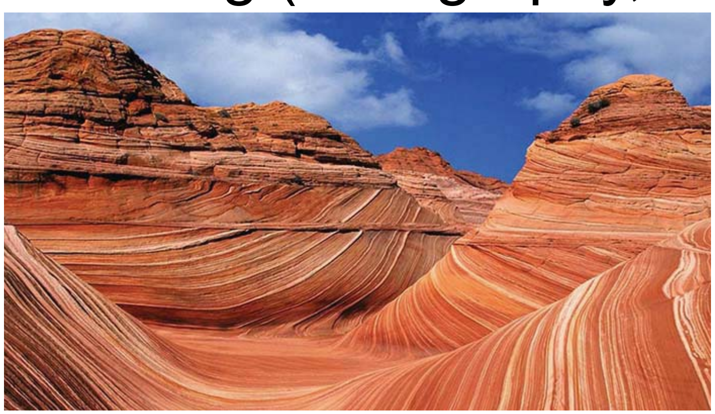
Geologic dating of planetary surfaces

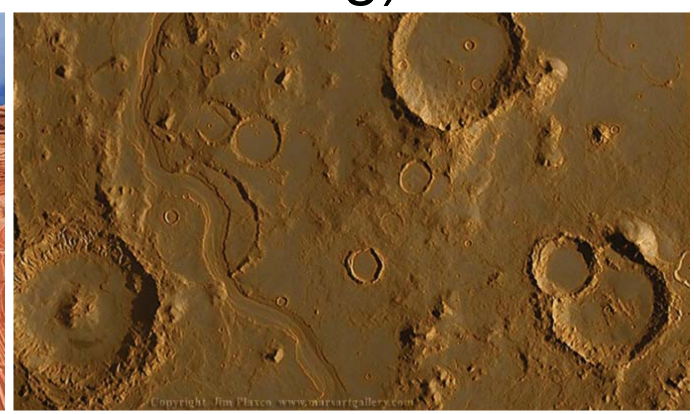
- Absolute dating (U-Pb, Ar-Ar, K-Ar, Rb-Sr, luminescence, etc.)





- Relative dating (stratigraphy, crater counting)





KArLE principles

- Several in situ instruments to measure rock ages have been proposed and developed (e.g. AGE, MAX, etc.)….but none have yet flown, because
  - Isotopic measurements with sufficient resolution are challenging
  - Correct interpretation of results as an age (rather than a numeric ratio) is challenging
- The ^{40}K-^{40}Ar system (and its variant, Ar-Ar) is a proven technique sensitive to crystallization, aqueous alteration, and impact in returned samples

$$D = D_0 + P\,(e^{\lambda t} - 1)$$ *event separates parent from daughter*

$$t = 1/\lambda \ln [\, 1 + \Delta D/\Delta P]$$ *age isochron from multiple points*

$$\sigma_t = 1/\lambda\ \sigma_D\ /\ (\Delta PD)$$ *uncertainty from technique and sample heterogeneity*

- KArLE is a new development effort under the NASA Planetary Instrument Definition and Development Program (PIDDP) begun in 2011
  - Based on flight components (limited new technology development)
  - Uses instruments that you would want on a lander/rover anyway
  - No consumables – can take thousands of measurements
  - No special sample preparation
  - Target accuracy ±100 Myr for a 4 Ga sample

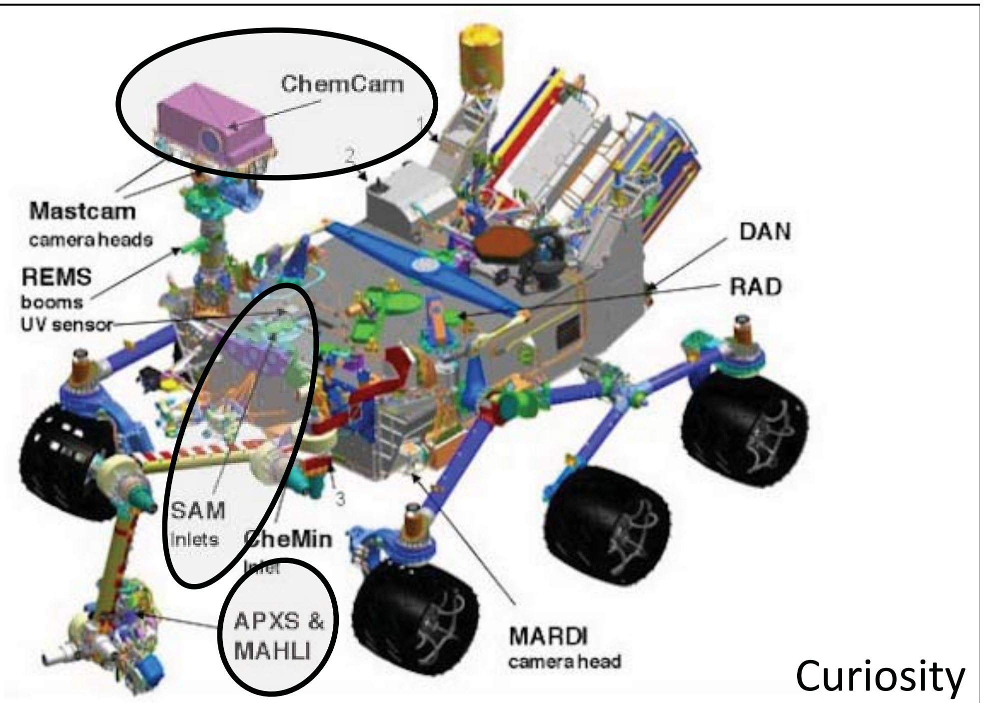
Projects

IN SITU MEASUREMENT
Actual projects using K-Ar method:

Double-spike (Farley, Mahaffy,..) Jet Propulsion Laboratory	Micro-K-Ar (Solé) Instituto Geologia Uni. N.A. Mexico	LIBS+QMS *« KArLE »* (Cohen et al.) Marshall S.F.C. NASA	LIBS+QMS *« KArMars »* (Devismes et al.) Paris Sud Uni. CNES	LIBS+QMS (Cho et al.) Tokyo University JAXA

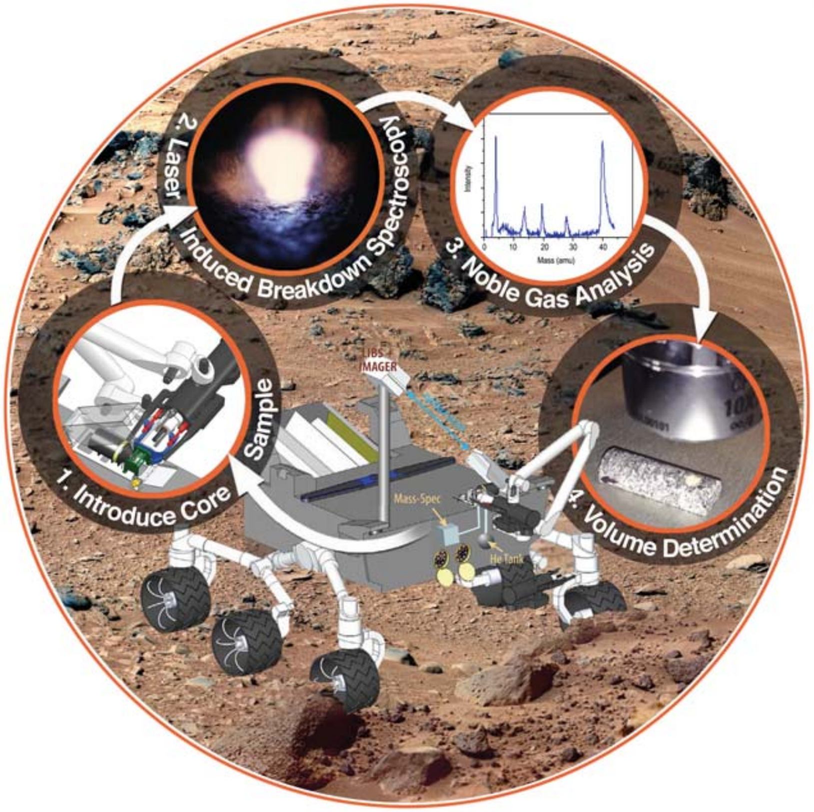
K-Ar in situ dating: first attempt

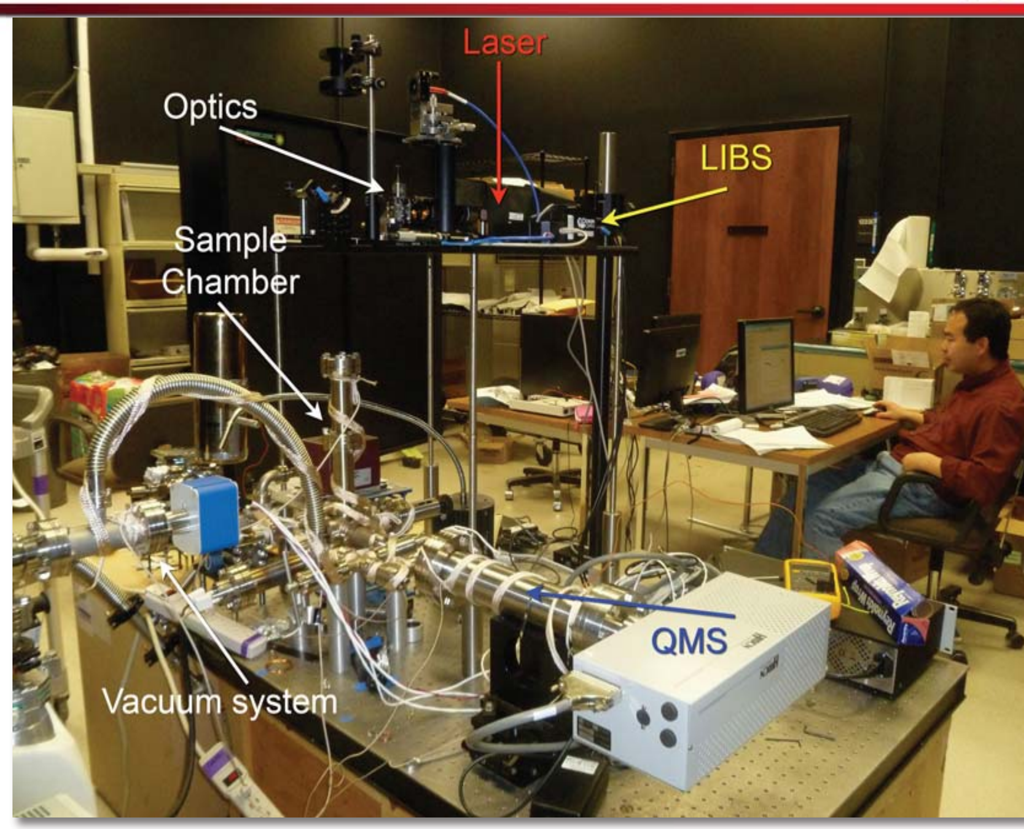
- In situ dating attempt (Farley et al., 2013) using MSL Curiosity instruments
- A lot of uncertainty making the measurements…but K-Ar methodology proven
- KArLE uses these flight-proven methods in a synergistic way



Curiosity

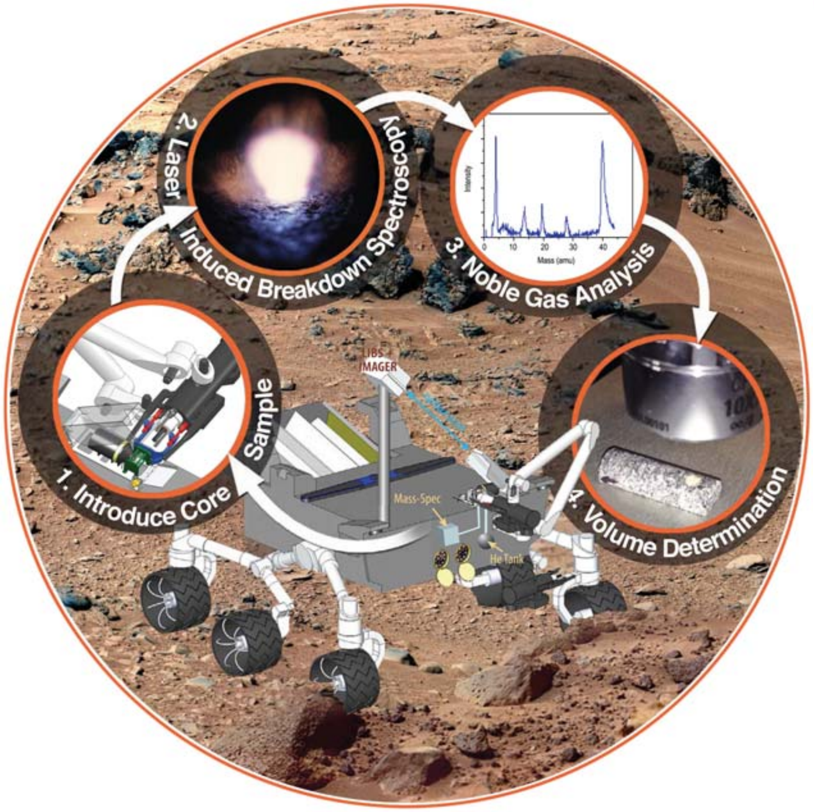
KArLE concept of operations

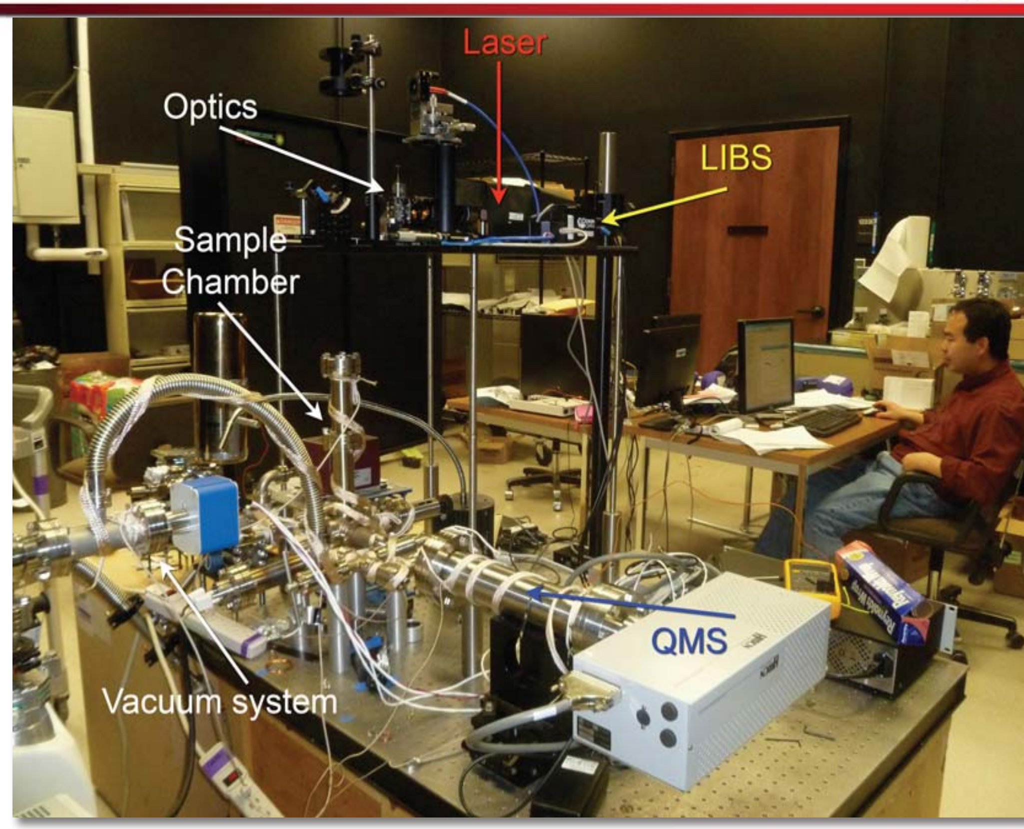




- Sample introduced by the spacecraft – no special sample preparation required
- Infrared laser ablates a pit in the rock
- K measured using laser-induced breakdown spectroscopy (LIBS)
- Liberated Ar measured using mass spectrometry (QMS or ITMS)
- K and Ar related by volume of the ablated pit using optical metrology (OM)
- Similar to laser (U–Th)/He dating technique in use in terrestrial laboratories

KArLE concept of operations



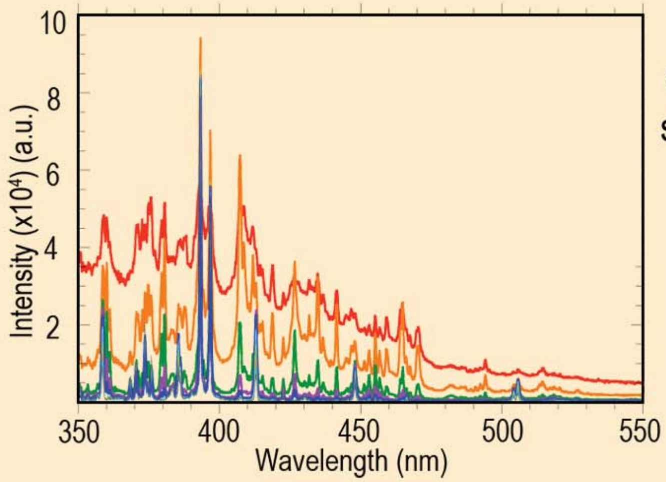


- Based on TRL9 components (no new technology development)
- Uses instruments that you would want on a lander/rover anyway
- No consumables – can take thousands of measurements
- No special sample preparation
- Precision ±100 Myr for a 4 Ga sample

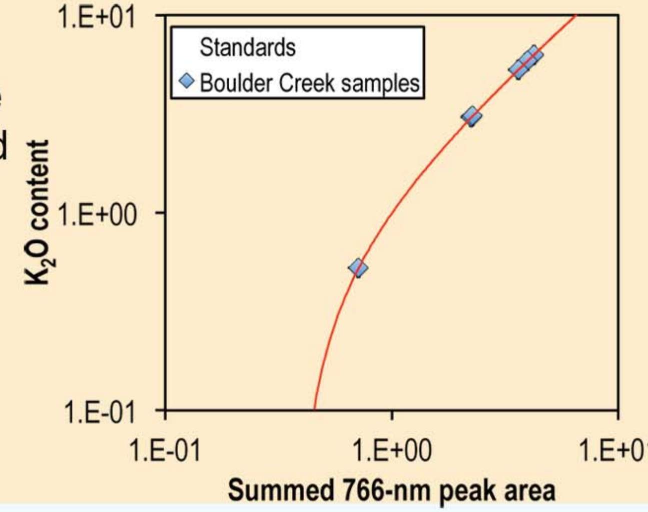
LIBS-MS

KArE

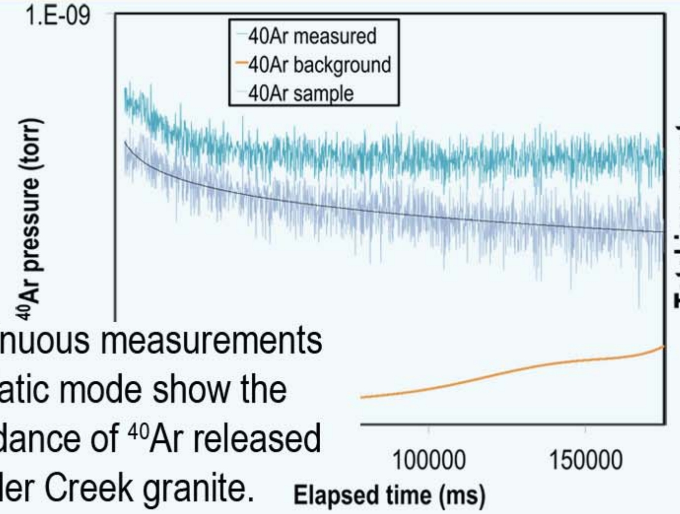
LIBS (L)



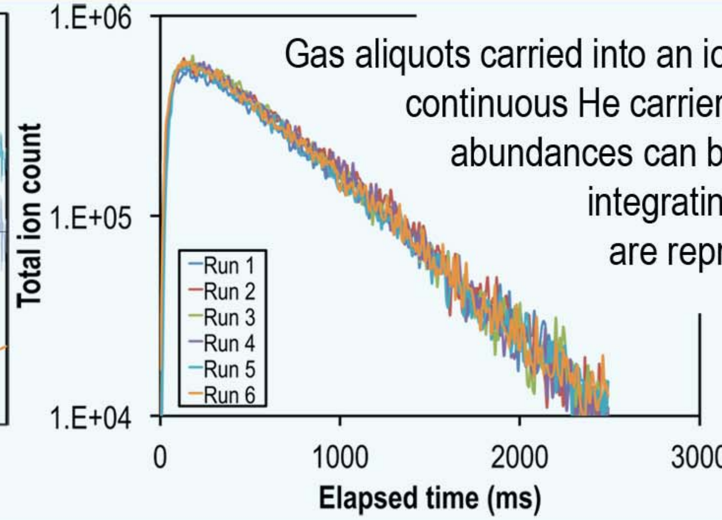
LIBS spectra are collected with every shot or gated over multiple shots (left). Spectra are corrected for background, normalized to total radiance, and continuum subtracted before [K] is determined by peak areas referenced to standards (right).



Mass Spectrometry (M)



QMS continuous measurements made in static mode show the total abundance of ^{40}Ar released from Boulder Creek granite.



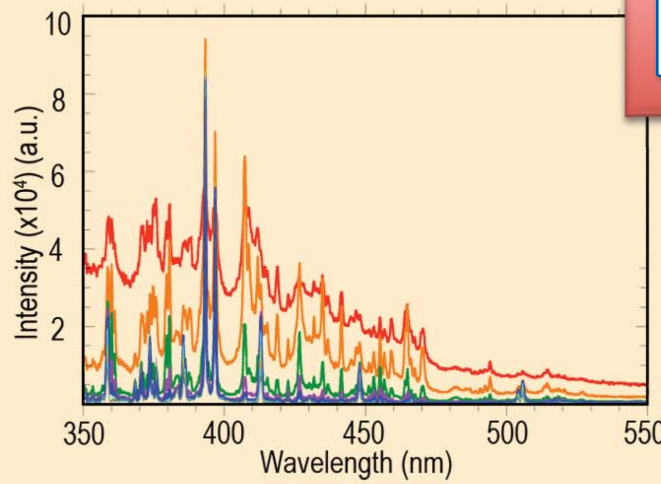
Gas aliquots carried into an ion trap MS by a continuous He carrier flow show that abundances can be measured by integrating over time and are reproducible to 3%.

LIBS-MS

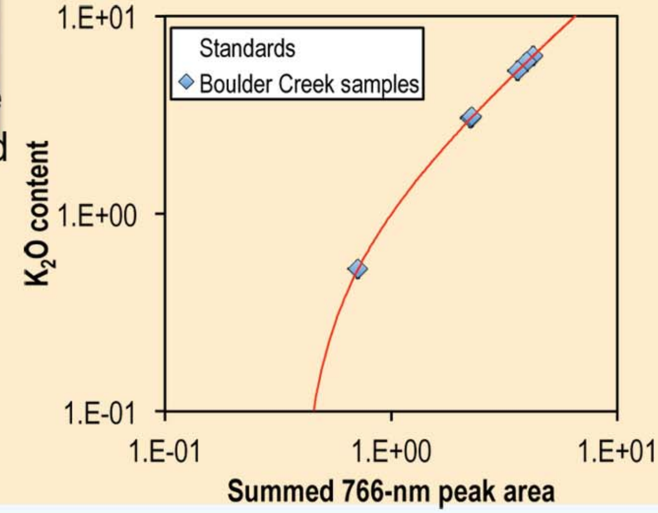
KArE

Relative

LIBS (L)



shots (left). Spectra are corrected for background, normalized to total radiance, and continuum subtracted before [K] is determined by peak areas referenced to standards (right).



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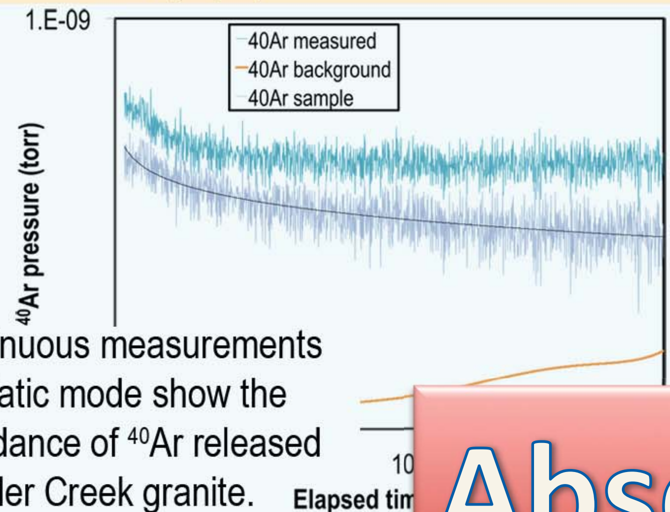

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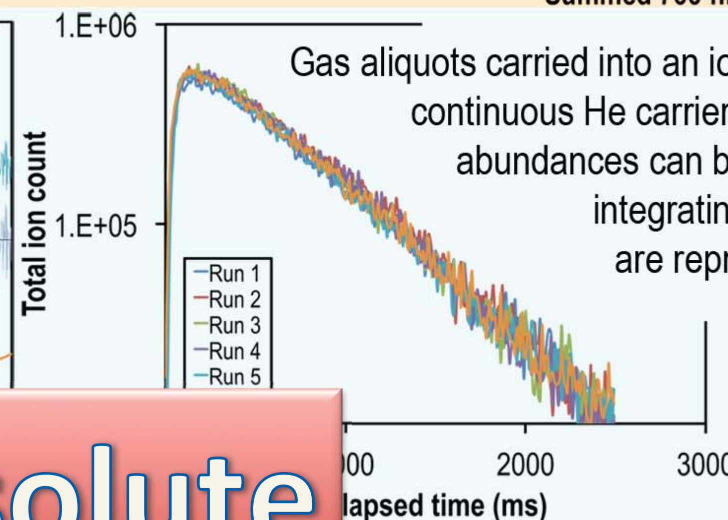

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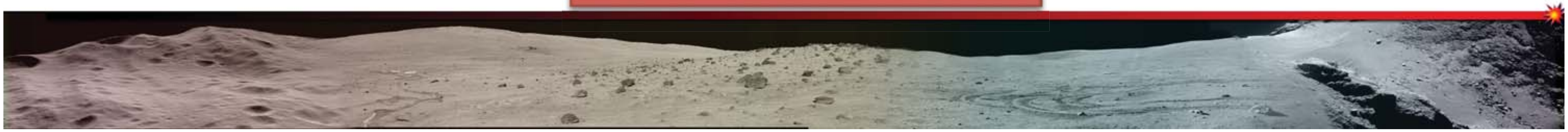
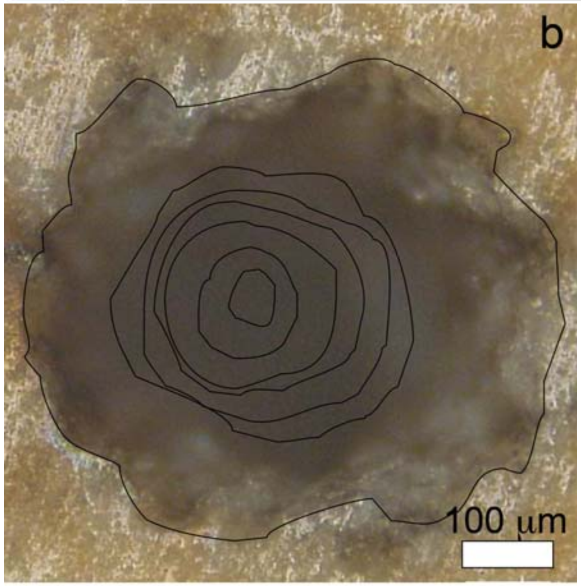
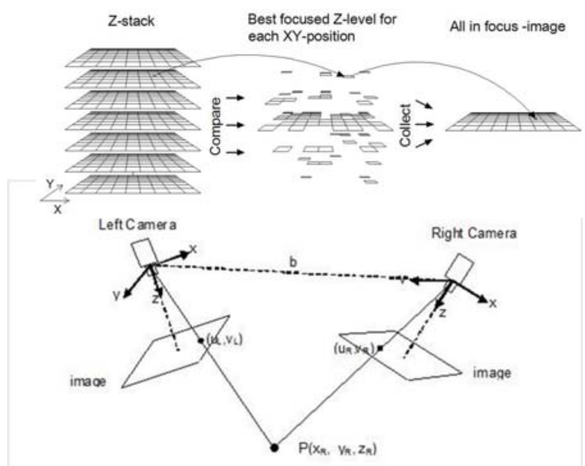
Absolute

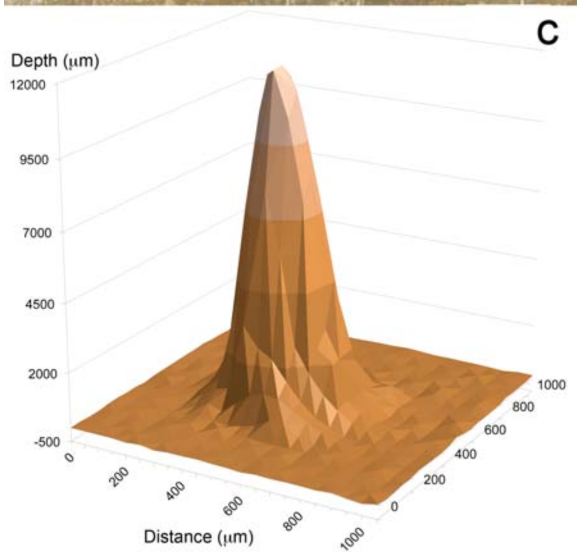


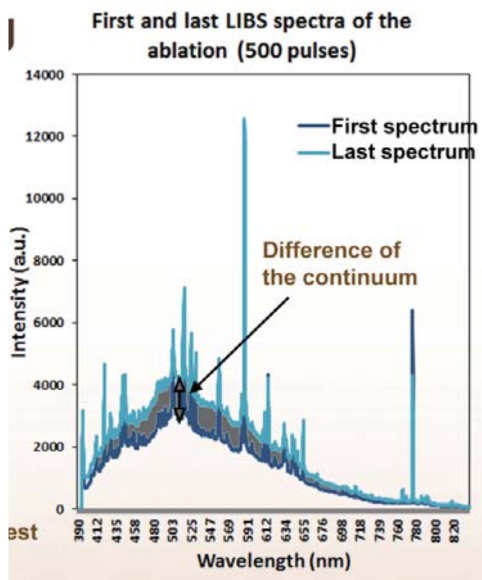
Mass = volume x density

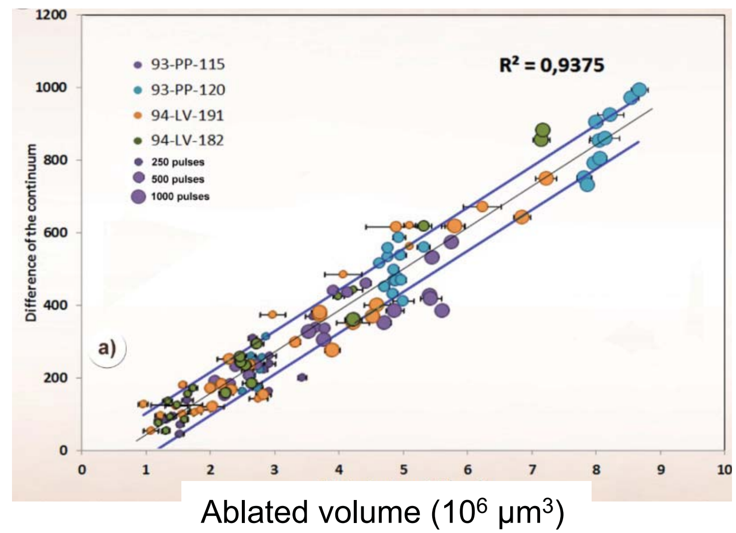




- Density from bulk composition
- Volume from optical reconstruction or LIBS continuum

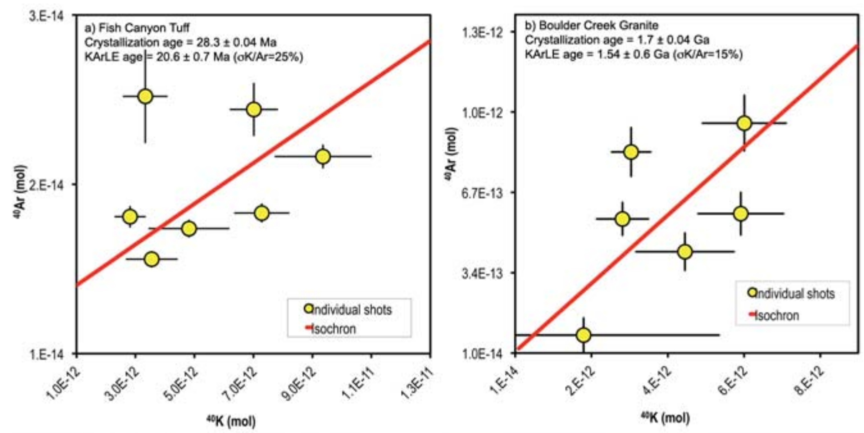


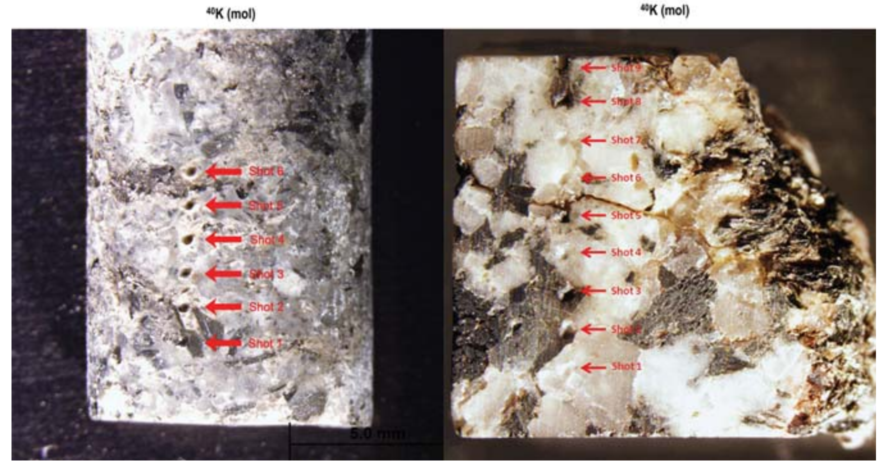




Proof-of-concept

- Each point represents 200-500 simultaneous LIBS and MS measurements
- Pit volume measurement by laser confocal microscopy, downsampled to MAHLI resolution
- Error bars set by the uncertainties in determination of K and Ar for each measurement, which have variable abundances, blanks, and backgrounds
- Results yield whole-rock ages within error of the accepted ages
- Precision has not reached theoretical precision because we found it depends sensitively on blanks and calibration, both of which can be substantially improved with further laboratory and flight article characterization



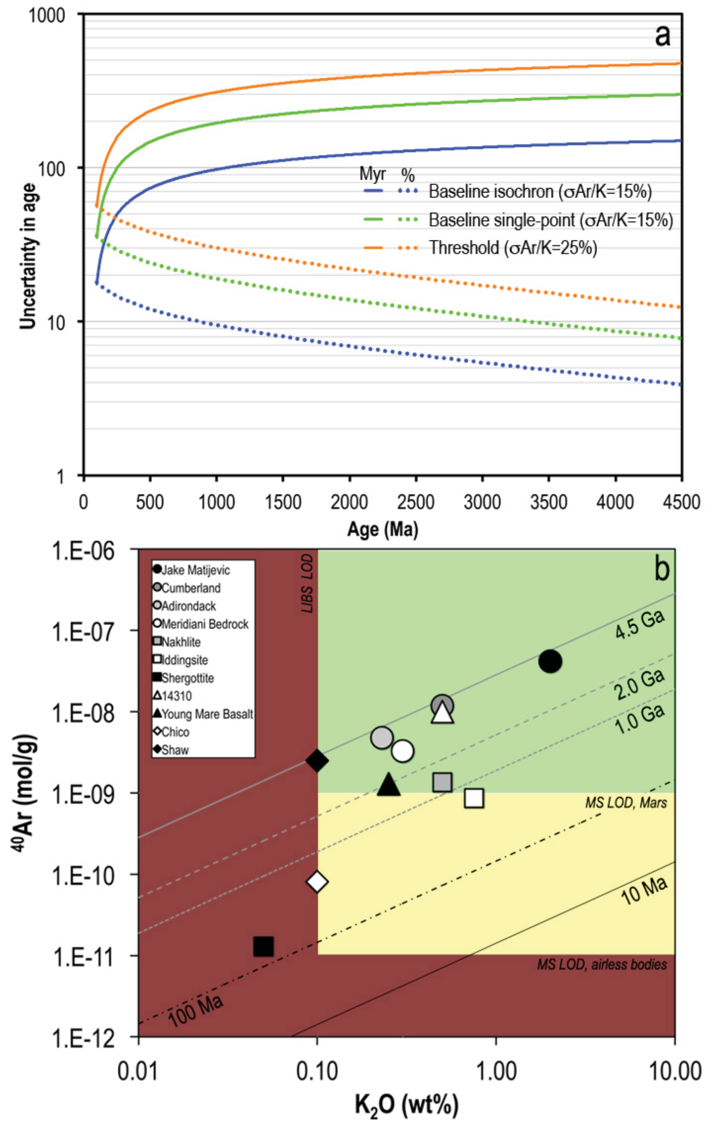


Precision and Range

$$t = \frac{1}{\lambda}\ln\left(\beta\frac{^{40}\mathrm{Ar}^{*}}{^{40}\mathrm{K}} + 1\right)$$

$$\mathrm{t} = \frac{1}{\lambda}\ln\left(1 + \mathrm{c}_1\frac{\mathrm{A}}{\mathrm{L}\rho\mathrm{V}}\right)$$

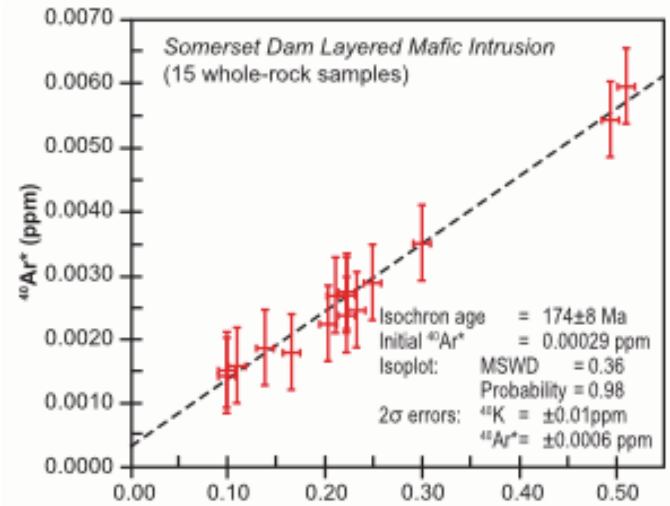
$$\sigma_{\mathrm{t}} = \frac{\mathrm{c}_2}{\lambda}\sqrt{\left(\frac{\sigma_{\mathrm{A}}}{\mathrm{A}}\right)^2 + \left(\frac{\sigma_{\mathrm{L}}}{L}\right)^2 + \left(\frac{\sigma_{\rho}}{\rho}\right)^2 + \left(\frac{\sigma_{\mathrm{V}}}{V}\right)^2}$$

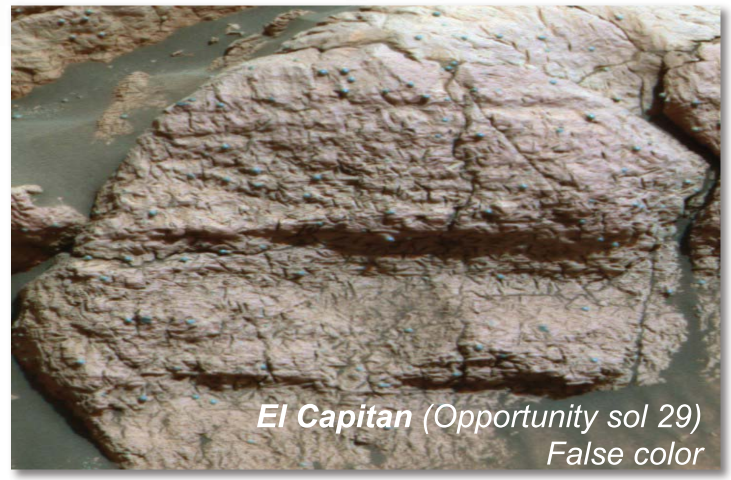


- K-Ar ages increase logarithmically with the Ar/K ratio
- uncertainty in the age increases as a quadratic combination of the relative errors.
- for fixed measurement uncertainties, the uncertainty in age becomes a smaller fraction of the age (more precise) as ages increase -- a feature for planetary samples

Deriving an age

- An age is the interpretation of a geologic event
  - remote sensing for geologic setting
  - imaging and microscopic imaging for petrology
  - microanalytical techniques for chemical and mineralogic composition and variation
- Multiple measurements to ensure validity of fundamental assumptions
  - Isochron helps age precision
  - Variation shows whether the sample components are cogenetic
  - Intercept shows whether the system has been closed to addition/loss





El Capitan *(Opportunity sol 29)*
False color

Additional Measurements

- MS instruments have the ability to measure noble gas isotopes other than ^{40}Ar (^{36}Ar, ^{38}Ar, ^{20}Ne, ^{21}Ne, and ^{22}Ne), which can enhance the experiment in two ways:
- Cosmogenic surface ages:
  - ^{36}Ar, ^{38}Ar, and Ne isotopes are produced in rocks on planetary surfaces by nuclear reactions caused by cosmic rays and their secondaries
  - This "cosmogenic" Ar builds up at a known rate, so its measurement can enable determination of a cosmic-ray-exposure age, or the length of time that the rock has been within ~1 meter of the surface
  - The measurement methodology and utility of Ne isotopic measurements to determine exposure ages has been demonstrated on the Martian surface using Curiosity (Farley et al. 2014)
- Trapped argon:
  - Magmatic or atmospheric ^{40}Ar would likely be accompanied by ^{36}Ar, which can in turn be used to correct the KArLE ^{40}Ar measurement for this trapped component
  - Not required for the baseline experiment, because a uniformly-distributed trapped Ar component is revealed by the isochron intercept, while the isochron slope (and therefore age) remains unchanged
  - May require supplemental ablation of a much larger pit to release more gas and determine the trapped Ar isotopic ratio (^{36}Ar is 2000x less abundant in the Martian atmosphere than 40Ar; Atreya et al. 2013)

Where can we go?

- Martian rover or lander (Mars 2020, Mars Exploration with a Lander-Orbiter Synergy (MELOS)
- Lunar lander (Oldest basins? Youngest basalts? Benchhmark craters?)
- Primitive and Differentiated asteroids
- And beyond….

Summary

- *In situ* radiometric dating is strategically aligned with the Decadal Survey science goals and NASA roadmaps for science instruments
- The aim of KArLE is to determine the age of geologic samples to ±100 Myr, sufficient to address a wide range of questions in planetary science
- We achieve this using flight-proven components with no consumables or inherently limiting steps, enabling thousands of measurements
- Each KArLE component achieves common analyses of most planetary surface missions, such as elemental analysis and imaging
- Flight heritage of components increases confidence that a package will fit (mass, volume, power) on future landers or rovers to Moon, Mars, Asteroids (Phobos, Mercury, Europa….)
- *In situ* dating enhances future missions but does not replace sample return - many problems in geochronology require the resolution and sensitivity of a terrestrial laboratory and cannot be solved by in situ instrumentation