PULLING MARBLES FROM A BAG: DEDUCING THE REGIONAL IMPACT HISTORY OF THE SPA BASIN FROM IMPACT-MELT ROCKS. B. A. Cohen and R. F. Coker, NASA Marshall Space Flight Center, Huntsville AL 35806 (Barbara.A.Cohen@nasa.gov).

Introduction: The South Pole–Aitken (SPA) basin is the stratigraphically oldest identifiable lunar basin and is therefore one of the most important targets for absolute age-dating to help understand whether ancient lunar bombardment history smoothly declined or was punctuated by a cataclysm. A feasible near-term approach to this problem is to robotically collect a sample from near the center of the basin, where vertical and lateral mixing provided by post-basin impacts ensures that such a sample will be composed of small rock fragments from SPA itself, from local impact craters, and from faraway giant basins. The range of ages, intermediate spikes in the age distribution, and the oldest ages are all part of the definition of the absolute age and impact history recorded within the SPA basin.

Impact melt in a scoop sample: SPA near-surface materials are a mixture of original SPA rocks, reworked SPA material from interior basins, and exogeneous material. Because ejecta deposition is a ballistic process, successive ejecta deposits excavate and mix the target substrate with the ejected material. Within the SPA basin, about 20% of the regolith at the site is foreign [1, 2], but much of the foreign material will not be impact melt, but cold ejecta. We calculated the fraction of contributed material that is likely to be impact melt using scaling laws in the literature related to the transient crater diameter (D_{tc}). These scaling laws are not proven to be valid in the largest basin-sized impacts such as Imbrium, but are used here as a starting point. The fraction of melt in each ejecta deposit (F_{melt}) can be expressed as the volume of impact melt created by the basin (V_{melt}) [3] $\times$the fraction of melt ejected from the basin (Efficiency) [4] / the total amount of ejecta (V_{ej}) [5]. F_{melt} can then be applied to the contribution by each basin at any site to estimate the relative fraction of impact melt rocks derived from each basin (Table 1).

In a sieved sample, 1 kg of rock fragments greater than 2 mm would yield some 10,000 2-4 mm particles, over 3000 4-10 mm fragments, and a significant number of rocklets >1 cm. Table 1 shows P_{melt}, the number of particles expected to be impact melt from each event in a sample of 15,000 fragments. This number is probably only good to an order of magnitude, but illustrates that SPA melt is by far the dominant impact-melt rock likely to be present.

Sampling statistics: On the lunar near side, mixing of ejecta and local bedrock has led to some ambiguity in the origin of specific impact-melt rock groups, because we do not have definitive information on the composition of the basin floors. In contrast, the unique geochemical signature of SPA materials links impact melt rocks to the SPA basin and subsequent interior basins and craters. It is likely that melt fragments will be grouped based on their petrography, geochemistry, mineralogy, and spectroscopy, and that perhaps only a few fragments from each group will need to be dated to recover the age of an event. However, we constructed a simple statistical model to understand how many randomly-selected impact-melt fragments would need to be dated, and with what accuracy, to confidently reproduce the impact history of a site, using the site and impact events chosen by Haskin [6].

Each basin event was assigned an age (A) and an uncertainty (σA) that represents the actual spread of ages a rock created in that event might have. The ages of Serenitatis, Imbrium, and Orientale are relatively precisely known [7]; the others are straw ages for illustration. A melt sheet the size of SPA might be expected to yield rocks with a relatively wide spread in ages as the sheet cooled, thus its higher σA.

A sample set of 2000 "marbles" was apportioned according to the melt fraction at the model site and assigned an age using a random number generator with a normal distribution corresponding to A$\pm\sigma$A. Each marble was also assigned an uncertainty from a distribution U$\pm\sigma$U, corresponding to a laboratory

Table 1: Calculated impact melt abundance and provenance at model site

Basin	D (km)	D_{tc} (km)	V_{ej} (km^3)	V_{melt} (km^3)	Efficiency (%)	F_{melt} (%)	Contribution (%)	P_{ejecta} (15000)	P_{melt}
SPA	2500	1035				50	82.0	12300	6150
Australe	880	426	1.01E+07	1.89E+06	41	7.6	1.7	255	19
M-R	630	321	4.32E+06	6.33E+05	42	6.2	1.5	225	14
Serenitatis	920	443	1.13E+07	2.18E+06	40	7.8	4.0	600	47
Bhaba	64	46	1.27E+04	3.56E+02	52	1.5	0.5	75	1
Imbrium	1160	539	2.05E+07	4.66E+06	39	9.0	6.5	975	87
Orientale	930	447	1.17E+07	2.26E+06	40	7.8	4.0	600	47

measurement uncertainty. A reference data set consisting of 2000 particles, each having the exact ages A±σA represented the "true" impact history. Marbles were randomly selected from the set and plotted on ideograms (Fig. 1). Subsets of 100, 1000, and 2000 marbles were selected and added together to compare the model datasets with the "true" distribution.

Scenario 1, with a large σA but small U, was run multiple times, because the discreteness of each sample curve sometimes flattened the ideogram peak, or even produced false subpeaks. Scenario 2 appears less discretized, aiding in determining A but masking differences in events that have a small ΔA. In Scenario 3, the reference set is rapidly reproduced with only a few hundred marbles. However, younger basins are still hard to recognize because only a few marbles represent them. If the reference set has half the SPA marbles removed, and the rest renormalized, the younger basins become more apparent, but the data still do not resolve the difference between them. It will be crucial to have more information (e.g. compositional, mineralogical, remote sensing) to cluster fragments with the same age as each other.

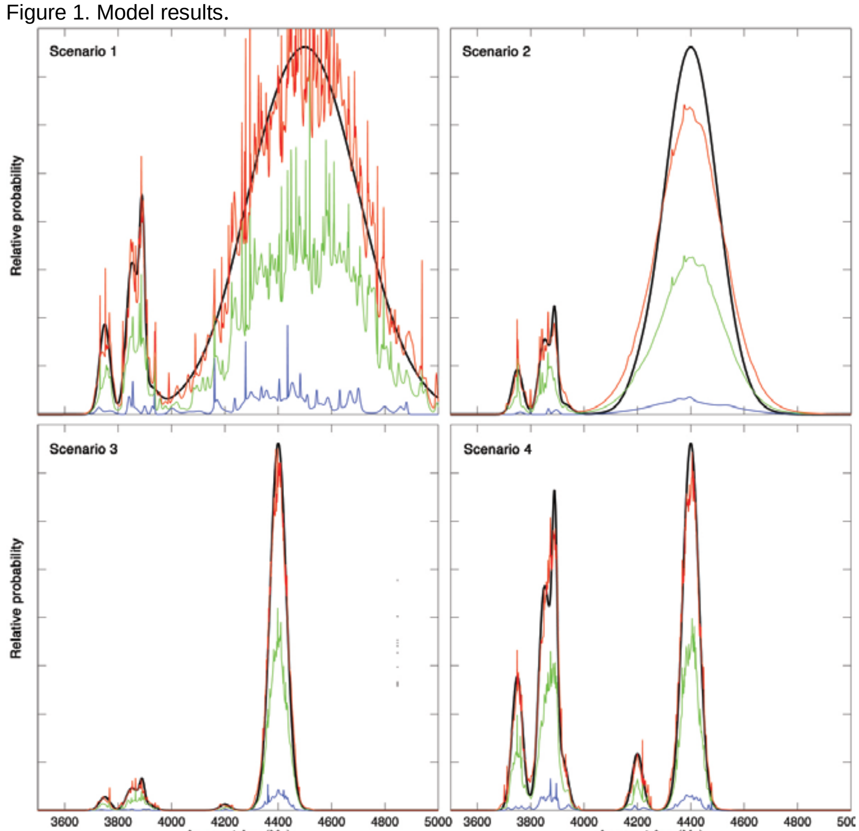
We plan to extend this simple model to any location by generalizing the to all large lunar basins as well as young, local events that dominate material derived from the upper surface [8]. A robotic sample should dig past this top layer, but will certainly contain many fragments from hundreds of successive nearby events. Also necessary is application of statistical tests by which individual impact event ages can be assigned to groups of samples, such as fitting to a normal distribution function [9]. However, these exercises show that SPA melt has a high probability of being present in a robotic scoop sample and that even if it weren't recognizable by geochemical or petrologic means, dating of a few thousand impact-melt fragments will still yield the age of the SPA basin from such a sample.

References: [1] Haskin, L.A., *et al.* (2003) *MAPS* 38, 13. [2] Petro, N.E. and C.M. Pieters (2004) *JGR-Planets* 109, doi 10.1029/2003JE002182. [3] Cintala, M.J. and R.A.F. Grieve (1998) *MAPS* 33, 889. [4] Warren, P.H. (1996) *LPSC* 27, 1381. [5] Collins, G.S., *et al.* (2005) *MAPS* 40, 817. [6] Haskin, L.A., *et al.* (2003) *LPSC* abstract #1434. [7] Stöffler, D. and G. Ryder (2001) *Space Science Reviews* 96, 9. [8] Cohen, B.A., *et al.* (2005) *MAPS* 40, 755. [9] Muller, R.A. *et al.* (2000) in *Accretion of Extraterrestrial Matter Throughout Earth's History*, ed B. Peucker-Ehrenbrink and B. Schmitz, Kluwer Publishers.

Table 2. Model run parameters

Basin	A ± σA (Ma)	U ± σU (Ma)	#
Scenario 1			
SPA	4400 ± 100	10 ± 10	1800
Australe	4200 ± 40	5 ± 10	19
M-R	3920 ± 30	5 ± 10	16
Serenitatis	3890 ± 10	5 ± 10	44
Bhaba	3870 ± 10	5 ± 10	5
Imbrium	3850 ± 20	5 ± 10	71
Orientale	3750 ± 20	5 ± 10	44
Scenario 2			
SPA	4400 ± 100	70 ± 30	1800
Australe	4200 ± 40	30 ± 15	19
M-R	3920 ± 30	10 ± 10	16
Serenitatis	3890 ± 10	10 ± 10	44
Bhaba	3870 ± 10	10 ± 10	5
Imbrium	3850 ± 20	10 ± 10	71
Orientale	3750 ± 20	10 ± 10	44
Scenario 3			
SPA	4400 ± 30	10 ± 10	1800
Australe	4200 ± 20	5 ± 10	19
M-R	3920 ± 20	5 ± 10	16
Serenitatis	3890 ± 10	5 ± 10	44
Bhaba	3870 ± 10	5 ± 10	5
Imbrium	3850 ± 20	5 ± 10	71
Orientale	3750 ± 20	5 ± 10	44
Scenario 3			
SPA	4400 ± 100	10 ± 10	948
Australe	4200 ± 40	5 ± 10	98
M-R	3920 ± 30	5 ± 10	87
Serenitatis	3890 ± 10	5 ± 10	231
Bhaba	3870 ± 10	5 ± 10	29
Imbrium	3850 ± 20	5 ± 10	376
Orientale	3750 ± 20	5 ± 10	231

Figure 1. Model results.



Pulling marbles from a bag: Deducing the regional impact history of the SPA basin from impact-melt rocks

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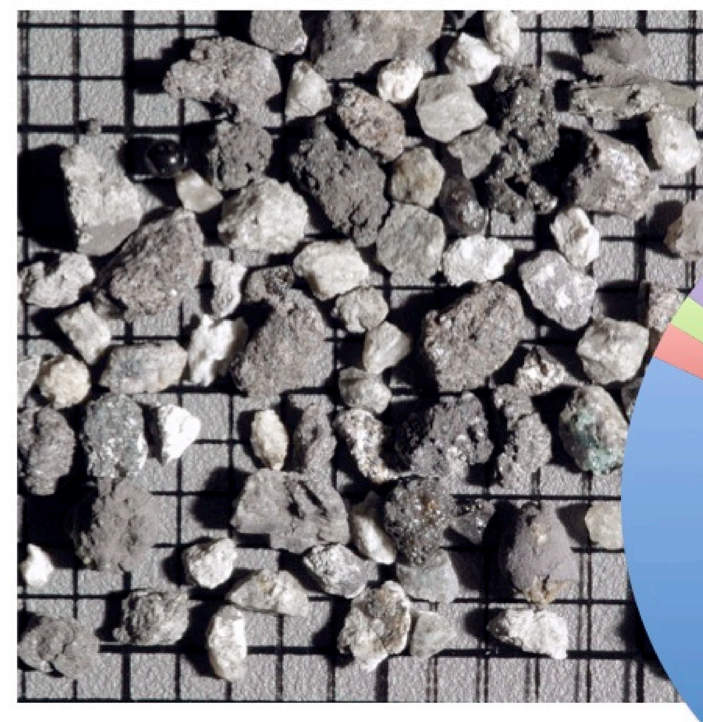
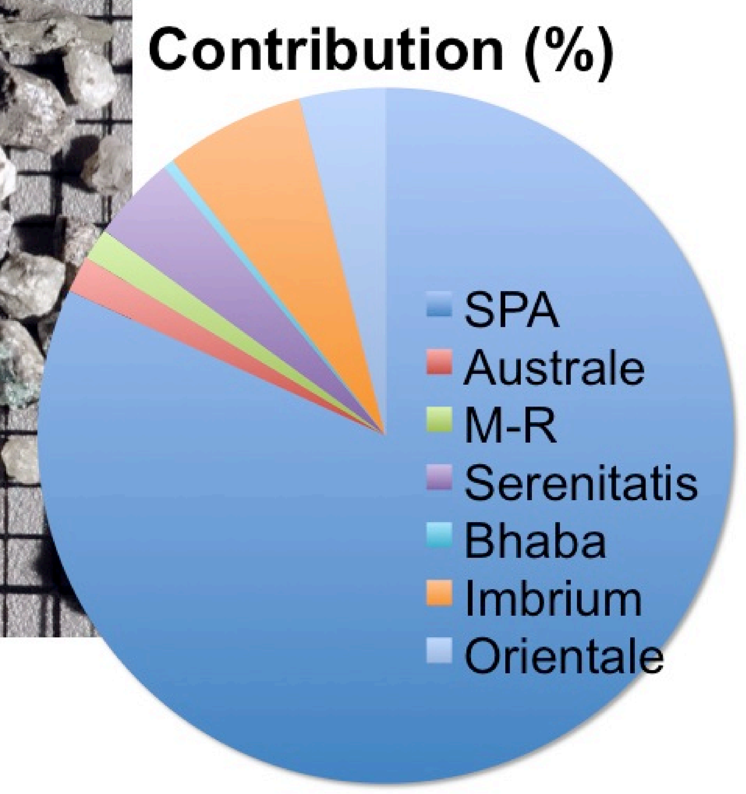
Introduction

- **South Pole–Aitken (SPA) basin is an important target for absolute age-dating to constrain ancient lunar bombardment history**
- **After formation, SPA surface materials became a mixture of original SPA floor rocks, reworked SPA material from interior basins, and exogeneous material**
- **This is a different starting point from Apollo sites - SPA floor is the substrate; remote sensing sees a unique SPA geochemical signature**
- **The range of ages, intermediate spikes in the age distribution, and the oldest ages are all part of the definition of the absolute age and impact history recorded within the SPA basin**





Provenance of melt rocks

- Because ejecta deposition is a ballistic process, successive ejecta deposits excavate and mix the target substrate with the ejected material
- Ejecta and mixing models (Haskin et al. 2003, Petro & Pieters 2004) show ~20% of SPA regolith is foreign – but much of the foreign material will be cold ejecta, not impact melt rocks
- Fraction of material that is likely to be non-SPA impact melt using scaling laws:

$$F_{melt} = (V_{melt} / V_{ejecta}) \times E$$

Volume of impact melt (Cintala & Grieve 1998)	Volume of ejecta (Collins 2005)	Efficiency, or Fraction of melt ejected (Warren 1996)

- One can use these relationships to calculate the volumetric amount of impact-melt rocks at any site
- Combine with mixing models to calculate the proportion at the site
- Calculations shown here are for the SPA site in Haskin et al. 2003

Age history of melt rocks

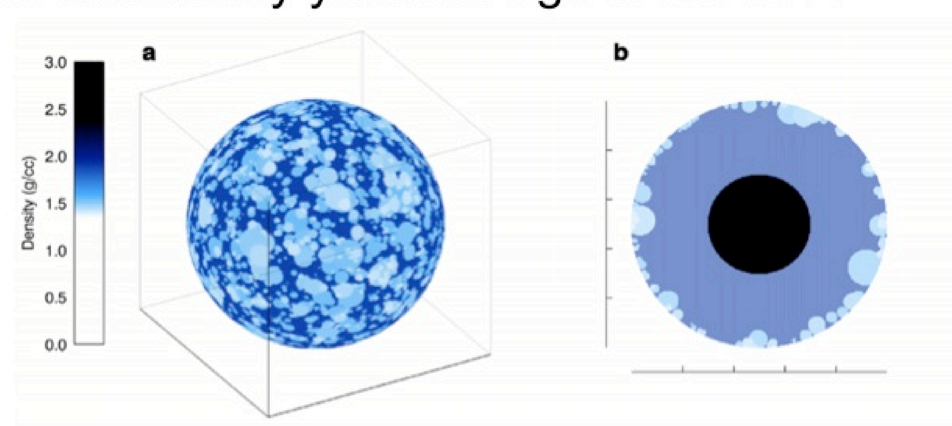
- If you randomly dated 2000 impact melt-rocks from this site, what would the age distribution look like?
- **Reference dataset**: Age (A) of 7 basins
  ± σA represents the range in real ages for a single event (e.g. slow cooling)
- **Model dataset:** 2000 impact-melt rocks apportioned according to the calculated melt fraction at the model site
  Assigned a sample age (A ± σA) from within the normal distribution σA
  Assigned an uncertainty (U ± σU) associated with laboratory measurement

Conclusions

- SPA-floor impact melt exists at interior landing sites and will be the dominant impact-melt rock type in any sample
- Corroborating information (petrology, elemental composition, regional context, RS) are important to correct interpretation
- Even if it weren't recognizable by geochemical or petrologic means, dating of a few thousand impact-melt fragments is still likely to statistically yield the age of the SPA basin

Future Work:

- A fuller regolith model to track the distribution of impact melt rocks from distant basins and young, local events
- A statistical test by which individual impact event ages can be assigned to groups of samples, such as a simple signal-to-noise threshold or fit to a normal distribution



Future work includes a full three-dimensional Monte Carlo model of impact-melt redistribution, proposed with Amy Barr and Clark Chapman at SwRI. The proposed 3D megaregolith model will run on the same numerical "backbone" as the core formation model applied to Saturn's moon Titan (after Barr and Canup, 2010). Shown here is the density (colors) of Titan's surface as a function of latitude and longitude after its bombardment by 3×10^{23} g of comets during an outer solar system late heavy bombardment. Dark blue indicates mixed ice and rock; light blue indicates ice-rich regions.

Basin	Diameter (km)	Volume of material ejected (km^3)	Volume of material melted (km^3)	Efficiency (%)	Fraction of impact-melt material ejected from each basin (%)	Contribution of basin ejecta to the study site (%)	For 15000 random fragments, # derived from each basin	For 15000 random fragments, # impact melt derived from each basin
SPA	2500				50	82.0	12300	6150
Australe	880	1.01E+07	1.89E+06	41	7.6	1.7	255	19
M-R	630	4.32E+06	6.33E+05	42	6.2	1.5	225	14
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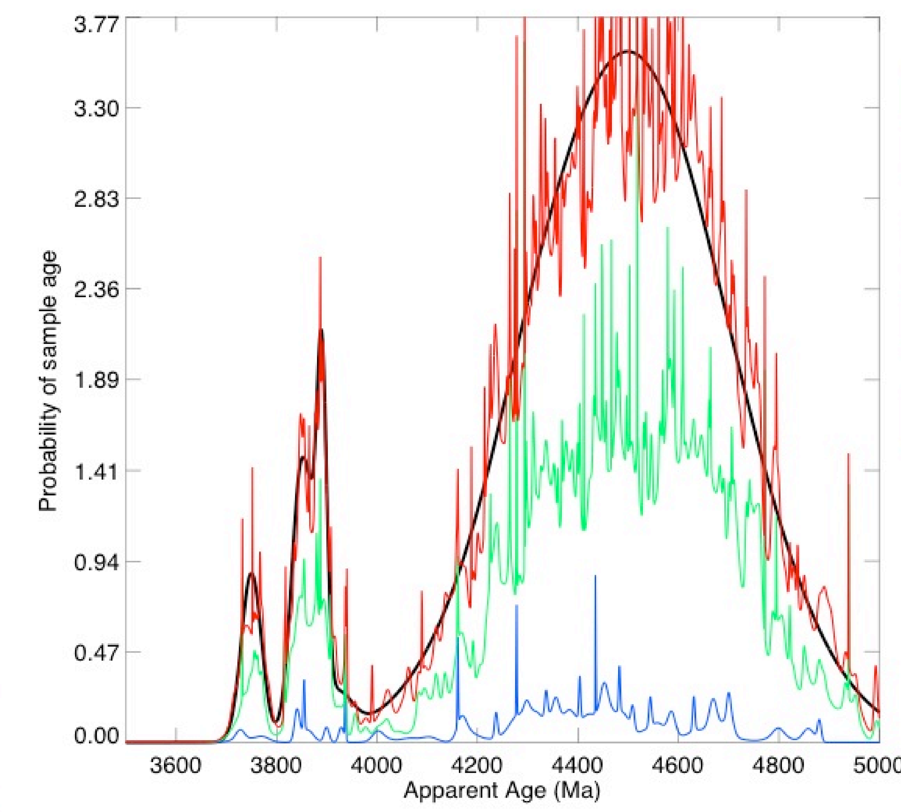
Orientale	930	1.17E+07	2.26E+06	40	7.8	4.0	600	47

Model results (so far)



Scenario 1

Basin	A ± σA (Ma)	U ± σU (Ma)	#
SPA	4400 ± 100	10 ± 10	1800
Australe	4200 ± 40	5 ± 10	19
M-R	3920 ± 30	5 ± 10	16
Serenitatis	3890 ± 10	5 ± 10	44
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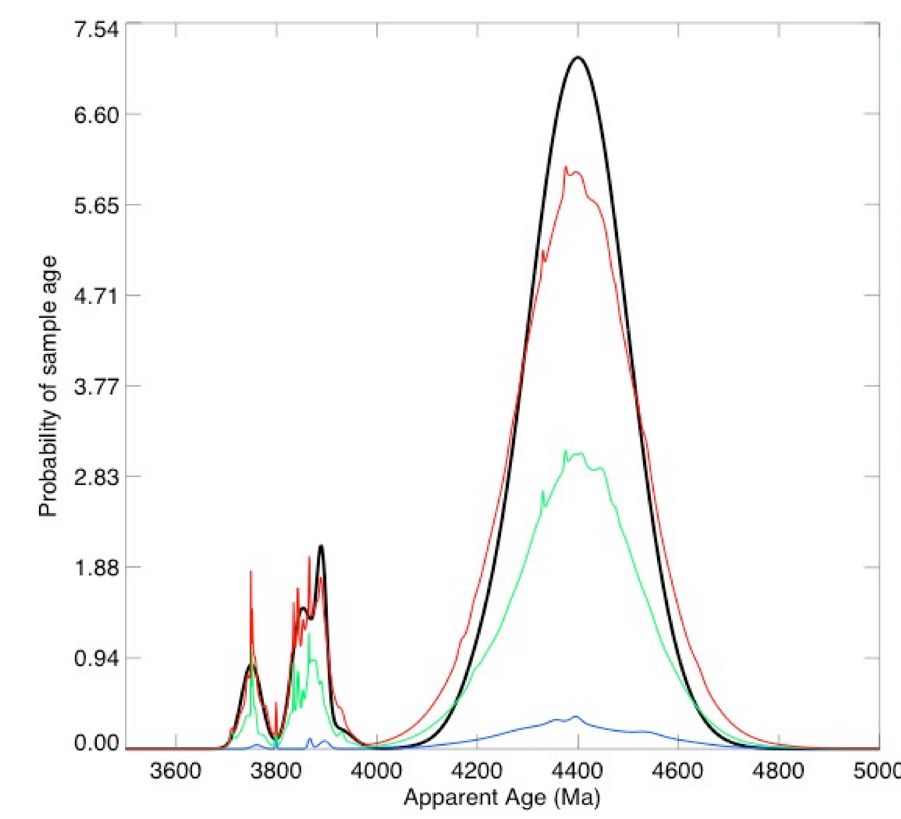
Imbrium	3850 ± 20	5 ± 10	71
Orientale	3750 ± 20	5 ± 10	44

Large σA small U

Small U discretizes the curve, sometimes flattening the ideogram peak, or even producing false subpeaks.

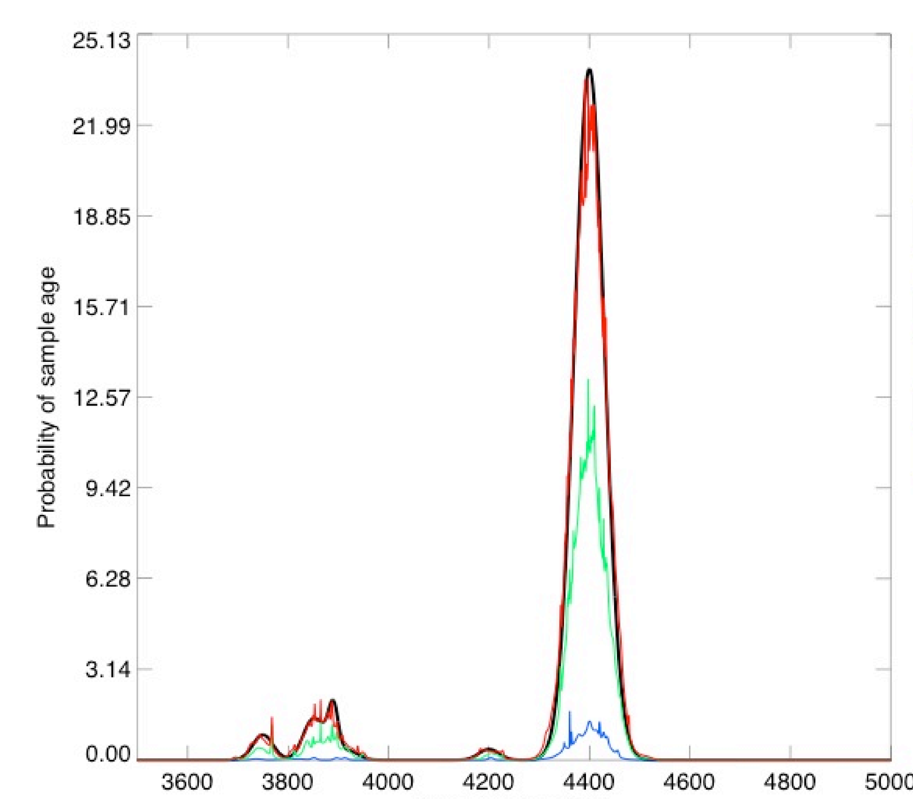


Scenario 2

Basin	A ± σA (Ma)	U ± σU (Ma)	#
SPA	4400 ± 100	70 ± 30	1800
Australe	4200 ± 40	30 ± 15	19
M-R	3920 ± 30	10 ± 10	16
Serenitatis	3890 ± 10	10 ± 10	44
Bhaba	3870 ± 10	10 ± 10	5
Imbrium	3850 ± 20	10 ± 10	71
Orientale	3750 ± 20	10 ± 10	44

Large σA, large U

Large U smooths the curve, more faithfully reproduces A but can mask events with small ΔA

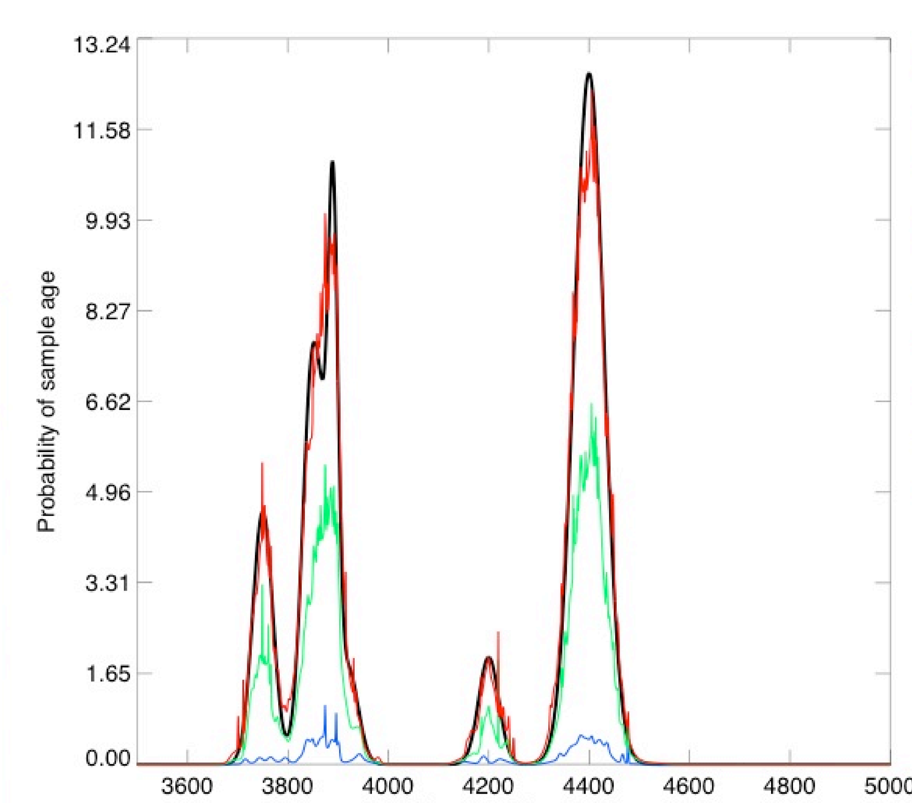


Scenario 3

Basin	A ± σA (Ma)	U ± σU (Ma)	#
SPA	4400 ± 30	10 ± 10	1800
Australe	4200 ± 20	5 ± 10	19
M-R	3920 ± 20	5 ± 10	16
Serenitatis	3890 ± 10	5 ± 10	44
Bhaba	3870 ± 10	5 ± 10	5
Imbrium	3850 ± 20	5 ± 10	71
Orientale	3750 ± 20	5 ± 10	44

Small σA, small U

Reference set reproduced with only a few hundred marbles, but younger basins are hard to recognize because only a few marbles represent them



Scenario 4

Basin	A ± σA (Ma)	U ± σU (Ma)	#
SPA	4400 ± 100	10 ± 10	948
Australe	4200 ± 40	5 ± 10	98
M-R	3920 ± 30	5 ± 10	87
Serenitatis	3890 ± 10	5 ± 10	231
Bhaba	3870 ± 10	5 ± 10	29
Imbrium	3850 ± 20	5 ± 10	376
Orientale	3750 ± 20	5 ± 10	231

Small σA, small U, fewer SPA

Same as Scenario 3 but reference set removes half the SPA samples and renormalizes the rest so the younger basins become more apparent