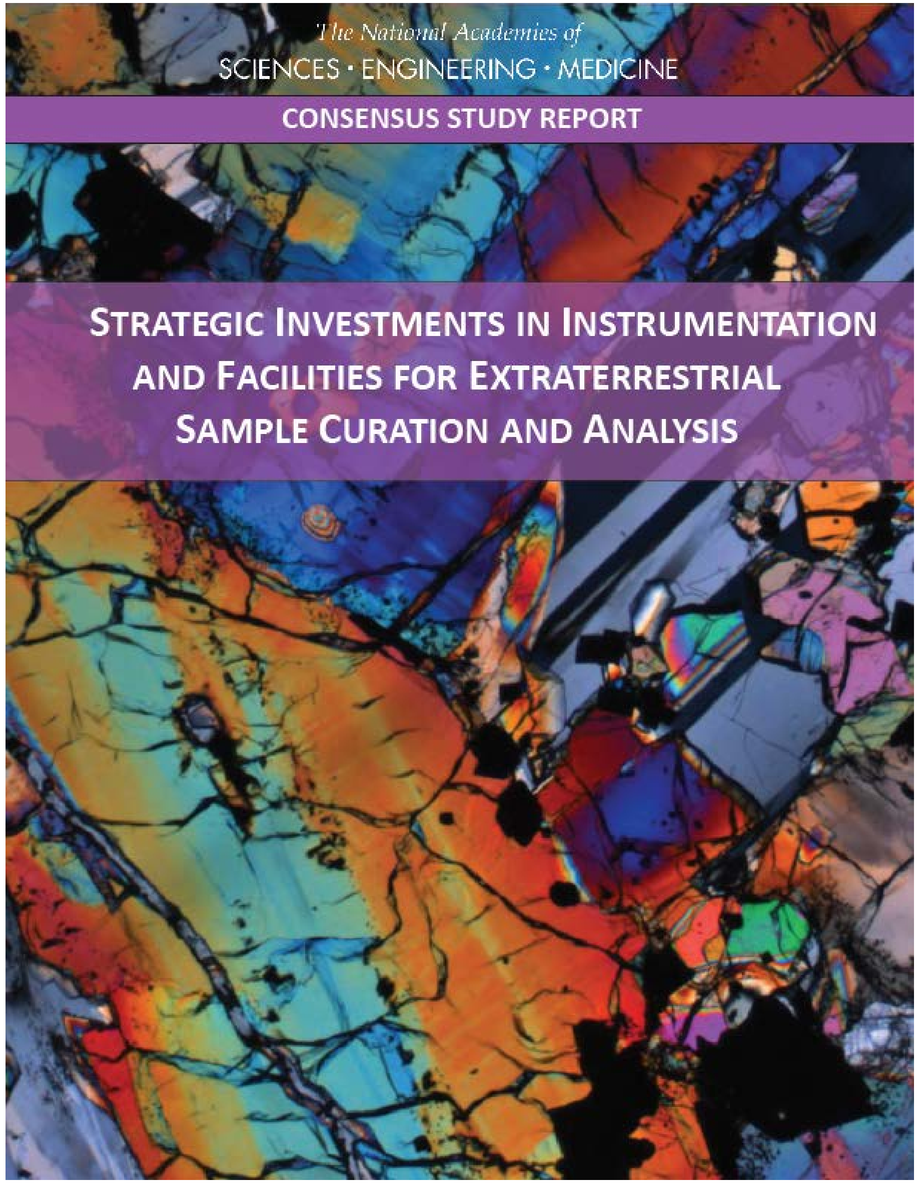
The National Academies of
SCIENCES • ENGINEERING • MEDICINE

Strategic Investments in Instrumentation and Facilities for Extraterrestrial Sample Curation and Analysis

Chair: Roberta L. Rudnick, University of California, Santa Barbara
George D. Cody, Geophysical Laboratory, Carnegie Inst. Science
James H. Crocker, Lockheed Martin Space Systems Company, Ret.
Vinayak P. Dravid, Northwestern University
John M. Eiler, California Institute of Technology
Abby Kavner, University of California, Los Angeles
Timothy J. McCoy, Smithsonian Institution
Clive R. Neal, University of Notre Dame
Hanika Rizo, Carleton University
Kimberly T. Tait, Royal Ontario Museum

Staff: Abigail Sheffer, Study Director
Sarah Brothers. Associate Program Officer
Anesia Wilks, Senior Program Assistant
Carson Bullock and Jonathan Lutz, Lloyd V. Berkner Space Policy Interns

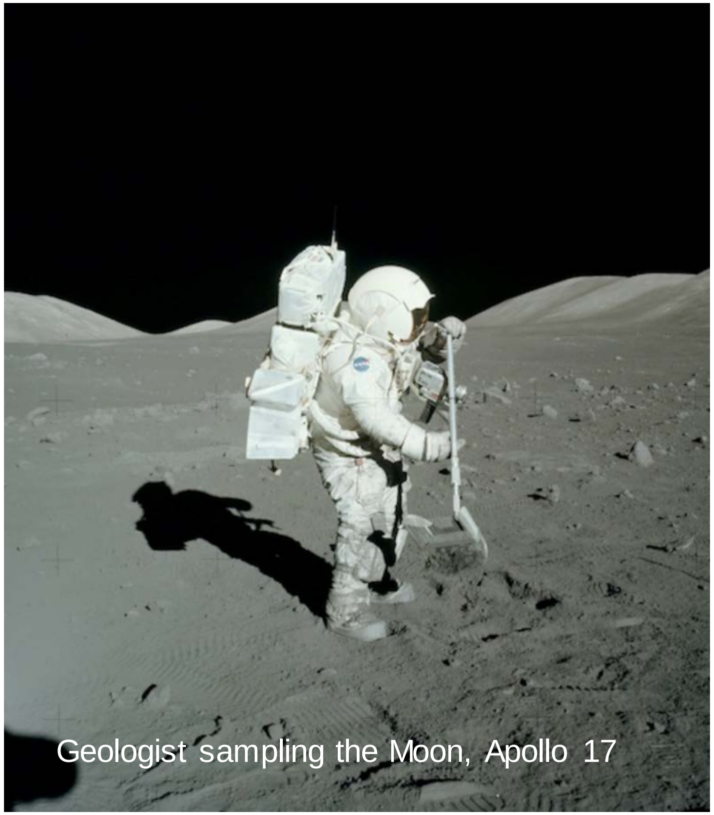


The National Academies of
SCIENCES · ENGINEERING · MEDICINE

Outline

- How the study was conducted
- Summary of extraterrestrial (ET) samples
  - Samples in hand (rocks, minerals, glasses)
  - Samples expected in the next 5 years
  - 'Near' future possibilities (20+ years out)
- Curation
- Instrumentation
- Investment strategies
- Technical support
- Training the next generation of innovators
- Technology development
- International collaborations


Cometary particles caught in astrogel StarDust Mission


Geologist sampling the Moon, Apollo 17

Statement of Task

To prepare for the analysis of diverse extraterrestrial samples in the coming decade, NASA requires information on the current capabilities of the planetary science community's analytical laboratory facilities, their future requirements, and any associated challenges. Therefore, the National Academies of Sciences, Engineering, and Medicine will assemble a committee to perform a study addressing the following questions:

- What laboratory analytical capabilities are required to support the NASA Planetary Science Division's (and partners') analysis and curation of existing and future extraterrestrial samples?
  - Which of these capabilities currently exist, and where are they located (including international partner facilities)?
  - What existing capabilities are not currently accessible that are/will be needed?
- Whether the current sample laboratory support infrastructure and NASA's investment strategy meets the analytical requirements in support of current and future decadal planetary missions.
- How can NASA ensure that the science community can stay abreast of evolving techniques and be at the forefront of extraterrestrial sample analysis?

Study Process

- 3 in-person meetings (Irvine, CA; Houston, TX; Washington, D.C.)
  – site visit to JSC, including curatorial facilities
- Invited >30 scientists to provide information (in person or via telecon)
- Sought information via email from
  – 23 US labs
  – 26 international labs
- Briefing from JAXA re Hayabusa2 and MMX
- Many videocons during report writing phase

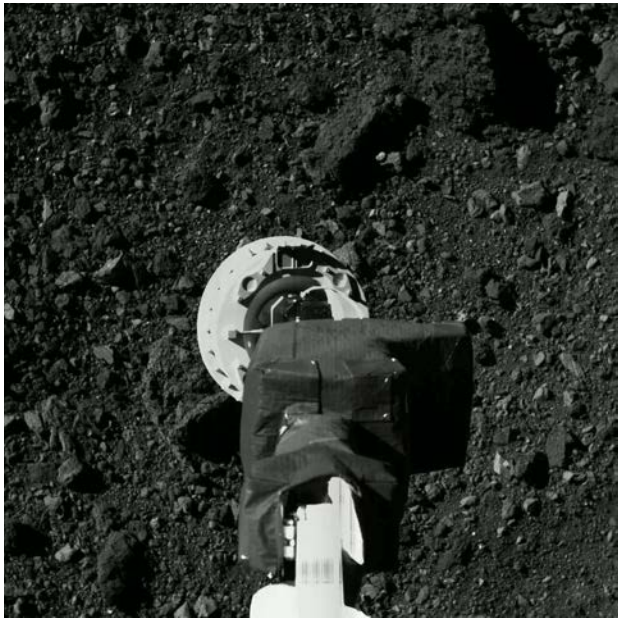
Historic sample return missions
(and other collections)

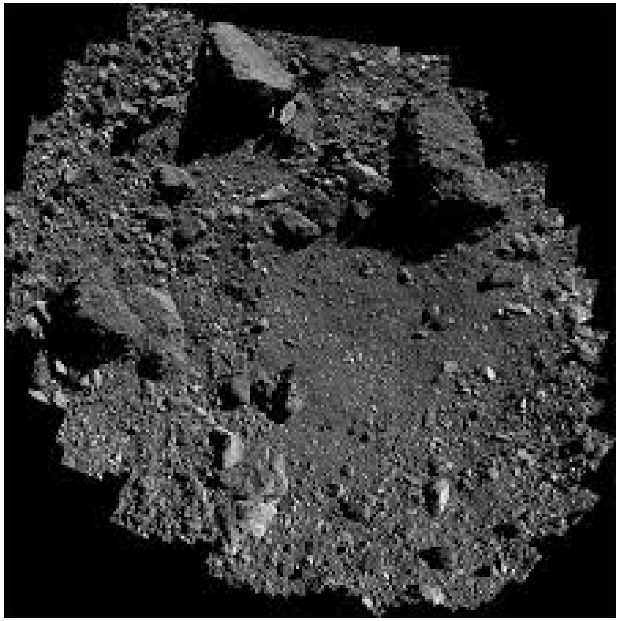
- Apollo >380 kg of rock and soil, 1969-72
- Luna ~0.3 kg of rock and soil, 1970-76
- Genesis solar wind particles, 2004
-
-
-

All samples returned so far are 'hard' samples (rock, mineral, glass, metal)

- Meteorites ~65,000 individual samples
- Cosmic dust 1982 onwards
- Analog materials witness plates, reference materials

In next 3 years





Bennu is a carbon (organic?)-rich, ‘primitive’ asteroid. Expected to shed light on ‘origins’.

Near future possibilities

- MMX sample the surface of Phobos (possible martian surface material?)
- Commercial lunar return to Moon to return more samples (rocks, soil, glass)

Far future possibilities

- Mars surface (Mars 2020)
- Comet surface or cryogenic
- Ices?
- Gases?

Sample Flow Chart

Sample Delivery

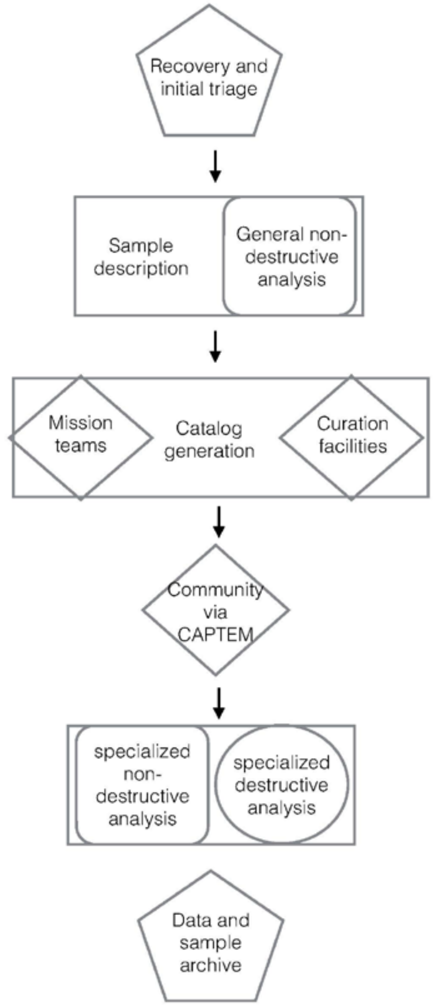
Initial Characterization
Curation Facilities

Mission Teams and
Curation

Distribution to
Community

More detailed
characterization at
distributed facilities

Archiving



Curation findings

Finding: Johnson Space Center's Astromaterials Acquisition and Curation Office is the world leader in curating and tracking returned samples, as well as the types of analyses conducted on those samples.

Finding: The impact of the JSC curatorial efforts go well beyond their immediate duties of curation, as they have been instrumental in helping to train the next generation of extraterrestrial materials scientists and have helped in the development of curatorial facilities at international partner institutions.

Curation recommendations

Recommendation: NASA Planetary Science Division should increase support for Johnson Space Center to develop appropriate curatorial and characterization facilities relevant to and necessary for future sample returns of organic matter, ices, and gases.

Recommendation: NASA Planetary Science Division should accelerate planning for curation of returned martian samples, seeking partnerships with other countries, as appropriate.

Instrumentation

Types of Analysis Types of Facilities	A. Sample & specimen preparation	B. Physical or Structural Analysis	C. Chemical or Compositional Analysis
1. Commonly available at most institutions—broadly accessible	1A e.g., cutting, grinding, thin section preparation	1B E.g., optical microscopy—zoom and petrographic microscopes	1C E.g. general analytical chemistry equipment
2. Multiple regional facilities—limited access*	2A E.g., scanning electron microscope (SEM) equipped with Focused Ion Beam (FIB) technology	2B E.g., X-ray tomography laboratories; M^3EGA Laboratory, JSC	2C E.g. many mass spectrometry laboratories Tabletop FTIR and Raman spectroscopy systems
3. Multiple regional facilities—with access open to users**	3A E.g., neutron activation sources	3B E.g., national Center for Electron microscopy	3C E.g. national ion microprobe centers
4. Unique facility—Limited access*	4A E.g., Creek Road Cryogenic Complex, NASA Glenn Research Center	4B E.g. shockwave laboratories, specialized laboratories at national labs and related research centers	4C E.g. MegaSIMS (UCLA), CHILI (University of Chicago)
5. Unique Facility—access open to users***	5A E.g., Molecular Foundry, Lawrence Berkeley National Laboratory	5B E.g. synchrotron-and/or neutron- based diffraction and or tomography techniques	5C E.g. synchrotron and/or neutron based spectroscopy techniques

Instrumentation

Mission Relevance Classifications (Additional mission-specific information is provided in comments in Table 4.2, where applicable)	**MR I** Fundamental tools relevant for all sample return missions.	**MR II** More specialized tools, required for rock and metal samples	**MR III** More specialized tools, required for organic, volatile, and other low temperature materials	**MR IV** Direct mission relevance not established; however, technique may generate unique data relevant to specific missions

Method	Purpose	Availability and Access and Mission Relevance (see Table 4.1)	Comments on Relevance to Extraterrestrial Materials and Sample Return Missions
Microscopy, Tomography, and Diffraction Techniques			
Light Microscopy			
Optical microscopy techniques: binocular, optical, reflected, polarized petrographic scopes	Non-invasive imaging, spectroscopy, depth and through-thickness analysis.	1B MR I	
Specialized and unconventional light-optical techniques: e.g., second harmonic generation SHG), waveguide- and near-field techniques	Non-invasive, optical and structural measurements; typically via light-optical response of the materials.	2B, 3B MR IV	
Computed and Computer-Aided Tomography (CT/CAT)	Radiation-based 3D (4D reconstruction) of objects/structures, down to submicrometer resolution.	4B, 5B MR I	Laboratory based X-ray tomography and synchrotron-based X-ray tomography
Electron Microscopy			
Scanning electron microscopy (SEM), including field emission SEM	Imaging the surface of materials at the nano- to micrometer scale; capable of wavelength and energy dispersive spectrometry, cathodoluminescence, and SEM-based Raman; low vacuum and environmental chamber SEMs can be used for unprepared surface observation of non-conductive materials.	1B MR I, MR III	Capable of characterizing both hard and soft materials.
Electron probe microanalysis (EPMA), including field emission EPMA	In situ major and trace element analyses; quantitative microchemical measurements, typically by wavelength-dispersive spectrometry (WDS), but electron-dispersive spectrometry (EDS) also possible, as is concomitant CL spectral acquisition. Combined WDS-EDS mapping for trace and major element composition at the micro-scale.	1C, 2C MR I	

Method	Purpose	Availability and Access and Mission Relevance (see Table 4.1)	Comments on Relevance to Extraterrestrial Materials and Sample Return Missions
Spectroscopy Techniques			
Light Spectroscopy Techniques			
Laser-based Raman Spectroscopy	Non-destructive method for phase identification and estimates of pressure (for inclusions within minerals)	2B, 2C MR I	First-line characterization for curating most ET materials
Synchrotron-based X-ray Raman Spectroscopy	Non-destructive method for phase identification and estimates of pressure (for inclusions within minerals)	5B, 5C MR IV	Specialized phase identification in fine-grained mixed solids
Laboratory-based Infrared, UV-Vis, multiphoton/related spectroscopy	Vibration, absorption and electronic structure determination of structures, suspensions, gases and hybrids	2B, 2C 3B, 3C MR I	Identification of water and volatiles within small samples
Synchrotron-based Infrared, UV-Vis, multiphoton/related microscopy, spectroscopy	Characterization of absorption features of materials for comparison with remote sensing IR spectra, identification of organic C-H and C-O features. High spatial and energy resolution.	5B, 5C MR II, MR III	Identification of water and volatiles within small samples
Nuclear magnetic resonance (NMR) and related magnetic techniques,	Non-invasive, sub-surface imaging, spectroscopy, and tomography (e.g., MRI imaging).	2B, 3B MR II	Provides a quantitative analysis of functional groups in organic solids. Sensitive detection of hydrogen in inorganic solids.

Instrumentation conclusions

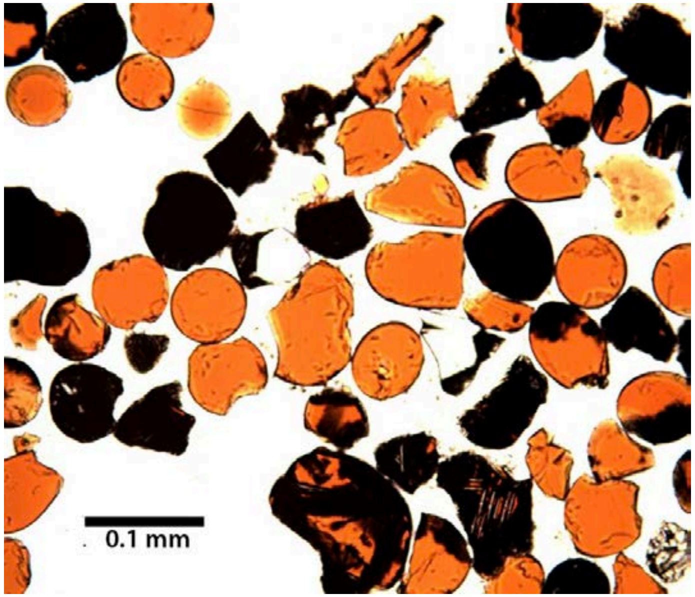
- Conclusion: The committee's analysis of analytical equipment available at U.S. laboratories indicates that there is a wide range of instrumentation that is currently accessible for returned sample analyses. **There are no obvious gaps in instrumentation for analysis of returned rocks, glasses, minerals, and the current inventory of organic materials.**

- Conclusion: Missions in flight will not return samples for at least five years, therefore, **some of the current analytical capabilities will be decommissioned before the samples are available.**

- Conclusion: Future sample return missions are focused on returning and analyzing **more challenging materials** (e.g., gases, ices, organic compounds, see Chapter 3) and **will require investment in technologies that are not currently widely utilized by the sample return community.**

Investment strategies: LARS program

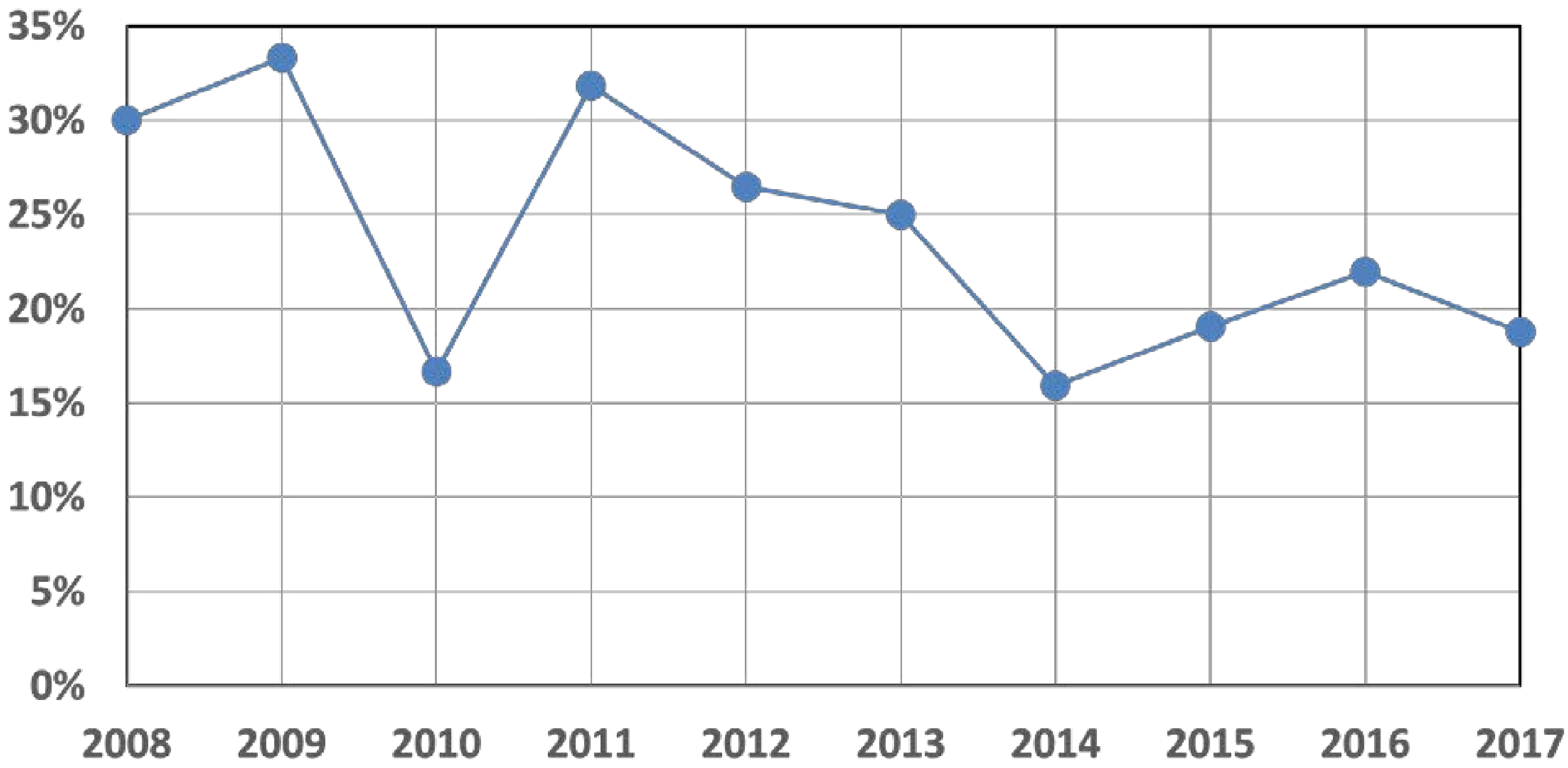
Recommendation: NASA Planetary Science Division should consider opening the Laboratory Analysis of Returned Samples (LARS) grant program to all mission returned extraterrestrial samples.



Apollo 17 orange glass where indigenous lunar water was first detected by Saal et al., 2008

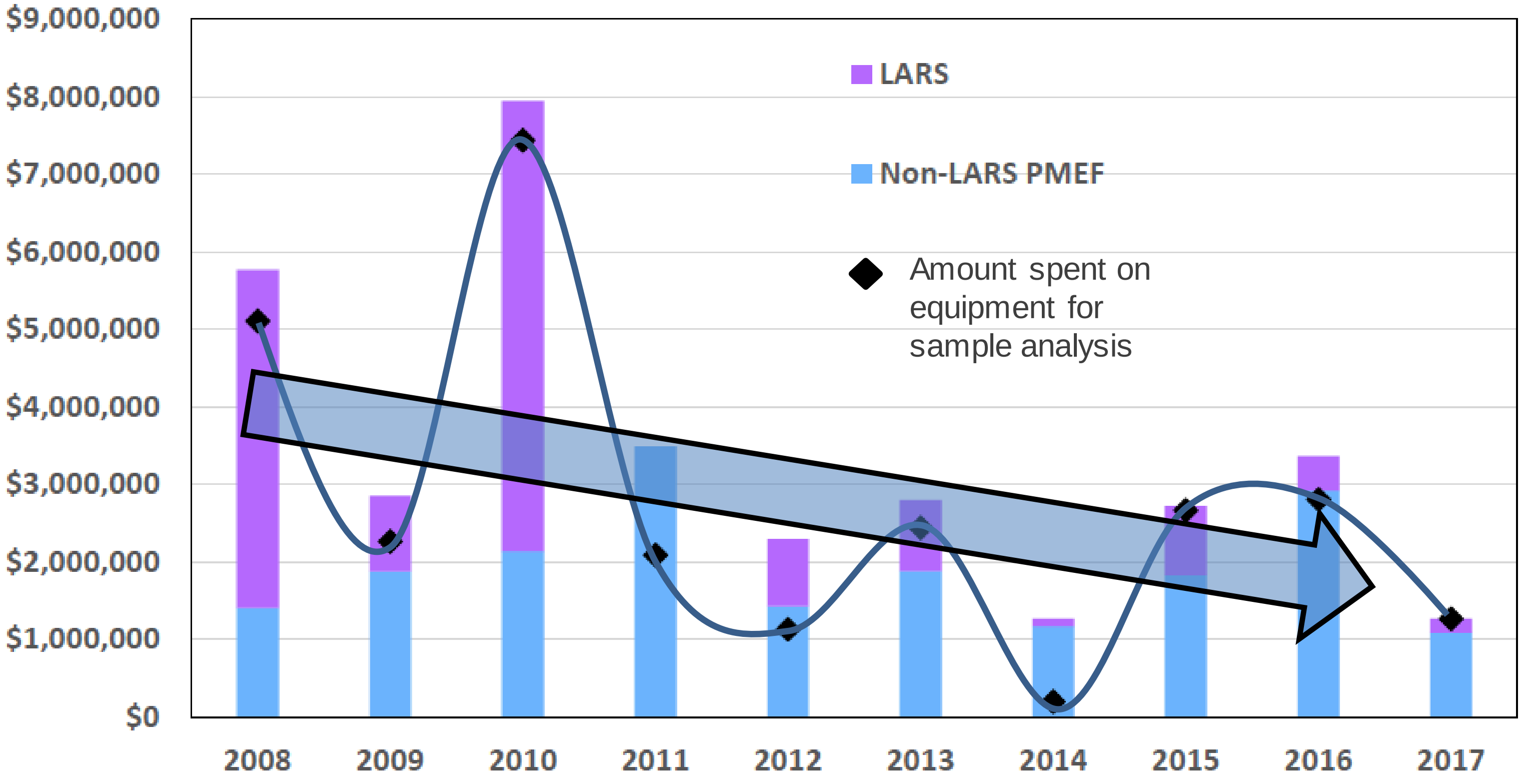
Investment considerations

PMEF proposal funding rate*



*2017 numbers incomplete; excludes LARS proposals with integrated equipment

Investments* in major equipment: PMEF & LARS

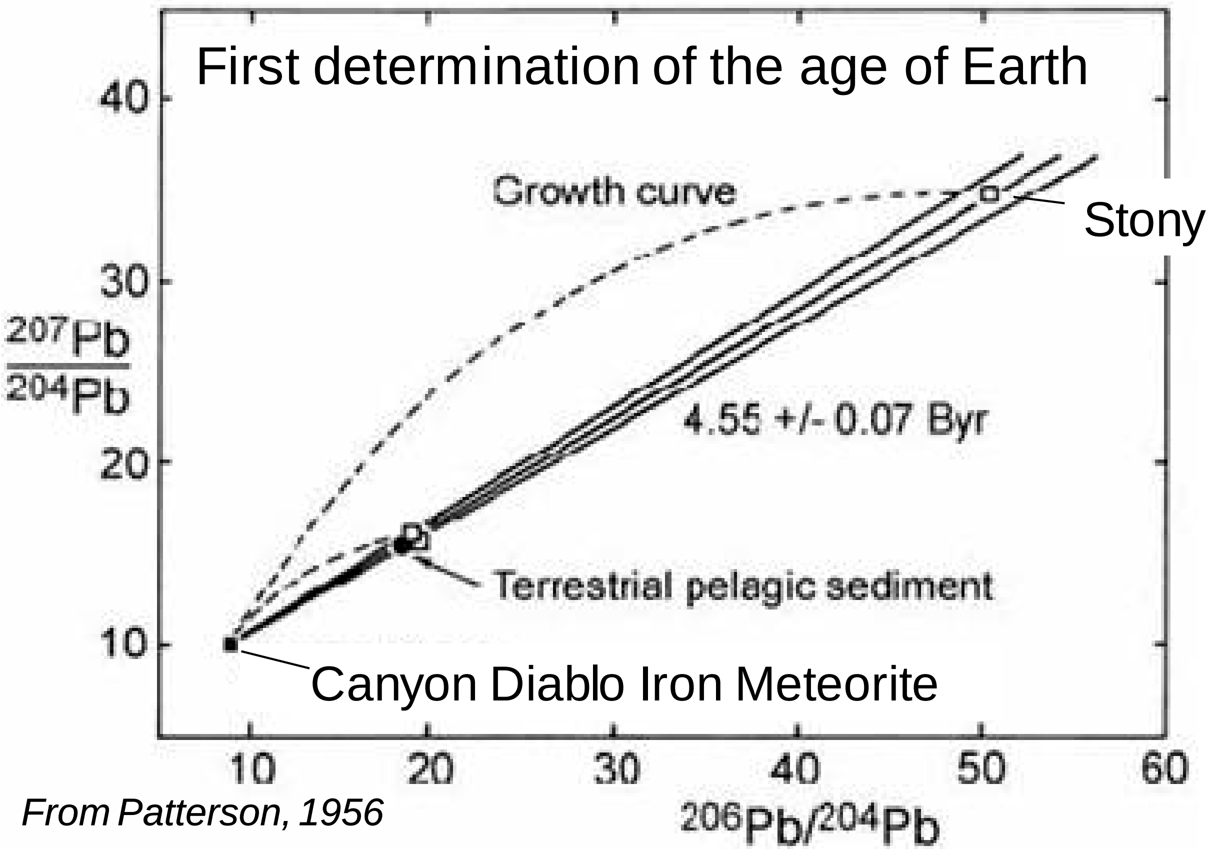


*2017 numbers incomplete

Investment outcomes

- If funding for instrumentation is flat or decreased, labs will need to be cut in order to develop new capabilities.
  - mitigate by funding regional or national facilities?
- If modest funding increase, could support current labs and new capabilities, but developing methods for new materials (e.g., ices, gases) would be challenging.
- If significant funding increase, maintains current capabilities; allows pursuit of new capabilities, funding tech staff; spurs innovation.

Some historic major advances made in university labs



From Patterson, 1956

Clair Patterson

Investment considerations

Conclusion: If future instrument funding decisions must be made under the constraint of flat or decreasing overall funding levels, then the several competing demands of sample return science will likely exceed available resources, necessitating a focus on a few highest priority needs.

Investment recommendations

Recommendation: NASA Planetary Science Division should continue to engage in and encourage cost-sharing arrangements for laboratory analytical equipment with other funding sources.

Recommendation: NASA Planetary Science Division should continue to invest in both multi-user facilities and individual principal investigator labs.

Investment recommendations

- Prioritize support for instrumentation, technical staff and equipment maintenance
- Need to replace existing capacity & *develop new capabilities*

Recommendation: NASA Planetary Science Division should place high priority on investment in analytical instrumentation (including purchase, maintenance, technical oversight, and development) and curation (facilities and protocols) sufficient to provide for both replacement of existing capacity and development of new capabilities. This will maximize the benefit from the significant investment necessary to return samples for laboratory analysis from asteroids, comets, the Moon, and eventually Mars and outer solar system moons.

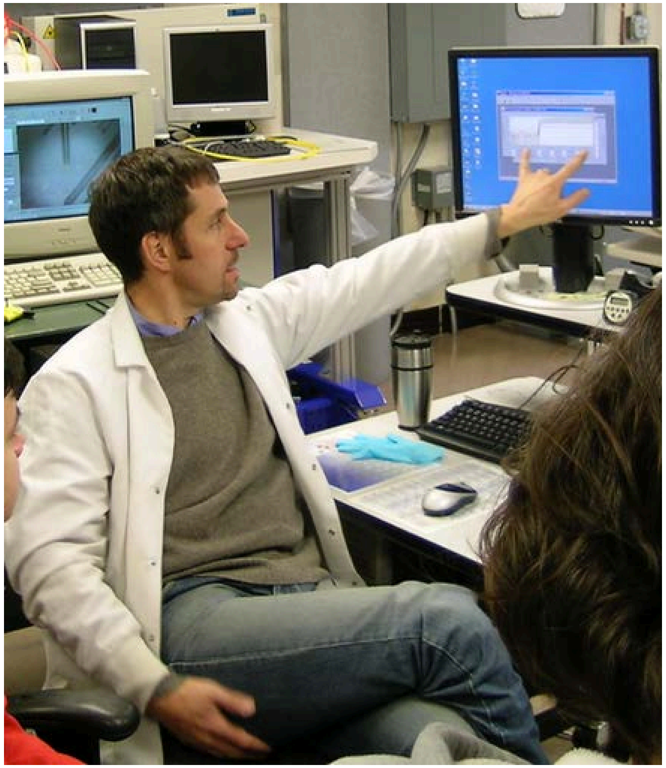
Funding technical support is challenging

Finding: U.S. extraterrestrial sample analysis laboratories are experiencing increased difficulty finding and retaining good technical support staff because of the soft money funding model.

Conclusion: Having laboratories dependent on recharge to pay technical support staff and maintain instruments suggests that NASA's investment in analytical facilities is not being maximized.

Conclusion: NASA's investment in analytical facilities could be enhanced by providing sustained funding for technical support staff, so that the analytical work undertaken by a laboratory remains focused on extraterrestrial sample analyses.

Recommendation: NASA Planetary Science Division should provide means for longer term (e.g., 5-year) technical staff support for analytical instrumentation.



Training the next generation

Conclusion: A highly-qualified workforce that is able to perform both routine, and state-of-the-art laboratory analyses, as well as develop the instruments of the future, is necessary to fulfill NASA's goals for the characterization and analysis of future returned samples.

Training the next generation

Recommendation: NASA Planetary Science Division should encourage principle investigators to specifically address in their research proposals how the work will contribute towards training future generations of laboratory-based planetary scientists.

Technology Development

- Invest in developing novel instrumentation
- Especially for non-traditional samples

Recommendation: NASA Planetary Science Division should make appropriate investments in the technological development of novel instrumentation and unconventional analytical techniques, specifically for curation, as well as characterization and analysis of non-traditional samples that are expected to be returned from future missions. These would likely include gases, ices, and organic matter, including volatile organic compounds (VOCs) and related hybrids and complexes.

Collaborations

- Explore collaborations with ‘adjacent’ communities, other federal agencies and national labs
- Especially for organic matter analysis

Recommendation: With the rapid developments in related fields such as molecular biology, and concomitant advances in bio-organic analytical methodologies, NASA should consider partnerships with relevant federal agencies (e.g., DOE and NIH) and laboratories (e.g., the National Laboratories). NASA should implement information exchange activities (e.g., joint workshops) to enhance cross-fertilization and cooperative development of analytical instrumentation and methods, specifically to enhance analysis of organic matter (both macromolecular/polymeric and molecular-moderate molecular masses, as well as volatiles-low molecular weight compounds), in the study of extraterrestrial returned samples.

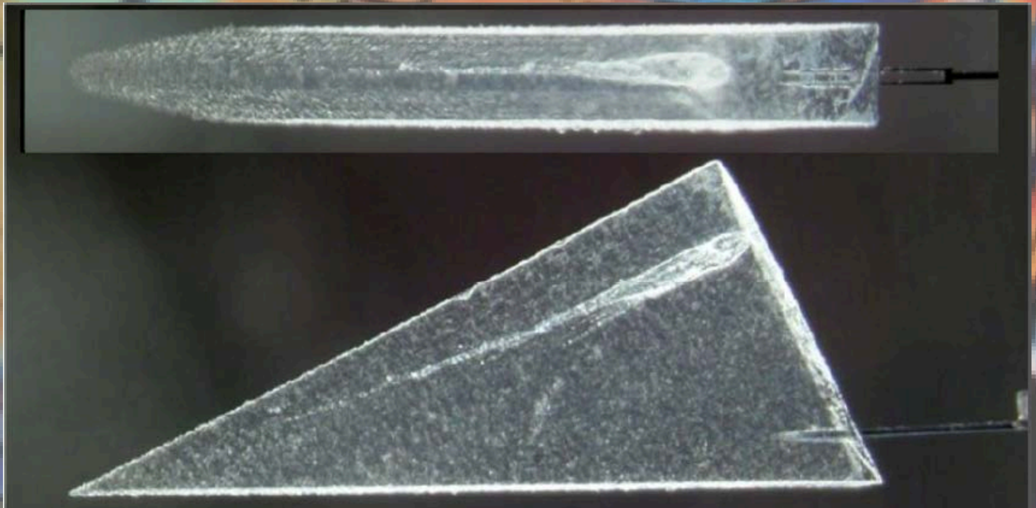
Collaborations and Sharing Knowledge

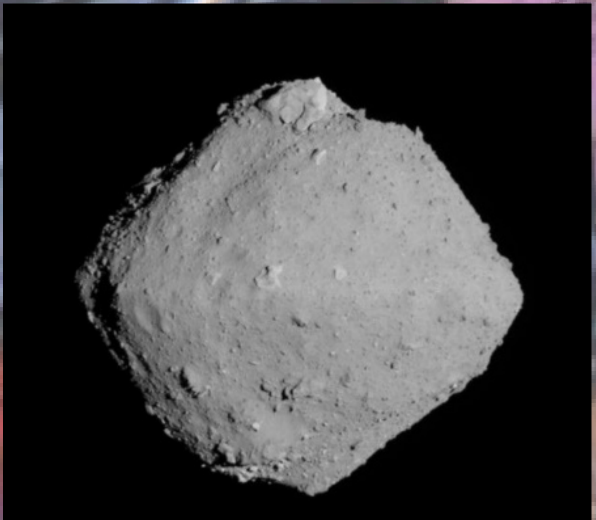
Recommendation: NASA Planetary Science Division should continue to engage in strategic relationships with international partners to ensure that the best science possible is extracted from extraterrestrial samples with the limited resources available to all space agencies.

- Examples of unique international labs: Argus collision cell, Bristol; RELAX instrument, Univ. Manchester; Cosmorbitrap, Univ. d'Orléans.

Recommendation: NASA Planetary Science Division should consider ways to facilitate the dissemination of information about present and future international, state-of-the-art facilities relevant to sample analysis. This could, for example, include organizing workshops to be held with existing international conferences.

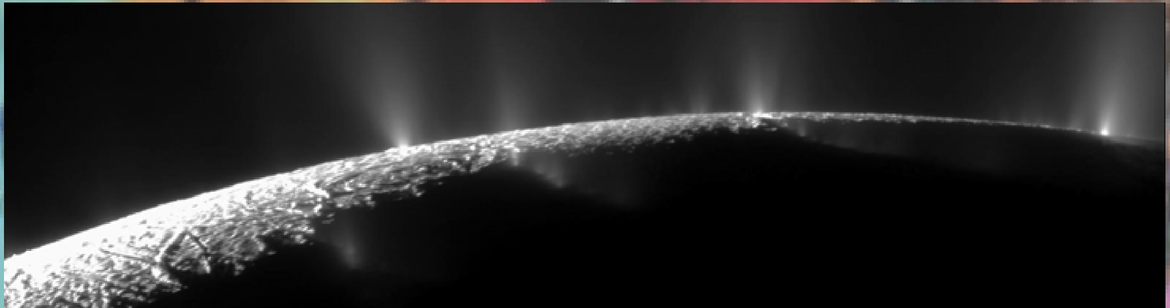
Concluding thoughts


Particle from comet 81P/Wild2, brought back to Earth by Stardust Mission



Ryugu, from Hayabusa2


Comet 67P/Churyumov-Gerasimenko


Jets of water ice on Enceladus, as seen from Cassini