

STATISTICAL ANALYSIS OF APOLLO BASALT WHOLE ROCK COMPOSITIONS REVEALS FOUR COMPOSITIONALLY DISTINCT LAVA GROUPS. A. J. Gawronska¹, A. Chamroontaneskul², M. R. Hughes³, C. L. McLeod¹, ¹Department of Geology and Environmental Earth Science, Miami University, Oxford OH, 45056. ²Cincinnati Children's Hospital Medical Center, Cincinnati OH, 45229. ³Department of Statistics, Miami University, Oxford OH, 45056. (gawronaj@miamioh.edu).

Introduction: As products of mantle melting, basaltic magmas provide insight into mantle source region compositions and mantle differentiation processes [1]. On the Moon, it was the evaluation of mineral textures and chemistries in the Apollo 11 basaltic suite that underpinned the initial Lunar Magma Ocean theory, broadly accounting for the range of lunar rock types produced during primordial lunar differentiation [2-3]. Since then, much of the work aimed at understanding the composition of the lunar mantle has relied significantly on detailed analysis of whole rock compositions of the Apollo basalt suite. Through this, researchers concluded that the greatest compositional differences are associated with TiO₂, Al₂O₃, and K₂O, and rare earth element abundances (see summary in [4]). Different depth of melting, degree of partial melting, and/or distinct assimilation/fractional crystallization processes have been used to explain these variations [i.e., 4]. These interpretations may become better informed on a Moon-wide scale by applying statistical analyses to the range of compositional differences observed [i.e., 5]. In this work, we applied principal component analysis (PCA; [6]), and cluster analysis to statistically evaluate these compositional variations throughout the Apollo lunar basalt suite.

Methods: This project utilized whole rock data stored in the Astromaterials Data System (<https://www.astromat.org/>). Descriptions from the Lunar Sample Compendium [7] were used to split samples into previously defined lithological suites, which generated 26 distinct groups (see Fig. 1). This data was then split into two datasets: major elements (Table 1; n_{samples}=319), and trace elements (Table 2; n_{samples}=202). This ensured that analysis of the differences between trace elements would not be skewed by the more elevated major element contents.

PCA was performed to identify patterns across the compositional elements to help determine the general structural "components" that explain the bulk of the variation within each multi-element dataset. Data were standardized prior to performing PCA by subtracting the mean composition from each individual sample content and dividing this by the element's standard deviation. Next, hierarchical clustering using Ward's linkage was performed on the extracted principal components to determine which samples cluster into distinct groups

based on these compositional components. All analyses were performed using R statistical software.

Results and Discussion: Within the framework used here, each PCA component is a unique linear combination of all element proportions, determined such that the first component maximally explains the variability in chemical composition, with subsequent components determined in like fashion contingent on being independent of other components. PCA indicated that variability in major elements is best summarized by four components, while variability in trace elements is best summarized by three components (Tables 1-2). Each of these components specifically corresponds to distinct associations in element signatures, referred to as loadings. A few particularly distinct relationships were found. As summarized by component 2, some of the highest Si contents are weakly positively correlated with Al, K, and P, but more strongly negatively associated with Ti, while component 3 suggests that increasing Si content can also be associated with increasing Al, Fe, and Mn, and decreasing Ti, K, P. These distinct correlations may represent distinct petrogenetic evolutionary histories for lunar basaltic magmas. In terms of trace elements, component 1 may summarize the general variation in lunar basaltic compositions, with component 2 summarizing variation resulting from inclusion of more primitive magmas (with elevated Cr), and component 3 summarizing variation in the dataset corresponding to more evolved compositions (i.e., elevated La and Ce which are negatively correlated with all other trace elements studied).

Clustering work suggests that based on separate analyses of both major and trace element contents, Apollo basaltic samples cluster in four groups. Apollo 11 and 17 samples form one cluster (cluster 1), which is defined by high Ti and low Si contents (Fig. 2), suggesting that the role of TiO₂ phases was significantly distinct during lunar magmatic evolution. Cluster 2 is defined by Apollo 12 and 15 samples with higher Si, Al, Ca, and Na contents, while cluster 3 is made up of primarily Apollo 12 and 15 samples of more mafic composition (Fig. 2), indicating that magmas which erupted at these distinct locations produced similar suites (of both evolved and primitive compositions). Cluster 4 represents KREEPy basalts (elevated in K, Rare Earth Elements, and P) which

appear to be statistically distinct from other lunar magmas.

This work corroborates inferences made by previous authors [i.e., 1-4] that compositional variation in Ti and K is significant, likely stemming from differences in mantle source region compositions and/or incorporation of distinct materials en route to the surface (i.e., ilmenite/armalcolite or KREEP, respectively). This work additionally suggests that the processes associated with lunar magma petrogenesis operated similarly at spatially and temporally distinct locations to generate bulk rock compositions that are statistically indistinguishable (i.e., Apollo 11 and 17 high-Ti basalts). However, the correlation between Apollo 12 and 15 basaltic groups that are either evolved or primitive was not expected, and future studies should work to evaluate this further.

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References: [1] Basaltic Volcanism Study Project (1981) Pergamon Press Inc., New York, 1286 pp. [2] Smith, J. V. et al. (1970) *J. Geol.* 78, 381-405. [3] Wood, J. A., et al. (1970) *LPS XI, 1*, 965-988. [4] Shearer, C. K., et al. (2006) *Rev Mineral Geochem*, 60, 365-518. [5] Cone, K. A., et al. (2020) *Icarus*, 346, 113787 [6] Wold, S., et al. (1987) *Chemom Intell Lab Syst*, 2, 37-52. [7] Meyer, C. (2016) <https://curator.jsc.nasa.gov/lunar/lsc/>.

Table 1: Results of PCA analysis of major elements.

VARIANCE			LOADINGS										
Component	% explained	Cumulative % explained	Si	Ti	Al	Cr	Fe	Mn	Mg	Ca	Na	K	P
1	48.02	48.02	-	0.14	0.37	-0.32	-0.37	-0.30	-0.30	0.29	0.39	0.33	0.30
2	20.84	68.86	0.53	-0.55	0.16	-0.16	-	-0.23	-0.27	-0.32	-	0.23	0.31
3	13.8	82.66	0.46	-0.36	0.20	-0.24	0.12	0.28	-0.39	0.40	-0.12	-0.30	-0.21
4	5.9	88.56	-	-	-0.35	-0.24	0.51	0.39	-0.27	-	0.13	0.35	0.45

Table 2: Results of PCA analysis of trace elements.

VARIANCE			LOADINGS											
Component	% explained	Cumulative % explained	La	Ce	Sm	Eu	Tb	Dy	Yb	Lu	Co	Sc	Hf	Cr
1	73.19	73.19	0.25	0.28	0.32	0.29	0.33	0.33	0.33	0.32	-0.24	0.16	0.33	-0.22
2	15.15	88.34	0.45	0.37	0.15	-0.23	0.03	0.02	0.02	-0.01	0.44	-0.59	0.08	0.19
3	4.99	93.33	0.18	0.03	-0.1	-0.11	-0.11	-0.13	-0.07	-0.1	-0.15	-0.25	-0.15	-0.89

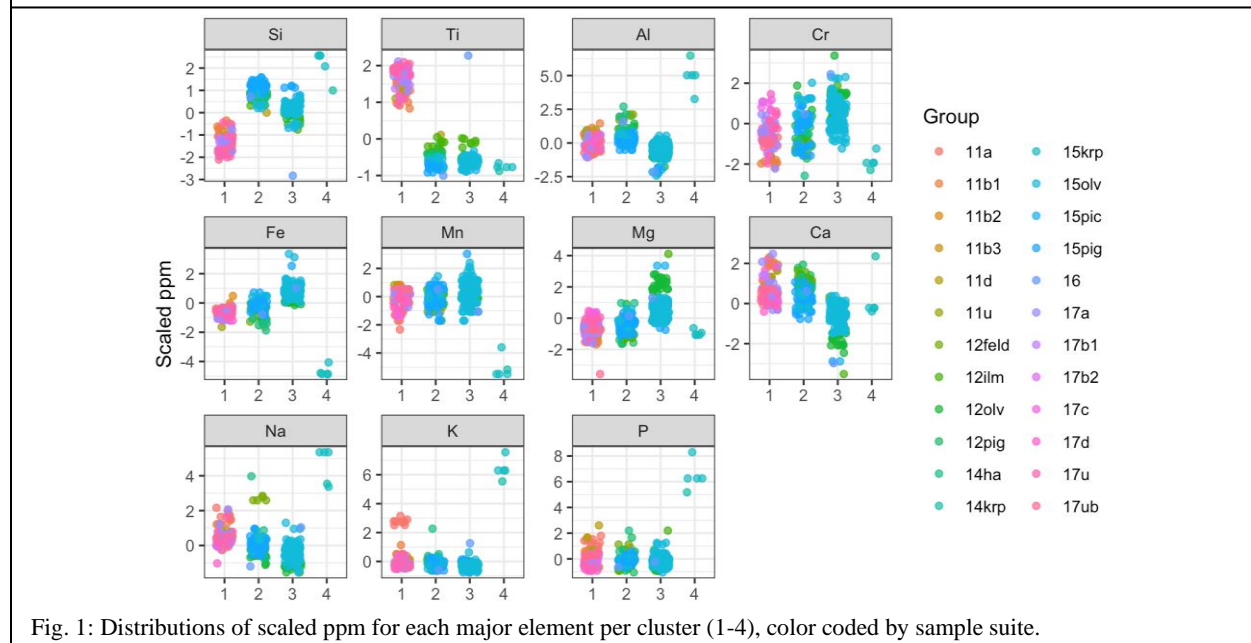


Fig. 1: Distributions of scaled ppm for each major element per cluster (1-4), color coded by sample suite.