In situ geochronology on Mars and the development of future instrumentation

Barbara Cohen Barbara.A.Cohen@nasa.gov

NASA Goddard Space Flight Center

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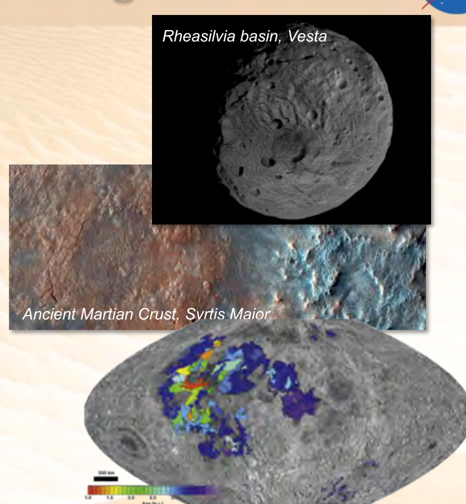
Geochronology: More than just rock ages

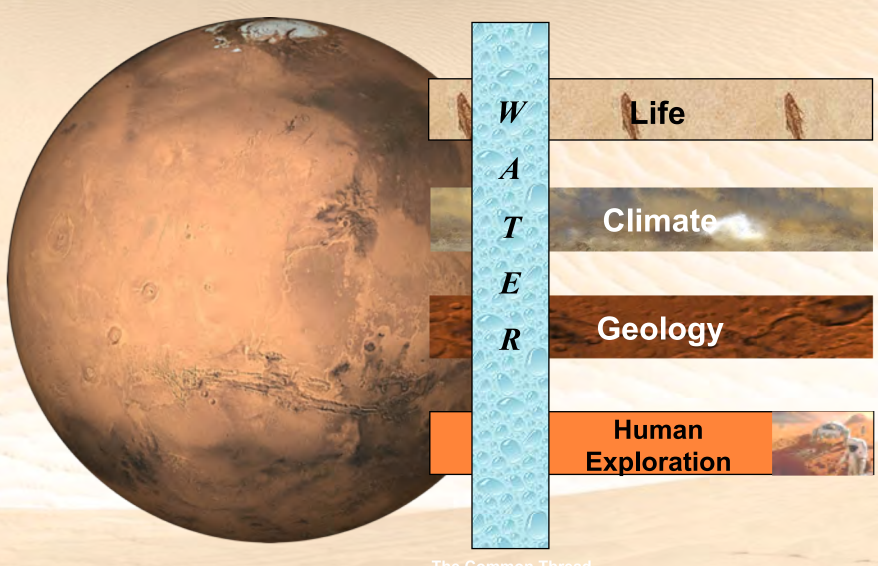
- What are the constraints on the time evolution of the dynamic solar system? When did the outer planets migrate and the asteroid belt lose mass? How did it affect other bodies at that time?
- When was Mars warm and wet? How much time did organisms have to thrive in this environment? What was going on elsewhere in the solar system at this time?
- How long were planetary heat engines active? When did planets cool and magma erupt on the Moon, Mars, and large asteroids?
- What are the rates of erosion and resurfacing? How long have current surfaces been exposed to (and possibly changed by) the space environment?



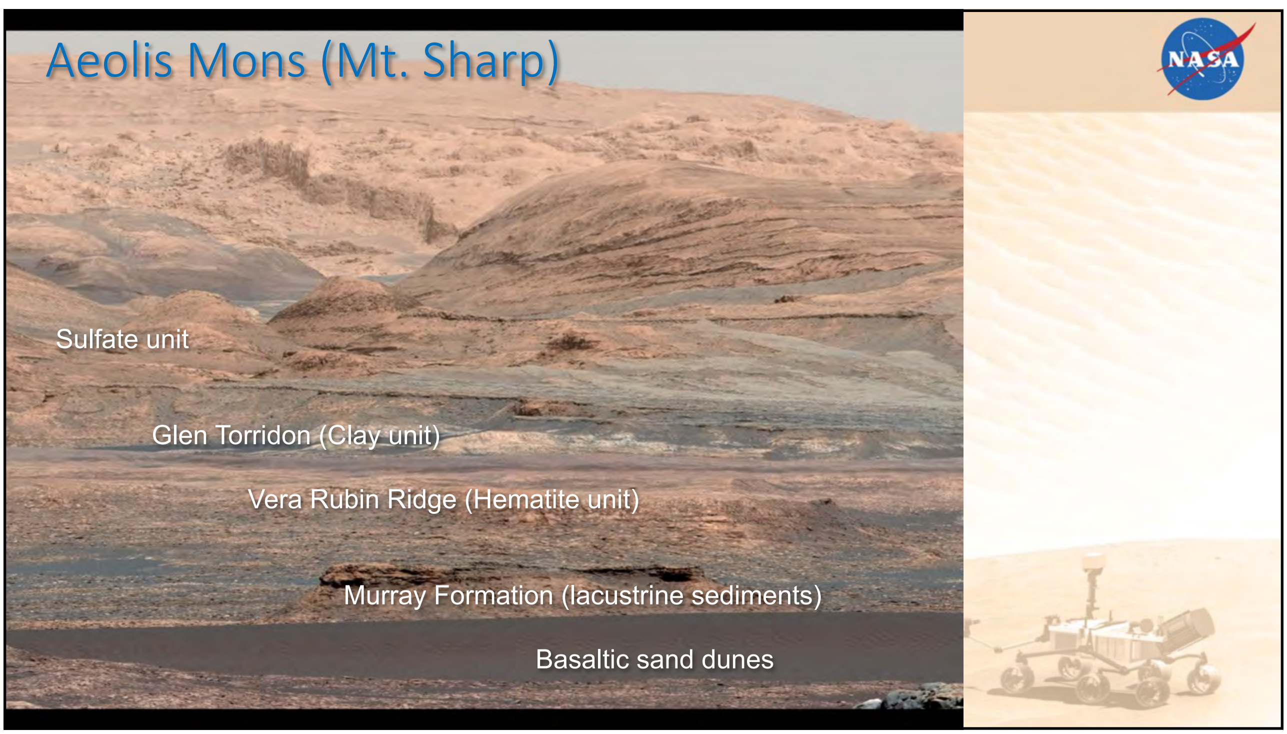
In situ geochronology

- Sample return from everywhere in the solar system! Unlikely.
- *In situ* radiometric dating is strategically aligned with the NASA Decadal Survey science goals and OCT roadmap for science instruments
- Several dedicated *in situ* instruments to measure rock ages have been proposed and developed – both measurements and age interpretation are challenging
- But: we would never say don't send APXS because we can do better on Earth!
- Flown: Beagle 2 (Talboys et al. 2009) – failed
- Accomplished: Curiosity!
- In development:
  - K-Ar via LIBS-MS: KArLE (Cohen et al. 2014), Paris (Devismes et al. 2016, Cattani et al. 2019), Japan (Cho et al. 2016)
  - K-Ar via isotope spike: ID-KArD (Farley et al. 2014), Time After Time (GSFC)
  - Rb-Sr: CODEX (Anderson et al. 2018)
  - Luminescence:

NASA's Science Drivers for Mars

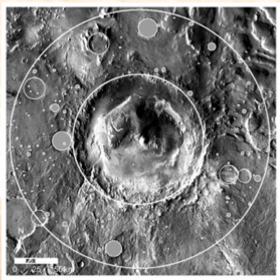


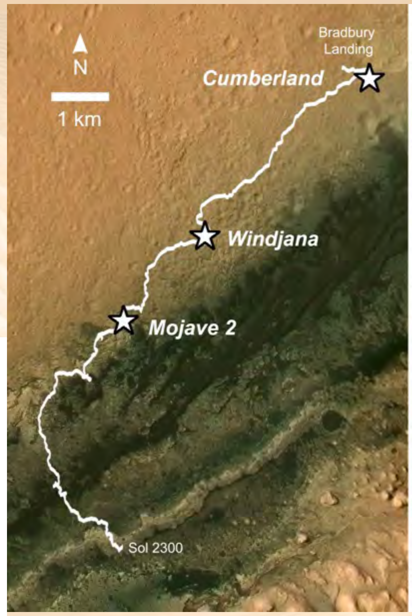

Aeolis Mons (Mt. Sharp)

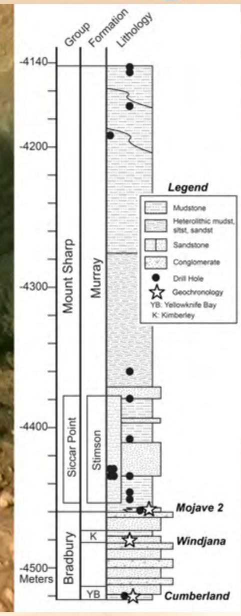

Aeolis Mons (Mt. Sharp)
Sulfate unit
Glen Torridon (Clay unit)
Vera Rubin Ridge (Hematite unit)
Murray Formation (lacustrine sediments)
Basaltic sand dunes

Aeolis Mons (Mt. Sharp)

- The sedimentary system within Gale crater is estimated to have been active 3-3.5 Ga ago in a relatively warm and clement environment (Grotzinger et al., 2015; Mahaffy et al., 2015)
- Surrounding basaltic plains have crater counting ages 3.6-3.8 Ga (Le Deit et al. 2013, Thomson et al. 2011)







Curiosity Rover & Science Payload

REMOTE SENSING

Mastcam (Malin, MSSS) - Color and telephoto imaging

ChemCam (Wiens, LANL/CNES) – Elemental composition; microimaging

CONTACT INSTRUMENTS (ARM)

MAHLI (Edgett, MSSS) – Hand-lens color imaging

APXS (Gellert, U. Guelph, Canada) – Elemental composition

ANALYTICAL LABORATORY (ROVER BODY)

SAM (Mahaffy, GSFC/CNES) - Chemical and isotopic composition, organics

CheMin (Blake, ARC) - Mineralogy

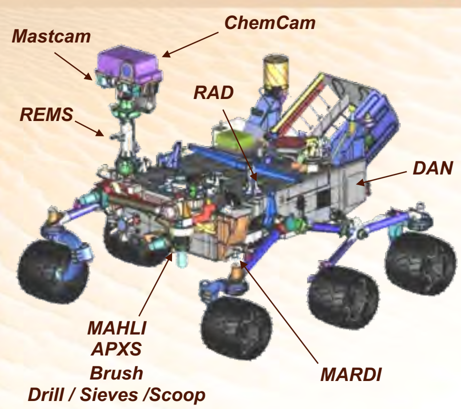
ENVIRONMENTAL CHARACTERIZATION

MARDI (Malin, MSSS) - Descent imaging

REMS (Gómez-Elvira, CAB, Spain) - Meteorology /UV

RAD (Hassler, SwRI) - High-energy radiation

DAN (Mitrofanov, IKI, Russia) - Subsurface hydrogen



Wheel Base: 2.8 m
Height of Deck: 1.1 m
Ground Clearance: 0.66 m
Height of Mast: 2.2 m

Curiosity in situ dating

- Geologic context considered using remote sensing and Mastcam
- K measured using APXS – surface measurement OR on drill tailings, bulk measurement of K and other elements
- Portion mass estimated from preflight engineering tests of CHIMRA
- K siting estimated using Chemin mineralogy
- Ar measured using SAM mass spectrometer on drilled portion

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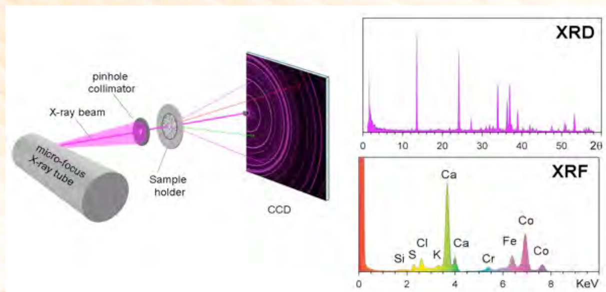

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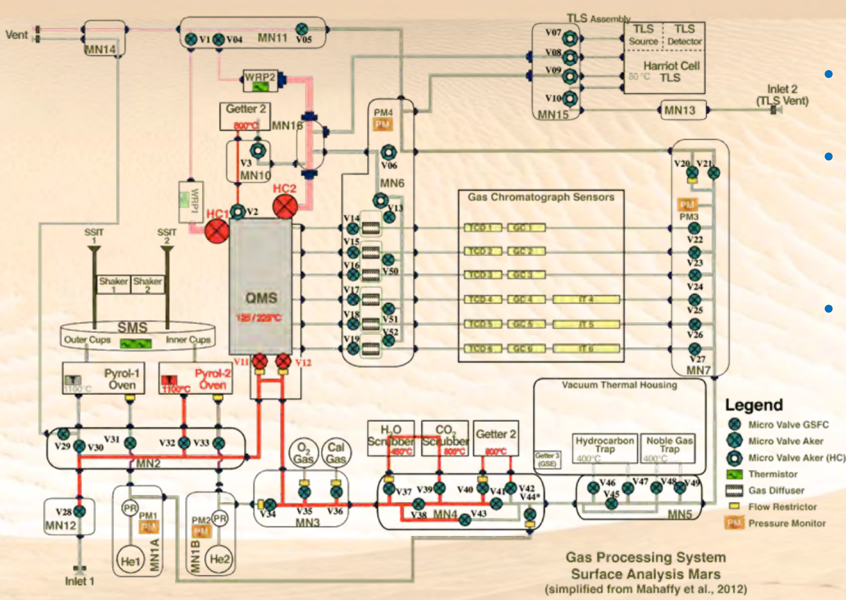
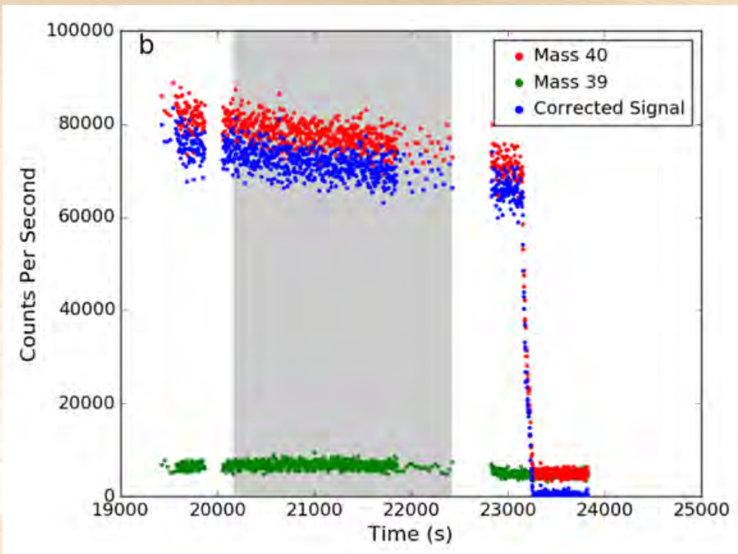
SAM Gas Processing System



Gas Processing System
Surface Analysis Mars
(simplified from Mahaffy et al., 2012)

- Sample aliquots heated in Pyrol-2 Oven
- Cleaned through the segment of the instrument illustrated in red
- Analyzed in dynamic (HC1 and HC2 opened) and semistatic modes (HC1 and HC2 partially closed)

SAM Gas Processing System

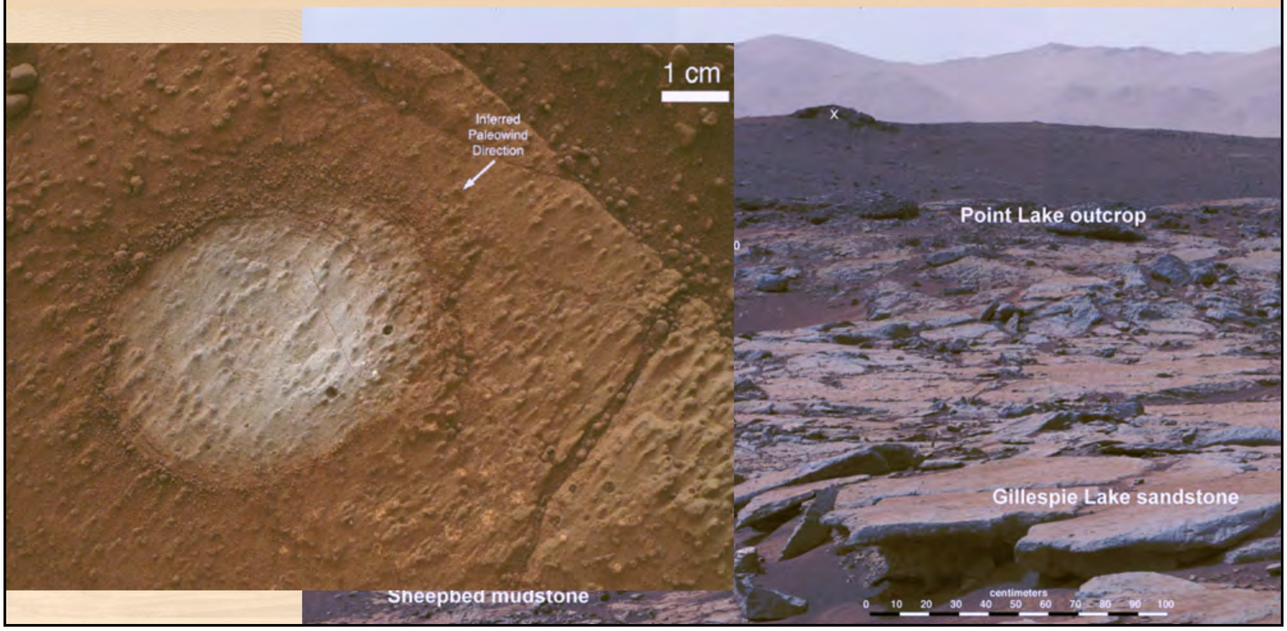


- Sample aliquots heated in Pyrol-2 Oven
- Cleaned through the segment of the instrument illustrated in red
- Analyzed in dynamic (HC1 and HC2 opened) and semistatic modes (HC1 and HC2 partially closed)

Cumberland

- Yellowknife Bay formation.
- Sample is in Sheepbed mudstone, underlying Gillespie Lake sandstone with a sharp contact that can be traced around the full width of the Yellowknife Bay trough.
- K-Ar age = detrital minerals
- cosmogenic age = exposure time of the mudstone as the Gillespie Lake member weathers away

Cumberland



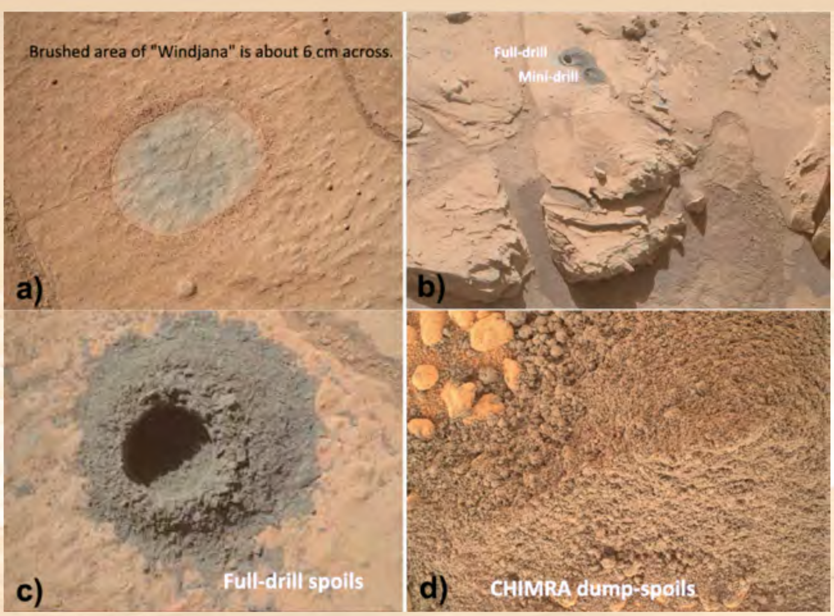
Cumberland

- 4.21 ± 0.35 Ga = basement lithology crystallization age
- Geologically short surface exposure time of 72-84 Ma (
- if caused by uniform denudation, would correspond to a few cm per Myr – but the relative elemental production rates are not consistent with steady erosion - scarp retreat more likely

Windjana

- Kimberley formation sediments, ~35m topographically and stratigraphically above the Sheepbed mudstone
- Postdeposition episodes of diagenetic alteration followed by significant aeolian abrasion
- Elevated K2O abundances attributable to sanidine
- K-Ar measurements = sanidine, cosmogenic ages = overburden removal

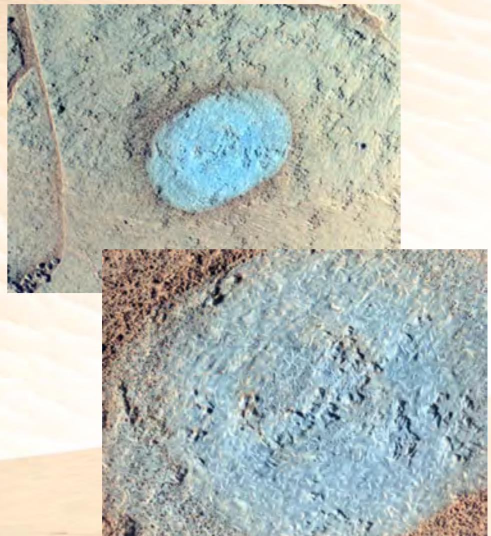
Windjana



- Heated to ~915°C for 25 mins but released only about 5% of the Ar compared with the Cumberland sample,
- Apparent ages of 627 ± 50 Ma and 1710 ± 110 Ma are too young to be interpreted as the detrital mineral age
- Incomplete degassing of sanidine
- Exposure age ~45 Myr or denudation rate of ~4-5 m/Myr – but probably also scarp retreat

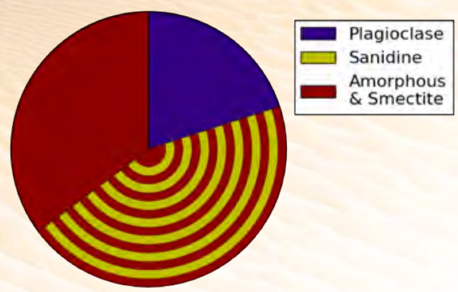
Mojave 2

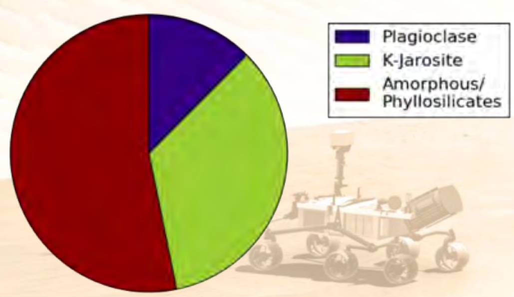
- A finely-laminated mudstone in the Pahrump Hills, grain size unresolvable by MAHLI (<60 µm)
- Contains detrital plagioclase and authigenic jarosite, both of which host K, but which have different Ar release temperatures
- Two-step heating schedule to release each phase separately
- Detrital plag = 4.07 ± 0.63 Ga (consistent with, though less precise than, Cumberland)
- Jarosite formation in a post-depositional fluid environment = 2.12 ± 0.36 Ga (!!)
- Complex/discrepant 36Ar and 3He ages may imply exposure prior to erosion into the Gale basin



Mineralogy

Mineral	Cumberland[d]	Windjana[c]	Mojave 2[b]
Plagioclase	22.2 ± 1.3	3.0 ± 0.3	23.5 ± 1.6
Sanidine	1.6 ± 0.8	21.0 ± 3.0	-
Olivine	0.9 ± 0.45	4.7 ± 1.0	0.2 ± 0.8
Augite	4.1 ± 1.0	20 ± 0.3	2.2 ± 1.1
Pigeonite	8.0 ± 2.0	11 ± 0.2	4.6 ± 0.7
Orthopyroxene	4.1 ± 1.0	-	-
Magnetite	4.4 ± 1.1	12 ± 0.2	3.0 ± 0.6
Hematite	0.7 ± 0.35	0.6 ± 0.4	3.0 ± 0.6
Anhydrite	0.8 ± 0.4	0.4 ± 0.3	-
Bassanite	0.7 ± 0.35	0.5 ± 0.4	-
Quartz	0.1 ± 0.1	-	0.8 ± 0.3
Jarosite	-	-	3.1 ± 1.6
Fluorapatite	-	0.8 ± 0.8	1.8 ± 1.0
Ilmenite	0.5 ± 0.5	0.8 ± 0.5	-
Akaganeite	1.7 ± 0.85	0.2 ± 0.2	-
Halite	0.1 ± 0.1	-	-
Pyrrhotite	1.0 ± 0.5	0.3 ± 0.3	-
Phyllosilicate	18 ± 9	10 ± 0.2	4.7 ± 2.4
Amorphous	31 ± 19	15 ± 0.3	53 ± 15





In situ ages on Mars: Summary

Location	Aliquot	Radiometric age (Myr)	CRE age (Myr)	Interpretation
Cumberland		4210 ± 350 (8.3%)	78 ± 6 (7.7%)	Crystallization age of detrital minerals from basaltic precusor; mm to cm/Ma denudation by scarp retreat
Windjana	Aliquot 1	627 ± 50 (8.0%)	145 ± 203 (140%)	Radiometric ages inaccurate due to incomplete degassing and/or mineralogic fractionation during sample handling
	Aliquot 2	1710 ± 110 (6.4%)		
Mojave 2	Plag	4070 ± 630 (16%)	300 (^{36}Ar) – 1000 (^{3}He)	Crystallization age of detrital minerals from basaltic precusor; pre-burial exposure
	Jarosite	2120 ± 360 (17%)		Fluid flow through the Murray bedrock

Precision, accuracy, interpretability

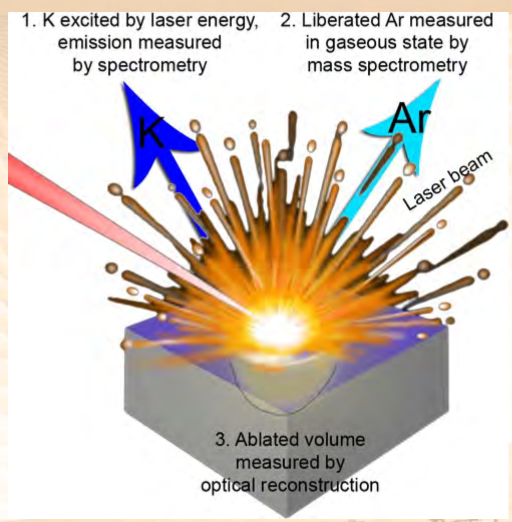
- K hosted in detrital and authigenic phases; bulk age is combination of basement lithology crystallization age, secondary alteration, and maybe shock-reset impactites
- Detrital ages have ~16% precision, but are older than the crater retention ages (though close to upper end of estimated impact event age) – but crater count ages also have uncertainty
- Authigenic ages are young – important for Mars hydrothermal activity. Corroborated by Amazonian-aged alluvial fans and chloride deposits near Gale (Ehlmann and Buz, 2015; Grant et al., 2014)
- Scarp retreat denudation – future missions could sample material protected from cosmic-ray irradiation by drilling or digging under a scarp
- Curiosity dates are important but insufficient for establishing more precise chronology

Developments in *in situ* dating instrumentation

- Must yield ages that are precise, accurate, interpretable, and meaningful
  - Cooperative, characterizable samples
  - Small uncertainties on the calculated age
  - Calibrated standards
  - Age must be recognizable and interpretable as a geologic event
- The NASA Technology roadmaps provide guidelines
  - Required ±200 Ma (or ±5% over 4.5 Ga)
  - Desired ±50 Ma (or ±1% over 4.5 Ga).
- Multiple techniques in development
  - Radiometric isotope dating (e.g., K-Ar, Rb-Sr, and U-Th-Pb systems)
  - Csmogenic nuclide dating
  - Dosimetry-based methods (i.e., luminescence)
  - Exploitation of processes on Mars such as variation in atmospheric stable isotopes and flux of extraterrestrial material
- None are standoff or remote techniques; common need for sample acquisition and handling
- Agreement between multiple chronometers increases confidence, though disagreement does not negate the inherent value of each measurement

K-Ar using LIBS-MS

- Use TRL 9 components to achieve new science – isochrons built from spot measurements
- K measured using laser-induced breakdown spectroscopy (e.g. Chemcam), also ablates the rock
- Liberated Ar measured using mass spectrometry (e.g. SAM)
- K and Ar related by volume of the ablated pit using optical measurement (e.g. MAHLI) or laser microscopy
- Cohen et al. (2014), Solé (2014), Devismes et al. (2016) Cho et al. (2016), Cho and Cohen (2018), Cattani et al. (2019)



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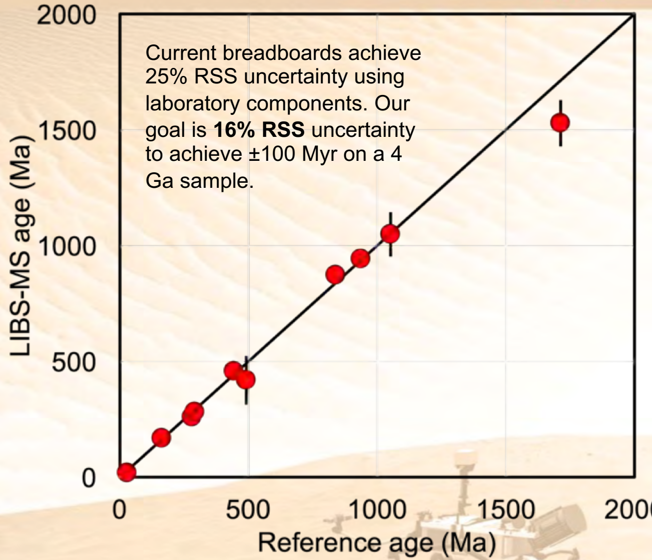

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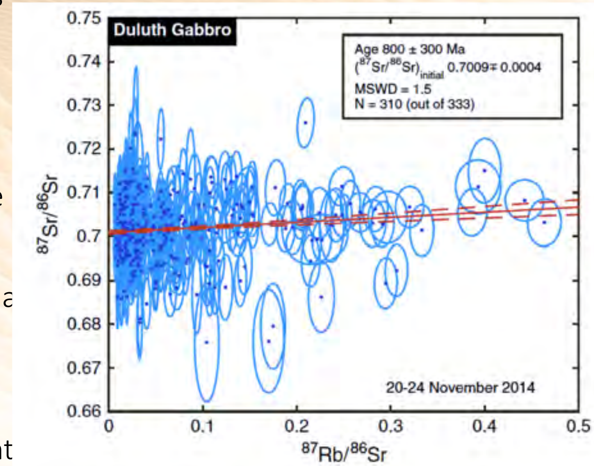
Additional K-Ar and Ar-Ar developments

- Farley et al. (2013) developed ID-KArD, uses powdered samples in cups similar to Curiosity, along with K-Ar spike with flux to enable degassing
- Morgan et al (2017) investigated the requirements for in situ 40Ar-39Ar dating – would require sufficient neutron fluence to create 39Ar, also high-resolution mass spectrometer to measure 39Ar

Rb-Sr

- Rb is highly incompatible, while Sr concentrates in crystallizing minerals (plagioclase)
- 87Rb and 87Sr are isobaric, requiring mass resolution better than m/z=300,000 to distinguish them
- Coleman et al. (2012) used ICP-MC-MS, assume variations in 87Sr resulting from radioactive decay produces only minor variations in overall Sr abundance; only valid for minerals that have a very high Rb/Sr ratio
- Anderson et al. (2014, 2015) Resonance Ionization - Mass Spectrometry (RIMS) after laser ablation, independently introducing parent and daughter to MS via ion optics



measurement precision ±100-200 Ma on 4 Ga rocks

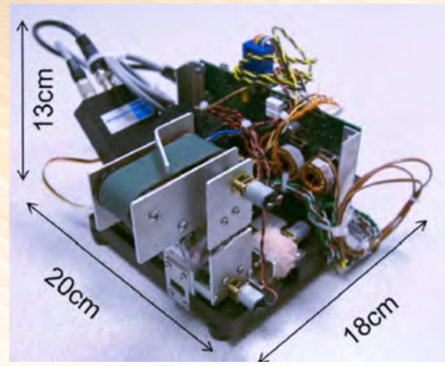
Dosimetric techniques

- Thermoluminescence (TL), optically stimulated luminescence (OSL), and electron spin resonance (ESR) - accumulation of free electrons from exposure to natural ionizing radiation (radioactive elements and/or cosmic rays)
- Sunlight can deplete the trapped charge
- Sample exposed to thermal or optical stimulation; intensity of the emitted luminescence is proportional to the dose absorbed since the last exposure to sunlight, dating the time since burial (i.e. the depositional age)
- Potential for dating of Martian sedimentary processes, such as the frequency of aeolian dust storms, polar layering, and fluvial activity - complementary to noble gas CRE age
- Luminescence dating typically concentrates on quartz and feldspar; iron-bearing materials dilute the OSL effect

TL/OSL for Mars developed by Risø National Laboratory

Dosimetric techniques

- For a rover- or lander-based instrument, material would be collected from the surface via an arm with a scoop or drill, deposited into a sample hopper for grain size and magnetic separation, and transported to the analysis and irradiation chambers (DeWitt and McKeever, 2013)
- The possible range in ages determinable by luminescence dating on Mars, assuming reliable doses can be measured close to apparent saturation, is ~ 40–600 ka (Jain *et al.*, 2006; Sohbati *et al.*, 2012)
- Complex mineralogy, poorly defined sample grain size distributions, high cosmic ray dose rates, anomalous fading, and low temperatures are among the challenges that need to be addressed in determining the success of Martian luminescence dating



ODIN TL/OSL unit (DeWitt and McKeever, 2013)

Summary

- The Curiosity measurements have served to validate radiometric dating techniques on Mars and guide the way for future instrumentation
- Needs: precise and accurate measurements as well as interpretation of the recorded geologic event
- Continued investment in in situ dating techniques is needed so that geochronology instruments can be selected and flown in the 2020's and 2030's
- These investments are crucial to be able to provide meaningful constraints on geologic and astrobiologic events on Mars and interpret Martian history within the context of wider Solar System.