PROVENANCE OF THE MOON THROUGH THE COMPARISION OF ISOTOPIC ABUNDANCES OF ^{50}Ti IN TERRESTRIAL, LUNAR AND MARTIAN SAMPLES

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ABSTRACT

The origin of the Moon continues to be a controversial topic. Giant Impact model simulations indicate that the material making the Moon originated predominantly from the impactor. Recently, the similarity of the isotope composition of the highly refractory element titanium in terrestrial and lunar samples has been used to indicate that the Moon was derived from the Earth's mantle. This has compelled astrophysical models to find physical conditions under which this could be possible. However, the existing Ti isotope measurements have failed to prove that large bodies, such as the Earth, the putative impactor, and Mars, would retain distinct Ti isotope compositions in spite of radial mixing in the solar nebula since that research did not include measurements of Martian samples. In this project, we are determining high precision Ti-isotope measurements of lunar, terrestrial and Martian samples to better test whether radial isotope anomalies are retained by objects as large as Mars (or Mars-sized impactors). Because titanium is a refractory element, this explanation fails to apply to the similarity of Ti isotopes. In this progress report, we show that we can (1) extract Ti from complex matrices (rocks, meteorites) in sufficiently pure form for mass spectrometric analysis, and (2) measure the Ti isotope ratios to a precision of 8 ppm or better.

INTRODUCTION

The Earth's Moon is anomalous in the solar system in having such a large ratio of mass to its parent planet. There have been many models proposed for the origin of the Earth's Moon: (1) fission from the Earth's mantle, (2) co-accretion with the Earth, (3) capture of a small protoplanet, and finally (4) a giant impact, the prevailing post-Apollo theory. The fission model (Fig. 2-1) supports the fact that the Moon's bulk of major oxide composition is very similar to the terrestrial mantle. The unresolved problems with the fission model include: how proto-Earth acquired a high enough angular momentum to fission and how the Moon would have subsequently lost this angular momentum after fission[1]. The co-accretion model (Fig. 2-2) would explain the similar composition between the Earth and Moon but not why the Moon lacks a core, and is lower in the abundances of volatile elements[1].
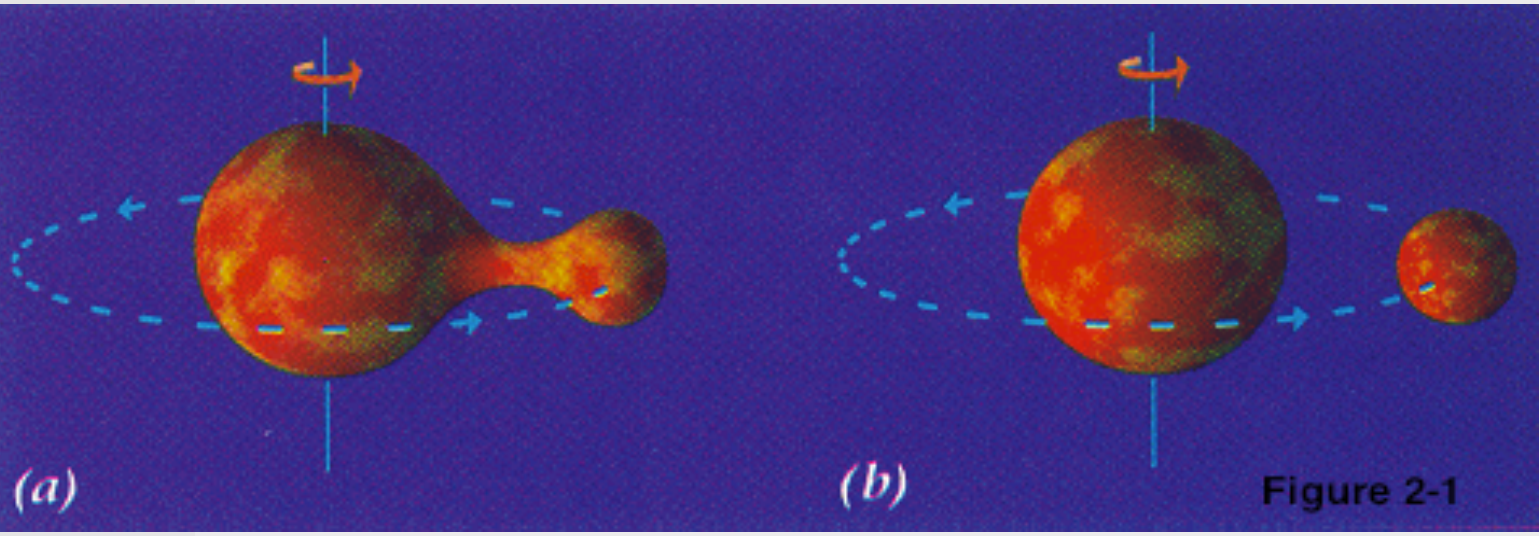

Figure 2-1: The **fission theory**[1], presented by George Darwin (1879), suggests that the Moon was once a part of the Earth separated by tidal forces.
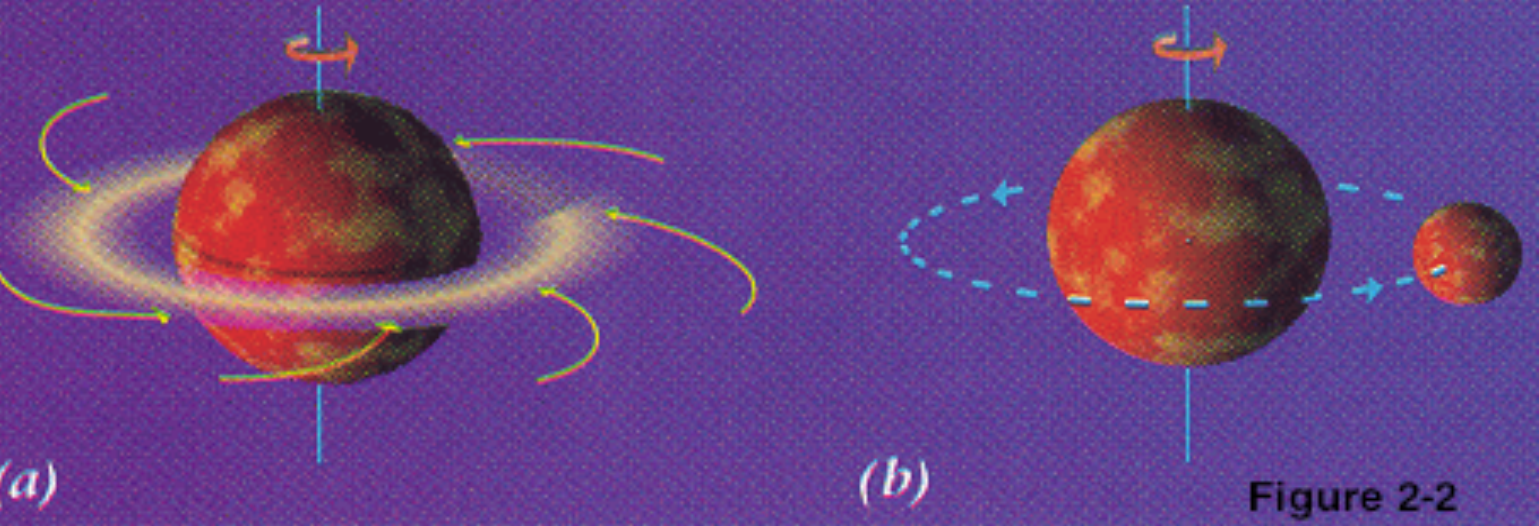

Figure 2-2: The **co-accretion theory**[1] states that the Moon and Earth formed at the same time.
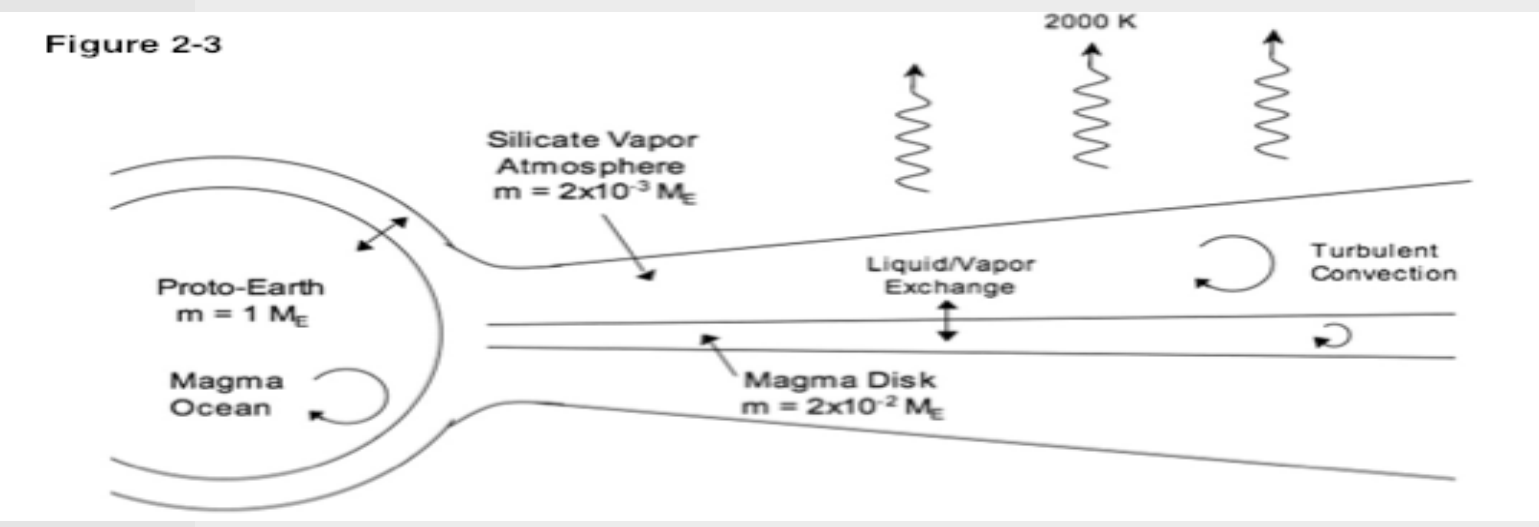

Figure 2-3: Pahlevan/Stevenson model[2] of the Earth and proto-lunar disk after the giant collision. Silicate Earth melts and forms a magma ocean and the proto-lunar material forms a magma disk around the Earth. Liquids and vapors and exchanged between the silicate vapor atmosphere until the two reservoirs equilibrate.
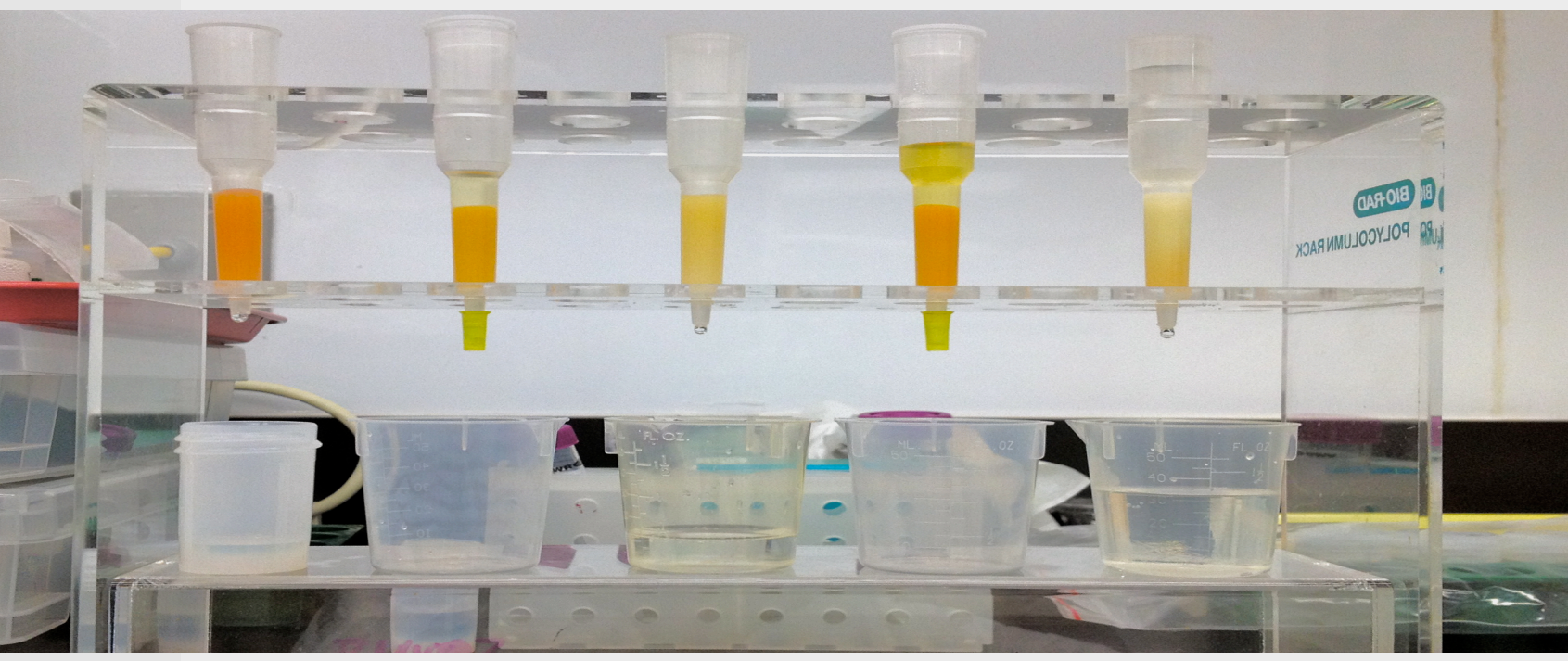
Most recently and a commonly accepted scenario as to the formation of the Moon is a collision between proto-Earth and a Mars-sized impactor. Prior simulations of the impact suggest that most of the material that formed the proto-lunar disk originated from the Mar-size impactor, rather than from the Earth. Isotopic similarities of measured isotope ratios for some elements (e.g., oxygen) between the Earth and Moon have been attributed to mixing in a vapor disk during lunar formation (Pahlevan & Stevenson, 2007). A recent study of Ti isotopes argued that the material that makes the Moon must have been derived from the Earth because they share the exact Ti isotope composition[4]. Because Ti is a refractory element, it cannot have been homogenized by vapor transport between the Earth and Moon, and so the Moon must have inherited its TI isotope signature from the Earth. This study neglected to prove that Mars had a distinct Ti isotope composition from that of the Earth and Moon. Because of the Pahlevan and Stevenson model it is important to test if it is applicable to highly refractory element like titanium. So far within their precision lunar samples and terrestrial samples show the terrestrial Ti isotopic abundances. Isotope nucleosynthetic anomalies are restricted to ^{46}Ti and ^{50}Ti while ^{47}Ti, ^{48}Ti and ^{49}Ti abundances of most meteorite samples are terrestrial. ^{46}Ti anomalies are far less abundant than ^{50}Ti so for our sample we will focus of ^{50}Ti[3].

Samples will be measured by the Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) to obtain high precision isotope ratios after purification of the Ti to eliminate isobaric interferences by ion exchange column chromatography.

EXPERIMENTAL METHOD

Figure 3-1: Anion exchange **column chromatography** using Biorad AG1-X8 resin for Ti separation

Isobaric interferences of ^{46}Ca, ^{48}Ca, ^{50}V and ^{50}Cr require that Ca, V and Cr be separated from Ti. The geostandard, BHVO-2, was doped with V and Mo for testing (Pahoehoe Iava; Fig. 3-2). Different acids with varying concentrations were used to remove separate elements:

- HF to remove matrix elements
- Weak HCl to remove V and Cr
- Strong HCl for Ti collection

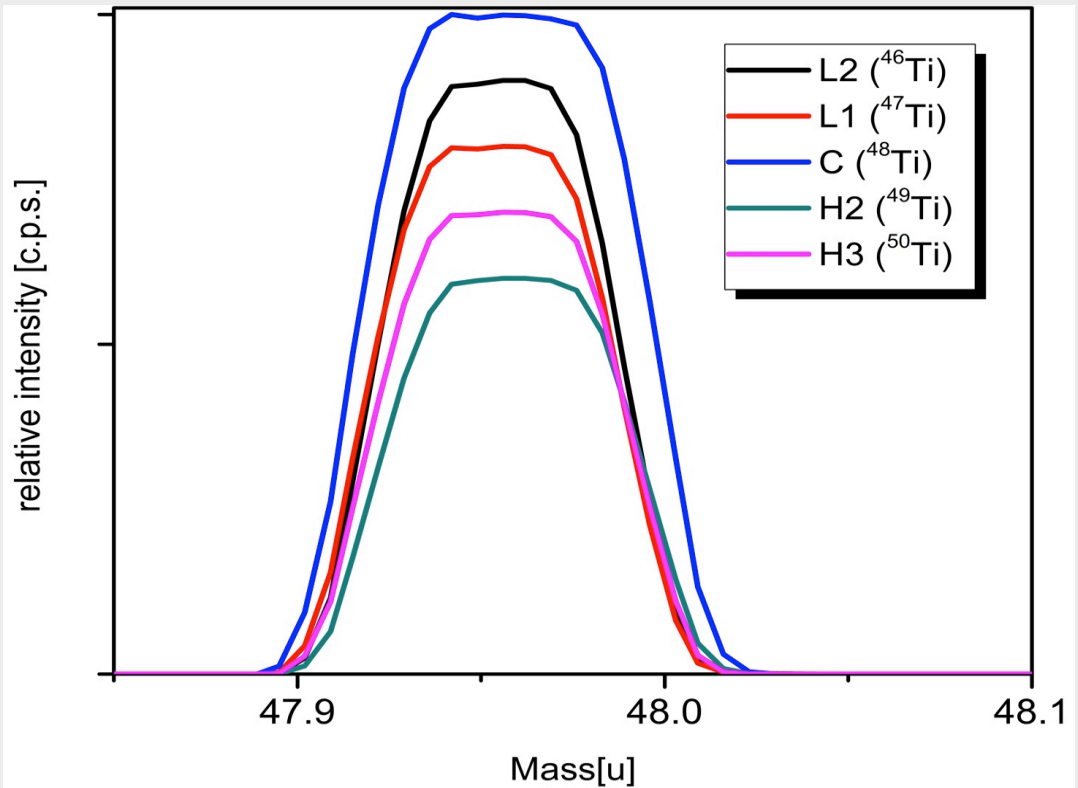

Figure 3-2: Hawaiian Pahoehoe lava.

Figure 3-3: Relative Intensities in different cups with a cup configuration with ^{48}Ti in the C-cup, ^{46}Ti at the L2, ^{47}Ti at L1, ^{49}Ti at H2, and ^{50}Ti at the H3 cup using a terrestrial titanium standard (SPEX). Obtaining an overlapping and centering of all these intensities within each other improves the accuracy and precision of each single measurement.

Figure 3-4: **Neptune (MC-ICP-MS)** used for high precision isotope measurements

The Neptune is a double focusing multi-collector that offers high sensitivity. It is equipped with nine Faraday detectors and five ion counters for studying isotopes with low signal intensities. With the high temperatures attained by the Ar plasma (~6000-8000K) virtually all elements on the periodic table are ionized to the extent of 75% or more. This makes the Neptune the appropriate mass spectrometer to measure a high refractory element such as Ti. A SIS spray-chamber as well as a Sapphire injector were used to measure our samples[5].
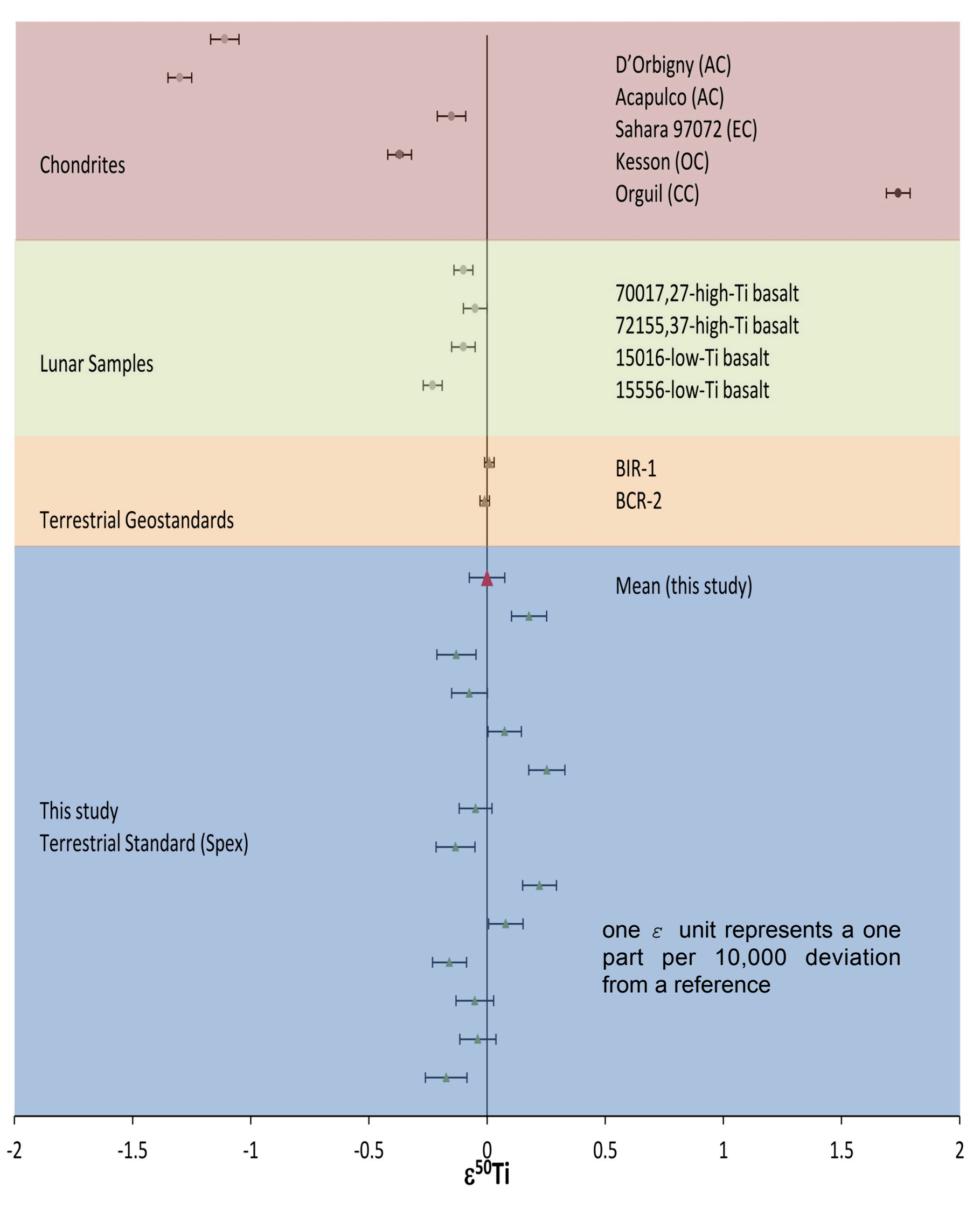
RESULTS & DISCUSSION

Chondrites
D'Orbigny (AC)
Acapulco (AC)
Sahara 97072 (EC)
Kesson (OC)
Orguil (CC)

Lunar Samples
70017,27-high-Ti basalt
72155,37-high-Ti basalt
15016-low-Ti basalt
15556-low-Ti basalt

Terrestrial Geostandards
BIR-1
BCR-2

Mean (this study)

This study
Terrestrial Standard (Spex)

one ε unit represents a one part per 10,000 deviation from a reference

Figure 4-1:
ε ^{50}Ti variation diagram normalized to ^{47}Ti/^{49}Ti=1.3775 for different samples. The error bars show the in-run 2 standard error. Preliminary measurements of the in-house terrestrial standard (Spex) gave a precision of about 0.08 2 Std. Error. For epsilon notation terrestrial samples were used as reference and therefore the terrestrial Geostandards BCR-2 and BIR-1 have ε ^{50}Ti equal to 0. Lunar samples show lower ε ^{50}Ti values where as chondrites vary from ε −1.5 (achondrites) to ε +2 (carbonaceous chondrites). Terrestrial, lunar and chondrite data are taken from Zhang et al., 2012. [4]
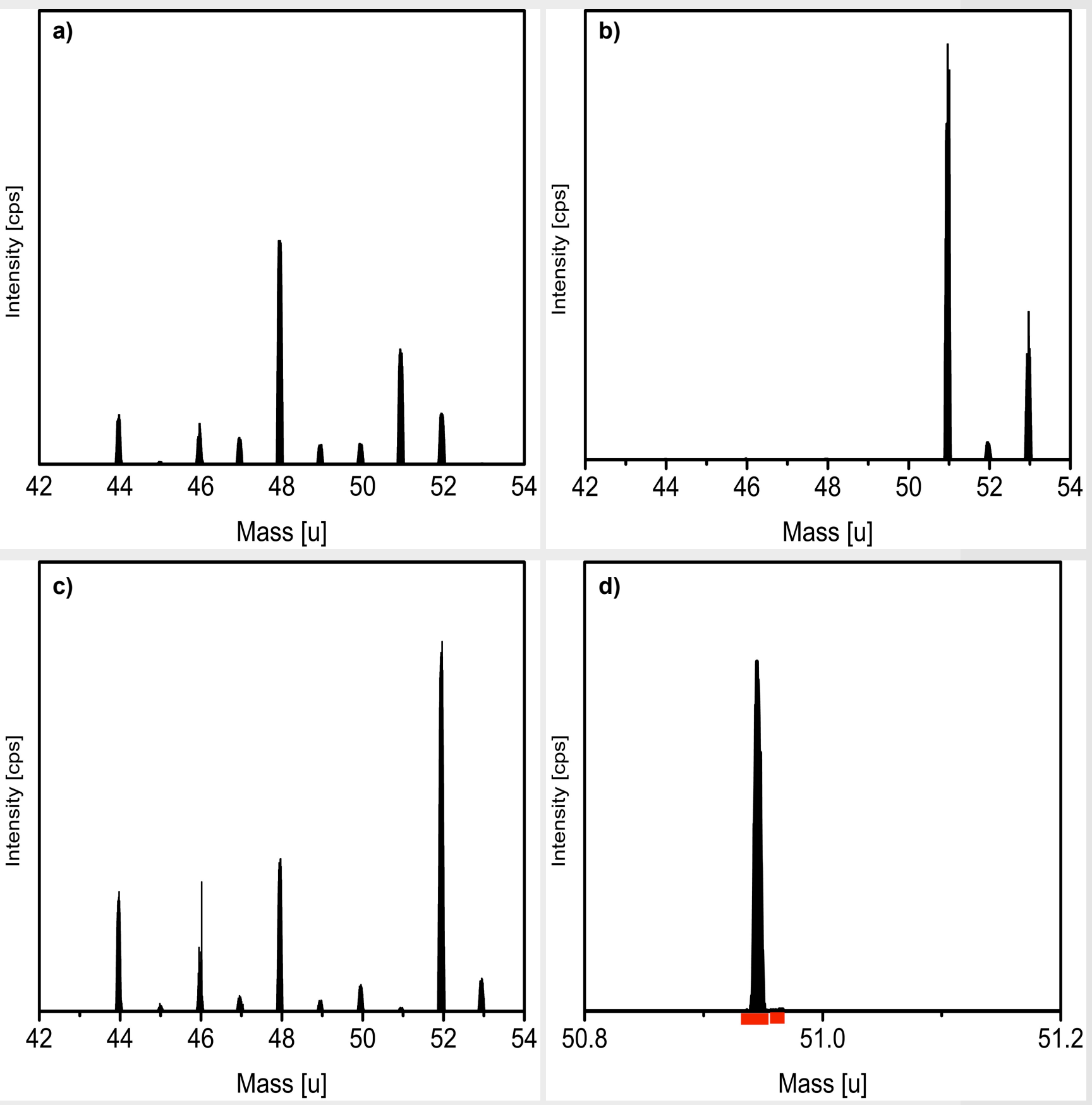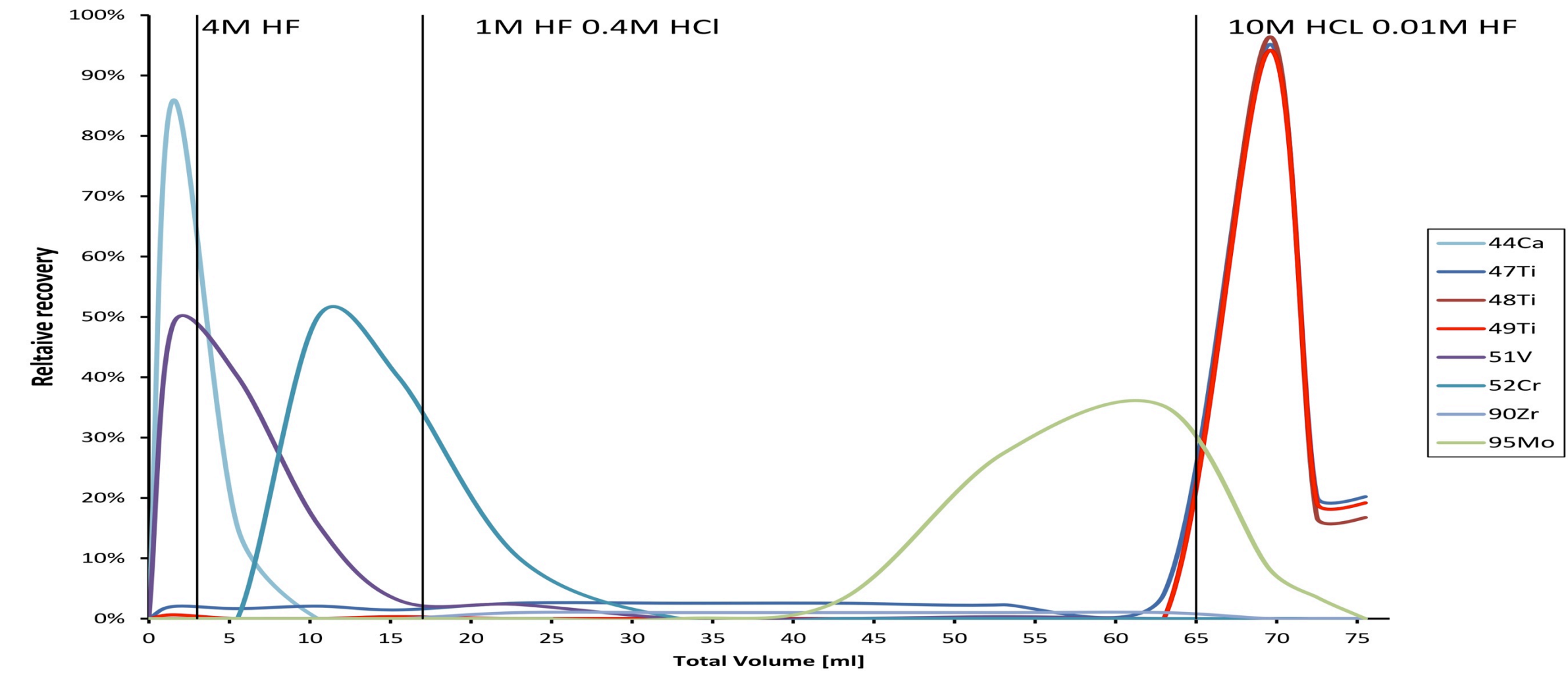

Figure 4-2:
Relative intensities of the elements Ti, V Cr, Ca measured with the Element-2 for different elution procedures used on the column. **(a)** BHVO-2 reference in low resolution. **(b)** Ti collection step of 10 M HCl/0.01 HF after being diluted in low resolution. Inference shown on the mass of 51u;
thought to be caused by ^{35}Cl^{16}O. **(c)** after drying the yield shown in figure4-1 (b) and dissolving in a new 1M HNO$_3$ 0.2M HF no intensities are measured on mass 51 u.**(d)** BHVO-2 reference again shown in medium resolution for the 51 mass range, resolving ^{51}V and ^{36}Cl^{16}O.

Figure 4-3:
Elution curves for 6 elements using AG1-X8 resin. Only elements that could cause isobaric interferences are shown. Sample was loaded in 4M HF and rinsed with 15mL 4M HF. This second step was successfully eluted. Step 3 was a rinse of 1M HF and 0.4M HCl and was used to remove Mo. Note that the volume for this step needs to be increased in order to avoid Mo being collected with Ti. Good separation of Ti was achieved with high molar HCl in the final step with no interferences from V or Cr.
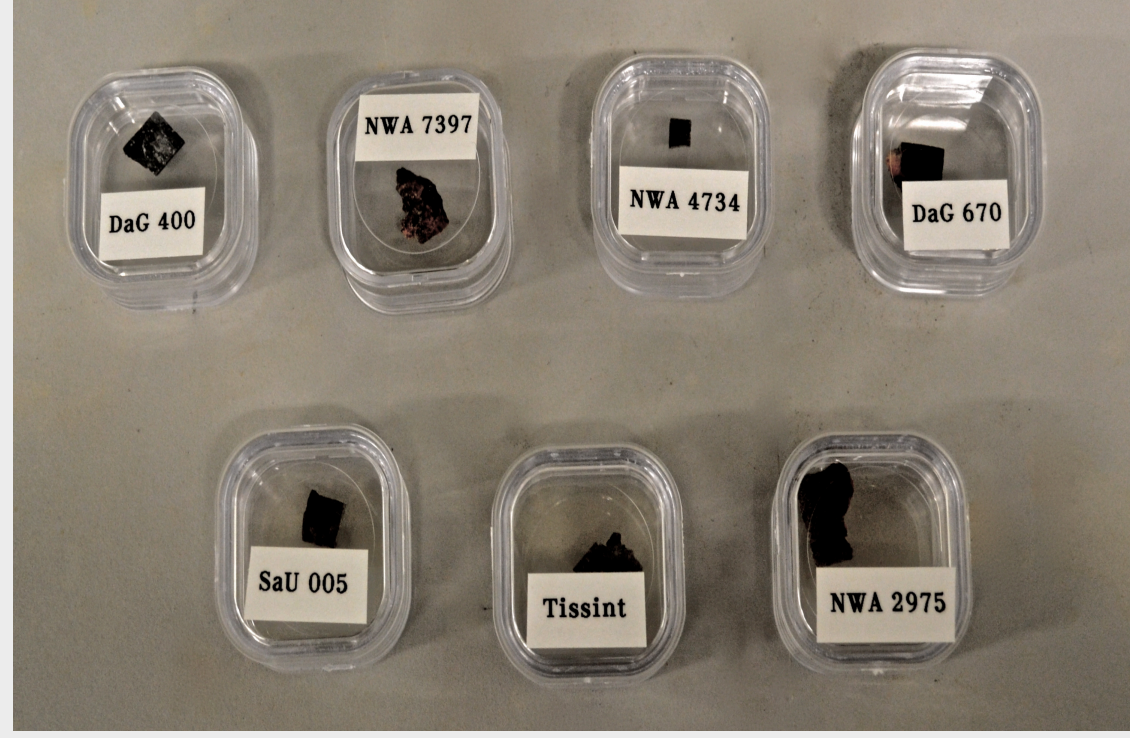

FUTURE WORK

Figure 5-1: Lunar (DAG 400) and Martian(NWA 7397,NWA 4734, DAG 670, SAU 005, TISSINT and NWA 2975) samples for upcoming work.

After we acquire high precision we begin on our Lunar and Martian samples. Exterior contamination will be removed through acid washing and polishing. The samples will then be grinded into a powder and digested by closed carius tubes at a high temperature.

ACKNOWLEDGMENTS

References

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