Student questions: SESE Postdoc Presentations

3/17/21

Hayden Miller: "Elucidating the History of the Moon's Surface - High Spatial Resolution 40Ar/39Ar Geochronology of Multigenerational Lunar Impact Melt Rocks"

How accurate is the argon-40–argon-39 dating method?

> Accuracy – our ability to determine the "correct" age – is not something geochronologists typically place specific bounds on. Since the $^{40}Ar/^{39}Ar$ method is a relative chronometer, the accuracy of an argon age is largely tied to how well we know the age of the co-irradiated neutron fluence monitor mineral. This, in turn, is controlled by how well we can determin the ^{40}K decay constant, our understanding of the nuclear reactions that occur durring irradiation, and the geologic conditions experienced by the standard and sample (i.e. few rocks cool instantly so argon diffusion kinetics often come into play). However, we do estimate the uncertainty assoicated with our age determination. This uncertainty is controlled by our analytical precision (i.e. how reproducible our argon measurements are) and how well we know the ^{40}K decay constant. Under ideal conditions, we are capable of producing argon dates with analytical uncertainties of 0.1%. The uncertainties associated with some of the age determinations I discussed are as high as a few percent, which is the result of very low K abundances and small analytical volumes that produce gas signals only a few times higher than the instrument's background abundances.

In your slides, you showed your rock samples from the moon using an electron microscope. The sample marked A shows some white spots in the section. What are they - are they minerals caused by the extreme heat and pressure from the impact on the sample or is it just showing some type of extinction under the microscope?

> The black and white images I showed are produced from backscattered electrons. Unlike a traditional microscope that utilizes light in the visible spectrum, a scanning electron microscope uses a focused electron beam. This electron beam is fired at a sample and the way in which these electrons are scattered while interacting with the matter is governed by the elements present (i.e. their atomic mass). High-mass elements manifest as 'bright' spots in the image. The white spots are predominantly the iron titanium oxide mineral ilmenite – $FeTiO_3$.

The impressive sensitivity and high spatial resolution of your laser-based analytical technique doesn't seem to match the significantly lower resolution of the electron microprobe that you use for your initial characterization. What am I missing?

> The x-ray elemental mapping is done with a low beam current (10 nA) and a larger beam diameter (20 microns) so it produces a lower resolution image / map. The reason for this is that there is some concern in the argon community that higher beam intensities may lead to thermally activated diffusion (i.e. loss of radiogenic argon). In particular, our samples are mounted with superglue when they are cut and polished (superglue is used because the mounting medium must be removed before introducing the sample to the noble gas mass

spectrometer and superglue easily dissolves in acetone) and vesicular regions may expose the probe beam directly to that superglue, which could cause heating induced by the lower thermal conductivity of the glue. Kip and I are not actually convinced this is a significant problem but, as it currently stands, if we tried to map at really high resolution then a reviewer could not like the fact that we are reporting ages younger than the expectation (of Imbrium) and cite diffusive ^{40}Ar loss during ion probe mapping as the reason. This isn't a hard thing to demonstrate is less of a concern than some think but unfortunately we just haven't gotten around to it yet. All in all, the low resolution reduces the wow factor of the maps but it is good enough for UVLAMP targeting purposes.

How does this quantitative method of dating the moon with Ar line up with a more qualitative method such as superposition?

Ultimately, any radiometric age provides considerably more information than a qualitative determination. For example, you do not need an age determination to know Spur Crater, which sits on the Apennine Mountain front, must be younger than the Imbrium impact event that formed the Apennine Mountains. But radiometric ages allow us to constrain the Imbrium image to ca. 3900 Ma and Spur Crater to 250 Ma.

What are the implications of the results of the dating of 15455 and 15445 samples for the LHB in terms of being a precedent inconsistent with the expectation of the planetary geological community?

One of the things that the Lunar Reconnaissance Orbiter has shown is that craters as small as 100 meters in diameter have melt sheets on their floor, meaning it is quite easy to produce impact melt on the surface of the moon. As a geochronologist, I believe we have to honor the ages we have determined (3.66 Ga melt in 15445 and 3.80 Ga melt in 15455). These ages are younger than our expectation for Imbrium and suggest these two samples may post-date the large Imbrium basin forming impact. The work I presented is part of a growing body of research showing lunar impact melt breccias record a prolonged history of bombardment, with many ages both older and younger the hypothesized LHB. These ages are produced from chronometric methods with high spatial resolution (e.g. UVLAMP Ar/Ar or SIMS U-Pb) and challenge the LHB hypothesis. I don’t believe we can outright reject the occurrence of a LHB yet, but I do believe we should treat it as the hypothesis it is rather than a given occurrence.

What is the composition that corresponds to the 405 dark matrix from 15455 sample with an average age near 4000 Ma (there was a figure displayed during the presentation)?

The dark-colored impact melt present in 15455,383, 15455,405, and 15445,343 have a groundmass (i.e. matrix) composition dominated by plagioclase and olivine. Suprisingly little pyroxene is present, a mineral that is typically found in lunar impact melts.

Is there any way to get the laser resolution smaller so you can analyze the fine grains of the lunar samples?

> We are already pushing the limits of our current analytical abilities (hence the uncertainties that are sometimes >1%). Noble gas mass spectrometers have largely remained the same for 70 years. However, the instrument in Group 18 laboratories here at SESE that was used for this study is over ten years old and there have been some notable improvements in the electronics of instruments such as this over that time. When we make an argon measurement, we ionize the argon atoms, accelerate those ions through a magnetic field to create spatial separation between the different mass isotopes (think of this as effectively an angular momentum filter), and then measure the voltage of each (now separated by mass) ion beam. If you remember back to Ohm's Law, Voltage = Current * Resistance. So if we have a bigger resistor then we can have a smaller current (i.e. less ions produced from the sample) and still measure the same voltage. Another advance has resulted from constructing smaller ion beam collectors. Single collector instruments require either changing the arc of the ion beam (by altering the magnetic field) or physically changing the position of the ion collector. Smaller collectors allow for multiple to be placed next to each other. Simultaneous collection of all isotopes of interest reduces the time necessary for a measurement cycle, which improves precision. We have submitted a proposal to acquire a state-of-the-art instrument such as this, which would let us reduce the volume of material needed for an age determination. Fingers crossed the proposal is funded!

You mentioned the Apollo sample 15405 was a comingled sample. I have heard other samples referred to like that but I'm not sure I understand what it means. Does it mean the other 2 samples (Apollo 15, station 4, samples 45 and 55) were returned in the same bag, and 15405 came from the dust upon return?

> The two samples discussed, 15445 and 15455 (which were both actually collected at Station 7, the naming schemes do not always make sense!) were both rock fragments collected and handled separately. Upon return, NASA allocates smaller portions of these samples to researchers and gives these allocations a subname. The samples I worked on here are 15445 (subsample 343), and 15455 (subsample 383, 386, and 405). Subsample 383 entirely consists of impact melt breccia. Subsample 386 is entirely plutonic rock. And I describe subsample 405 as co-mingled to say that there are regions of impact melt and plutonic rock intermixed at the millimeter scale. The textural relationship between the impact melt and plutonic rock was the result of geologic processes on the lunar surface, not sample handling by astronauts or researchers.

Was there a reason for meteorites thinning out over time?

> Asteroids (and their smaller meteoroid brethren) formed from the original solar nebula. They are the solid surface objects that did not accrete into rocky planets. Over time, through gravitational interactions with the sun and planets, they were either swept up (i.e. collided with the planets or sun), were ejected from the solar system, or had their orbits stabilized in the asteroid belt. Since no new asteroids have formed since the condensation of the original

solar nebula, these gravitational processes have gradually decreased the number of asteroids in the inner Solar System that could impact the rocky planets.

You mentioned that the geologic history represented on the moon has implications for the formation of life on Earth but what are these implications?

The flux of impactors (spike in delivery, i.e. Late Heavy Bombardment, vs. gradual decline) has implications for the habitability of the surface of the Earth in its early history. A significant spike in the number of impactors has been hypothesized to be capable of producing a planet wide melt sheet that could sterilize the surface of the Earth. While a graduate decline may have resulted in impactors triggering localized hydrothermal systems, which could have provided regions of habitability.