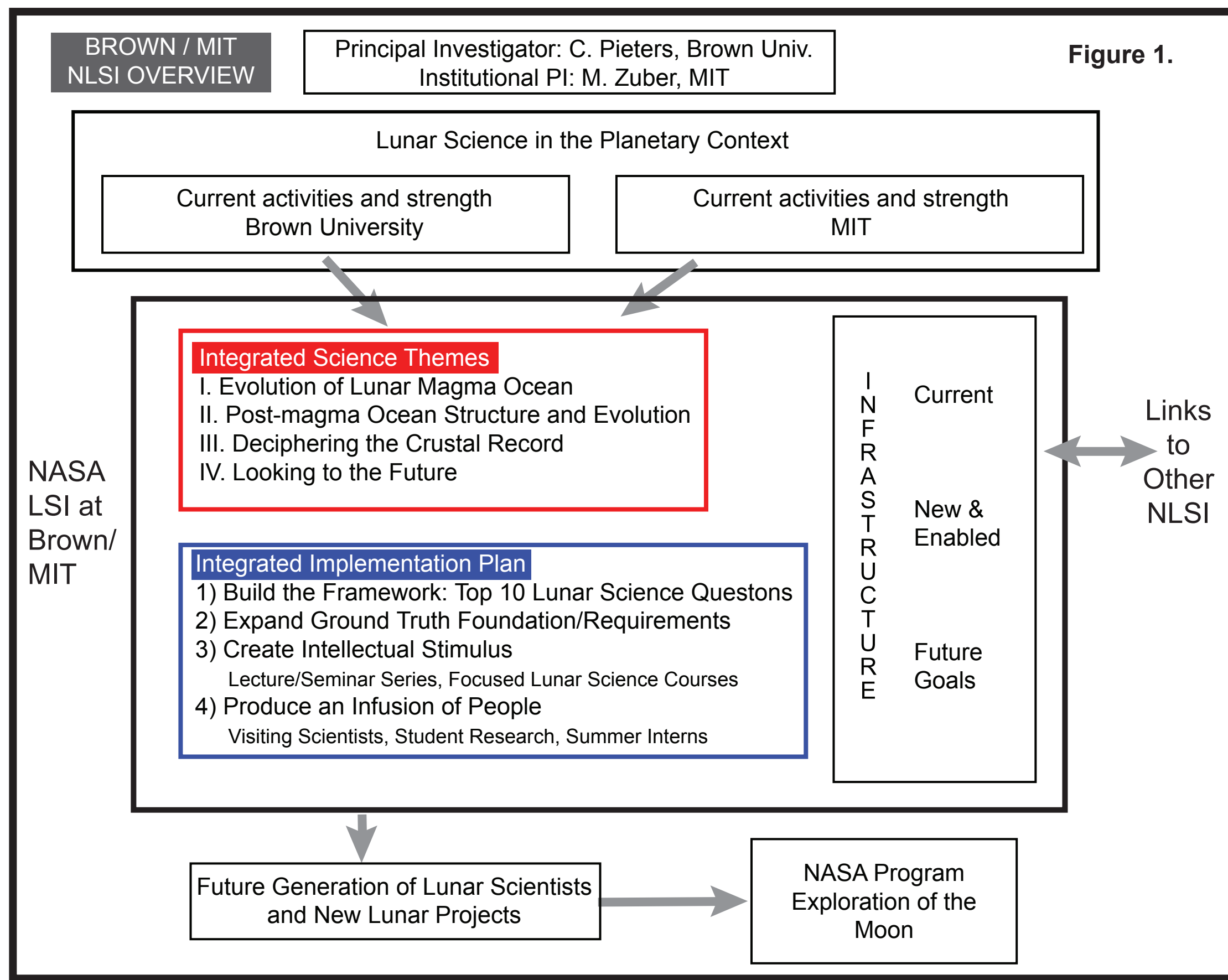
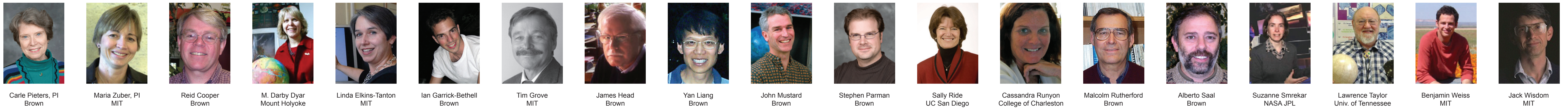


The Moon as Cornerstone to the Terrestrial Planets - The Formative Years



Our Brown/MIT NLSI TEAM activities are structured around **Four Integrated Science Themes**

I. Evolution of the Lunar Magma Ocean

We address the fundamental compositional and physical properties of the evolving magma system during the first few hundred million years of lunar history. What occurs during this critical period sets the stage for all subsequent events.

The Brown-MIT team has been active in understanding the formation of the major rock type that forms the lunar crust: anorthosite. A number of Apollo samples are anorthosites made of exceptionally pure (>98%) plagioclase feldspar. Recent spacecraft observations from the Japanese Selene mission have confirmed widespread occurrences of very pure anorthosite, suggesting it formed globally during the magma ocean epoch. The high purity of these anorthosites (Earth anorthosites are usually < 95% pure plagioclase) can plausibly be explained by a simple yet powerful conceptual model. A compacting liquid-crystal mush zone at the base of the early lunar crust slowly squeezes out trapped melt and can lead to efficient purification of anorthosite over millions of years (Parmentier and Liang, 2010, Figure 2). This model makes several predictions about the purity of anorthosite as a function of depth, which can be tested with newly available remote sensing data.

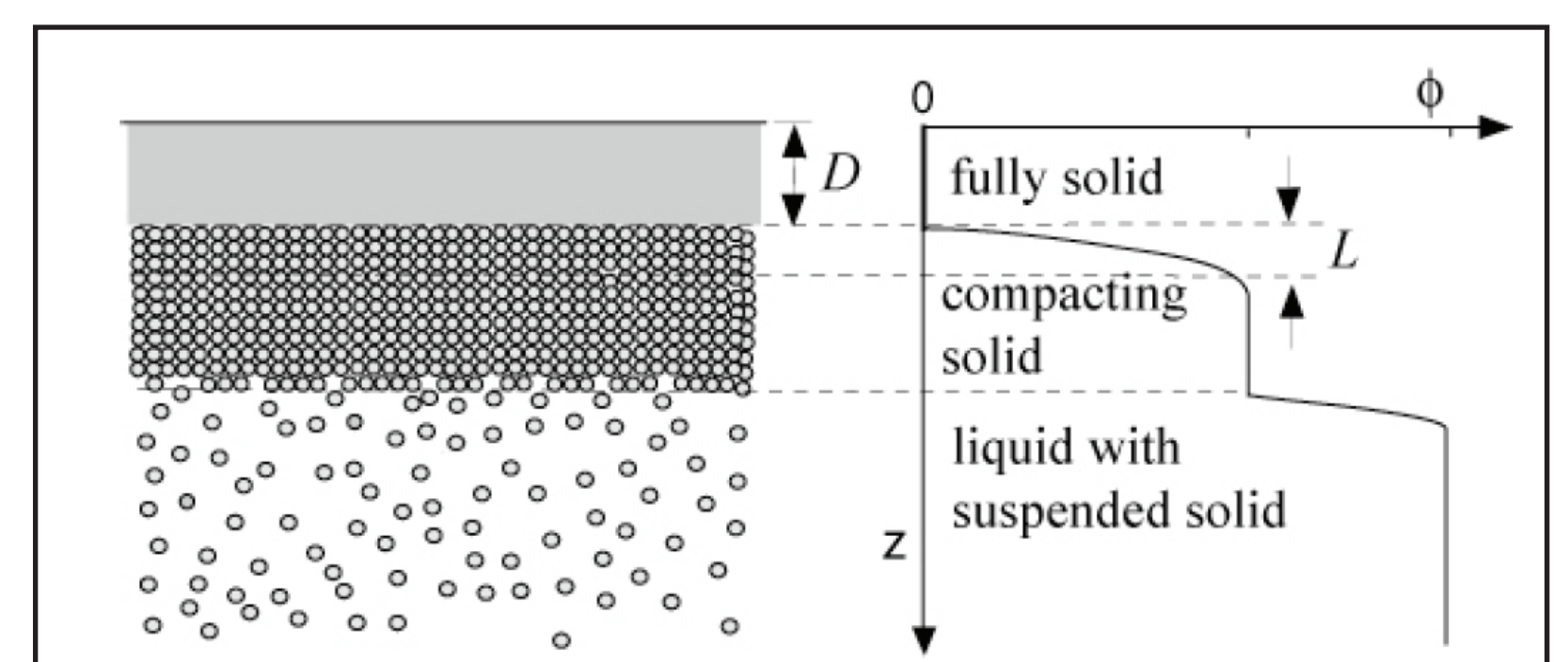


Figure 2. The base of the growing lunar crust during the magma ocean epoch. As plagioclase crystals float to the base of the crust in the compaction zone, they slowly squeeze out trapped melt, forming very pure anorthosite. From Parmentier and Liang (2010).

II. Post-magma Ocean Structure and Evolution

There is much to learn about how the resulting internal structure and thermal evolution of the Moon affected fundamental processes such as core formation and re-melting of the mantle producing basaltic volcanism on the surface.

The largest crater on the Moon, and one of the largest in the solar system, is the South Pole-Aitken basin. For decades, the exact extent of the basin and its structure have been poorly known, and it was assumed to be generally circular. However, multiple data sets were recently used to quantify the boundaries and shape of the basin (Garrick-Bethell and Zuber, 2009). This study found that the basin is in fact elliptical and mapped the extent of the lower crustal materials that were excavated by the impactor (Figure 3). The study also found indications of ring-structures that are known to exist for other large lunar craters, but were not obvious in South Pole-Aitken. This work has numerous implications for the local geology and geophysics, and the formation of large craters in general. Because South Pole Aitken is also a target for lunar sample return missions, this study will help by giving context to potential landing sites.

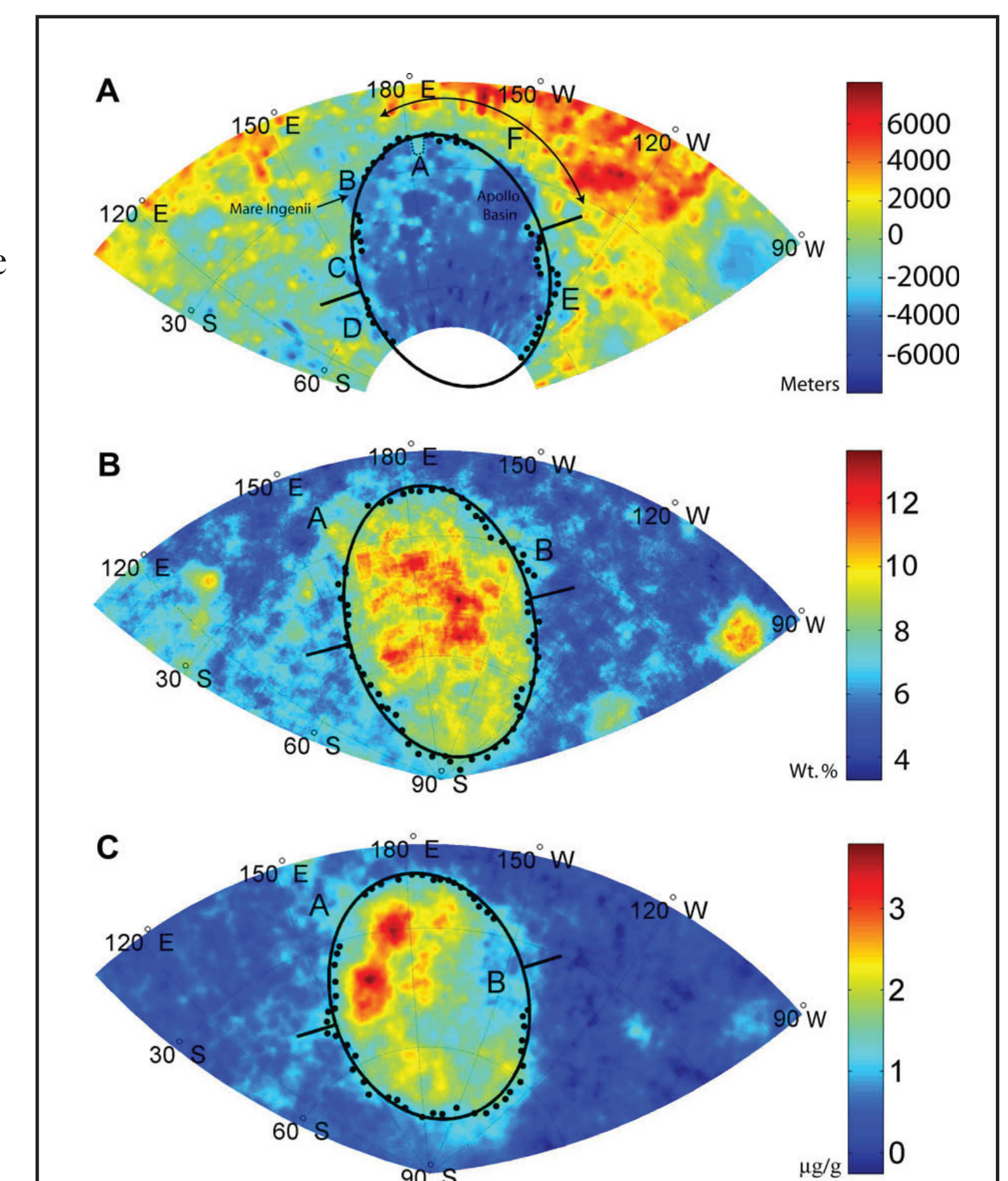


Figure 3. Topography (A), thorium (B), and iron (C) in the lunar South Pole-Aitken basin. The ellipses define the crater's structure. From (Garrick-Bethell and Zuber, 2009).

III. Deciphering the Crustal Record

Here we address the properties of the lunar surface that can be studied and explored with orbital data and processes that can be examined using the unique lunar environment. Our interest spans the chemistry and petrology of a thin section to the local and regional composition seen by remote sensors. Our overall objective is use diverse types of information (composition, mineralogy, morphology, geophysics) to address and test fundamental science questions about the formation, evolution, and current state of the crust.

In collaboration with SELENE colleagues, vast quantities of relatively pure anorthosite have been detected and mapped along the Inner Rook Mountains of Orientale Basin as well as within the central peaks of several large craters, validating the basic Magma Ocean hypothesis of lunar crustal formation (Ohtake et al., 2009; Pieters et al., 2009). This remote sensing discovery led to an experimental analysis of anorthosite in the laboratory led by a student to determine compositional and cooling constraints of this key mineral (Check, 2010). It also instigated coordinated investigation using Diviner data (Wyatt, 2009). Similarly, the discovery of an unusual Mg-spinel lithology along the inner ring of the Moscoviense Basin (Pieters et al., 2010) sparked a re evaluation of the role of spinel in lunar magma evolution (Taylor et al., 2009) and a more detailed investigation into the geology of the basin by a student (Thaisen et al., 2009; 2010).

Bright swirl-shaped features associated with magnetic anomalies on the Moon have remained one of the most enigmatic lunar geologic features. An innovative model has been proposed that involves horizontal fine dust transport to explain the unusual optical properties (Garrick-Bethell, 2010). The new mechanism linking solar wind, magnetic anomaly, and dust transport is illustrated schematically in Figure 5.

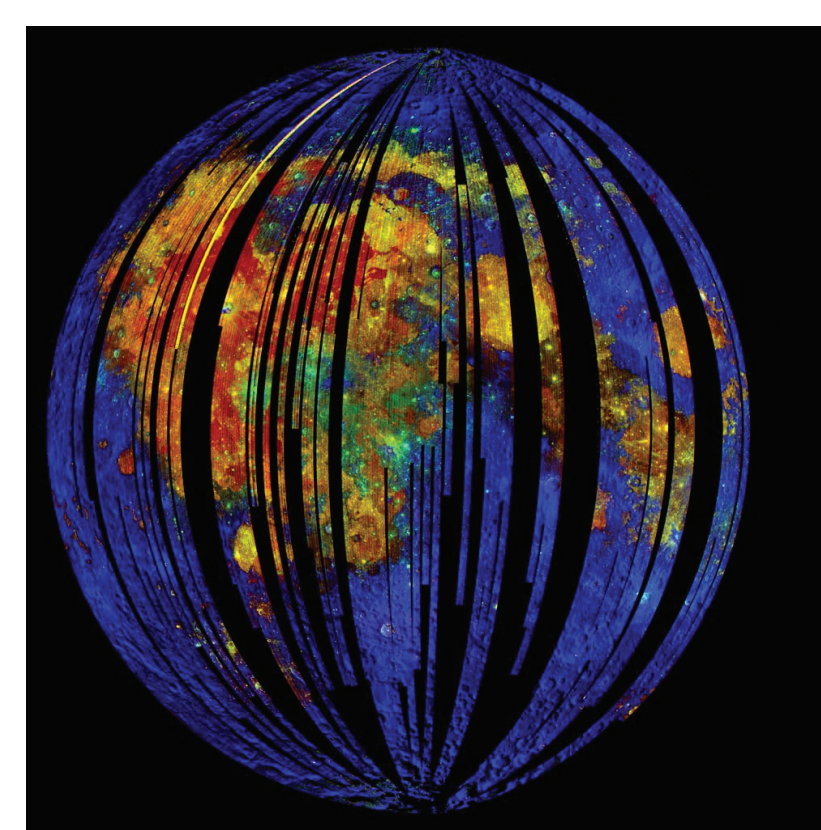


Figure 4. This color composite image [Isaacson et al., DPS, 2009] is derived from M3 data to illustrate the fundamental compositional difference between the mafic-rich mare and the feldspathic highlands. Red and green capture the integrated strength of mafic absorptions near 1 µm and 2 µm respectively, while blue reflects surface albedo at 1.5 µm.

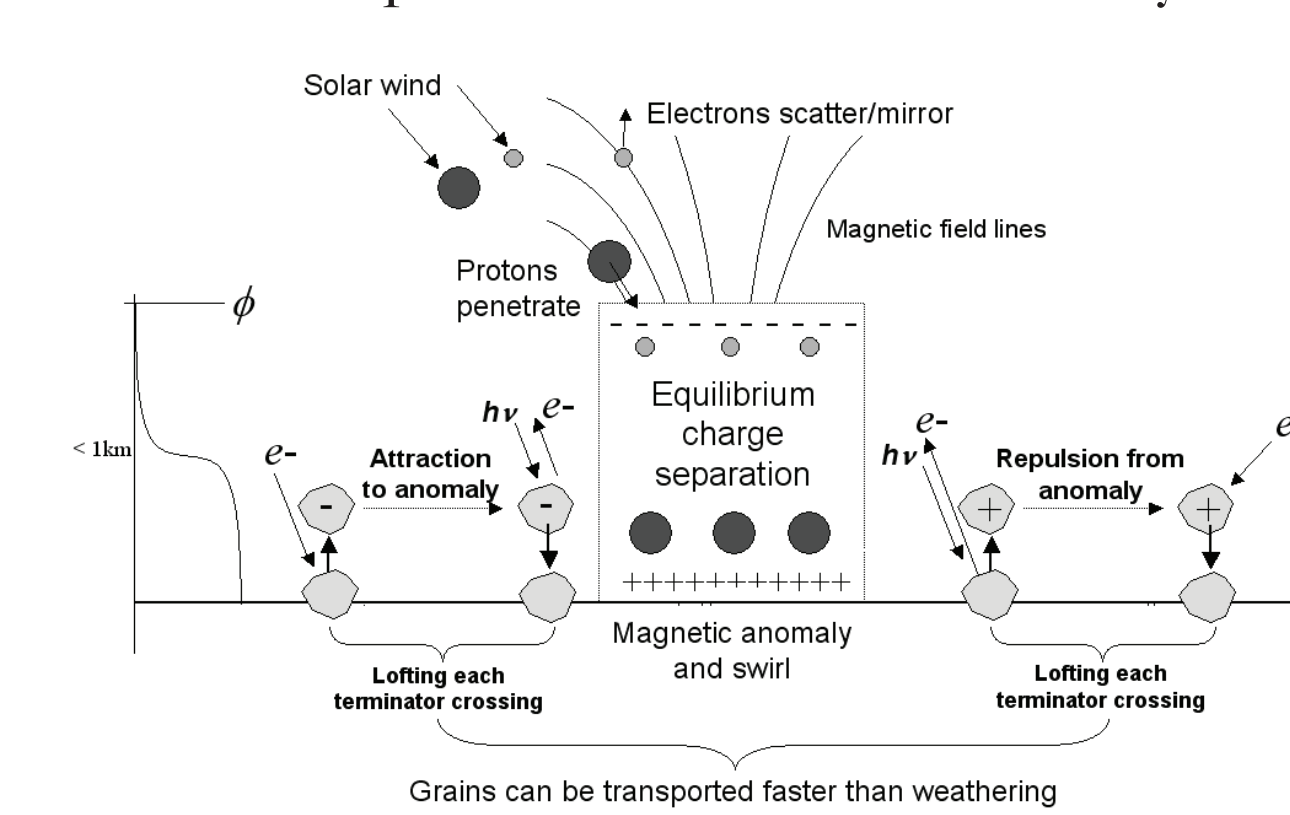


Figure 5. Charge separation at magnetic anomalies produces a monotonically increasing electric potential known as a double layer. The potential increase due solely to the charge separation is sketched at the left, and ignores the photoelectron sheath or other sources of electrical potential. There is no region of negative electrical potential. Fine dust that is electrostatically lofted each day can be repelled or attracted to the positive potential above the surface. [Garrick-Bethell, 2010].

IV. Looking to the Future, Learning from the Past

Long term planning in NASA's robotic and human exploration programs is essential for opening up new realms of discovery. To ensure the continued success of science and exploration of the Moon into the next decade and beyond, the Brown-MIT team has been defining major unanswered scientific questions and determining how to develop missions that address those questions.

Brown has developed a number of visualization technologies that display high resolution datasets in an immersive environment (Huffman et al., 2009; Loomis et al., 2010, Figure 6). For example, the Cave is an immersive 3D virtual reality environment that allows a user to explore photographic, multispectral, and topographic data. Computing and visualization technologies such as these will help to interpret the large amounts of data that have been returned from a number of international missions that have recently visited the Moon. Efforts are now underway to incorporate Lunar Reconnaissance Orbiter topography and high resolution camera data into our visualization tools. These data will help us to plan robotic and human reference missions that are expected to become feasible in the next 10-20 years.



Figure 6. Students using the Cave (a 3D visualization environment) to explore the topography of planetary surfaces.

Our overall objective is to use diverse types of information (composition, mineralogy, morphology, geophysics) to address and test ten fundamental science questions about the formation, evolution, and current state of the lunar crust.

10 Fundamental Science Questions:

1. How do magma ocean processes lead to the generation of the anorthositic crust and its complementary mantle cumulates? How do magma ocean cumulates evolve chemically and physically?
2. What processes created the Mg-suite and (asymmetric) distribution of incompatible elements (including KREEP) in the lunar crust?
3. What is the fate of mantle cumulates during the first billion years and what does their relation to the genesis of mare basalts tell us about processes of early mantle evolution and crystallization?
4. Why is the farside of the Moon so fundamentally different from the nearside? (crustal thickness, mare basalt abundance, heat producing elements)
5. How are the long-term thermal, chemical, and mechanical evolution of the Moon linked? How complete was the lunar global-scale planetary differentiation and how does it compare to the terrestrial planets?
6. How do the soils on the lunar surface reflect the local geology and what do they tell us of processes presently active in the lunar environment?
7. What are the internal and external sources of volatiles on the Moon and what is their history? How might the presence of volatiles in the mantle affect the evolution of the Moon?
8. How can properties of large impact structures on the Moon be used to understand major impact events on the terrestrial planets?
9. What is the nature of the mega-regolith (at scales from samples to regional geology to crustal structure) and what do its properties tell us about the processes active in the early solar system?
10. What are the next steps? Where do we go and what do we do on the Moon to answer the most significant scientific questions and what new exploration tools and technologies will be needed?

Expand Ground Truth Foundation/Requirements. Our NLSI cross-laboratory lunar sample consortium coordinates measurements of existing lunar rocks and mineral samples, identifies appropriate new samples, and maintains a data base of physical and compositional properties for each sample. [Figure 7].

Create Intellectual Stimulus and Infusion of People. Here are a few of the ways we have spread the word about the Moon, high-lighting events from this past year:

2 Symposia: Brown University-Vernadsky Institute-MIT-NLSI: Microsymposium 52: "The Moon: The First Billion Years of Crustal Evolution"; and, Commemorating the 50th Anniversary of the First Human in Space: The Flight of Yuri Gagarin, April 12, 1961

2 Seminars/Webinars: at Brown and at MIT

Several Informal Seminars. Held throughout the year, including the following, presented under the Brown Planetary Lunch Series:

- Deepak Dhingra, Spectroscopic signatures of Mare Tranquillitatis basalts as observed by Moon Mineralogy Mapper (M3)
- Mario Parente, Exploratory data analysis of multispectral and hyperspectral planetary datasets: Using statistical learning to enhance mission science return
- Jessica Flahaut, Lunar surface sites suitable for exploring NRC 2007 Concept 3: Key planetary processes are manifested in the diversity of lunar crustal rocks
- Leah Check, Goldschmidt crater in the context of the mineralogical variability of the Moon's North Pole: Results from the Moon Mineralogy Mapper (M3)
- Debra Hurwitz, Origin of sinuous rilles
- Harold Clener, Earth and planetary hyperspectral remote sensing: Applications to mafic mineralogy
- Peter Isaacson, Spectroscopy of lunar olivines
- Jennifer Whitten, Volcanism in the lunar Orientale Basin

Lunar Science Summer Internship. We have initiated a summer program for students to help create what will truly become the next generation of lunar scientists. In our 8-week program, students live in Providence where they work with Brown faculty and graduate students on a research topic in lunar science.

Focused Lunar Science Courses. Since its formation, our Brown/MIT NLSI TEAM has taught numerous courses that focus on the Moon, reaching several hundred undergraduate and graduate students. During the last academic year alone, Brown and MIT taught 14 courses with concentrations on the Moon.

Educator / Professional Development Workshops. Our Education / Public Outreach (E/PO) team has held or participated in hands-on, inquiry-based workshops for educators (e.g., formal, informal and home-school) in AL, CA, SC, and TN. Workshop content addresses National Science Education Standards. To date, more than 500 teachers have participated and learned about the exciting results from NLSI and this TEAM. "Getting a Feel for Lunar Craters" is a tactile book, which is also a part of our effort. Our next project will be about rocks and how we determine their composition (Earth-Moon examples).

Moon Exhibit. A 1500 sq ft exhibit is in development. Opening in November, 2011, Many Moons (working title) seeks to take measure of the complex relationship between humans and the Moon throughout history, with particular attention to the ways in which optical technologies have continually advanced our understanding. The exhibition explores past and current mysteries surrounding the Moon (scientific and otherwise) in an effort to generate a renewed fascination with our sister sphere.

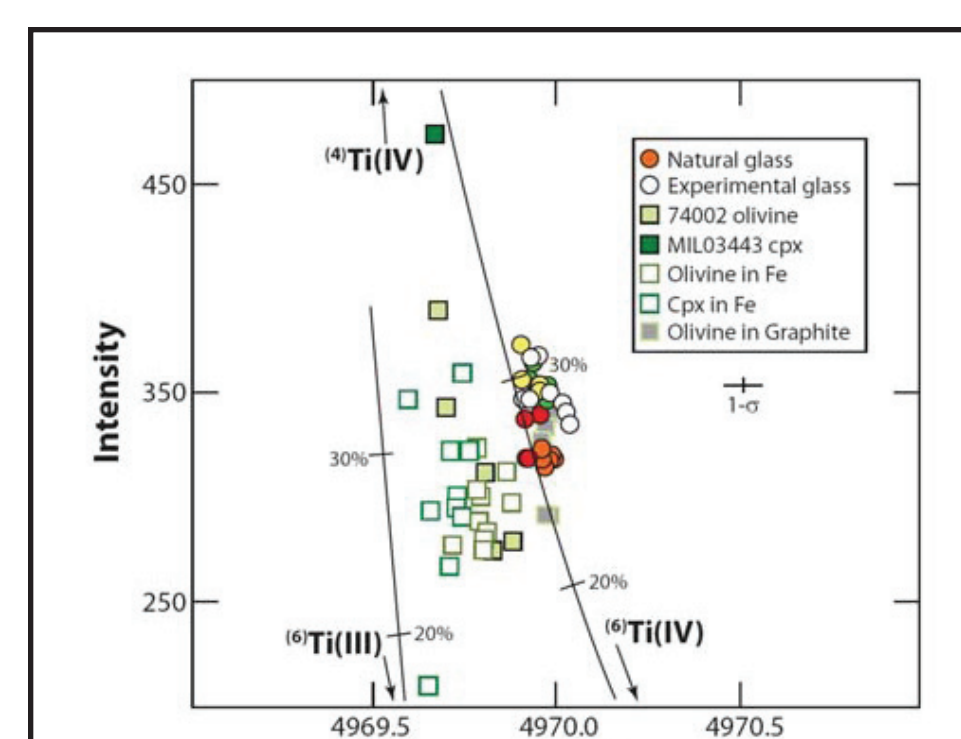


Figure 7. Ti-speciation diagram which addresses both the oxidation state and coordination of titanium in lunar materials. The XANES pre-edge peak intensity and energy of the peak centroid are a function of the Ti valence and coordination. Glasses correspond to their color, and all plot in the same vicinity no matter the composition and if they are natural or experimental. Also shown are olivines from 74002 and experimental charges as well as Cpx from MIL03443. Olivines from MIL03443 plot at ~800 intensity and thus are off the scale here. [Krawczynski et al., 2010]

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