**Chemical provinces of Mars complementing mapped geology.** A. Rani[1,2], A. Basu Sarbadhikari[1], D. R. Hood[3], S. Karunatillake[4], and S. Nambiar[1]. [1]Physical Research Laboratory, Ahmedabad, India (alka@prl.res.in), [2]Indian Institute of Technology, Gandhinagar, India, [3]Texas A&M University, [4]Geology and Geophysics, Louisiana State University, USA.

Introduction: Martian chemical provinces defined a decade ago clarified diverse regional processes, including aqueous alteration, the evolution of volcanic provinces, and sedimentary units on Mars [1-3]. However, the sensitivity of such provinces to data revisions remains unknown, along with poorly explored cross-method consistency and applications with mapped geology. Here we synthesize a trilogy of multivariate methods (Non-Hierarchical clustering (N-HC), Hierarchical clustering complement with Principal Component Analysis (HC-PCA) and Gaussian tail clusters (t-GTC)) in analyzing geochemical maps from Mars Odyssey gamma and neutron spectroscopy (GRS) to examine their utility for mapped geology.

Data and Methods: We have used nine elemental concentration maps (K, Th, Fe, Si, Ca, Al, stoichiometric H_2O, Cl and S) derived from GRS, with approximate area covering $\sim\pm45^0$ N projected at a resolution of $5^0 \times 5^0$. All these concentration maps are used in the multivariate analysis viz. N-HC, HC-PCA and t-GTCs. N-HC uses k-mean clustering [1], while HC-PCA consists of PCA followed by divisive clustering methods [2]. t-GTCs method uses a modified t-student test to distinguish spatially overlapping Gaussian tail clusters across subsets of the chemical maps (i.e., . two or more maps). It measures the deviation of chemical composition from bulk Martian crust for each element weighted by pixel-level numerical uncertainty. An area threshold of 40 pixels distinguishes significant geochemical provinces [3].

Result: The t-GTCs and HC-PCA derived provinces do not share boundaries and are smaller than N-HC, reflecting adjustments to address the effects of information redundancy from spatial autocorrelation [4]. The N-HC method derived provinces consist of juxtaposed (i.e., bordered-sharing) provinces, covering Mars entirely (±45º). The trilogy of techniques converge on six geochemical provinces (Fig. 1, labeled 1 - 6). t-GTC does not identify provinces 2 and 4, which shows that the composition of these provinces is similar to the composition of the average Martian crust; hence, there is no significant deviation at 1 sigma or higher (Fig 1c).

The progression of geochemical provinces across Fig. 1 A – C reflects the laterally narrowing effect of accounting for spatial autocorrelation and numerical uncertainties. Differences between C and the
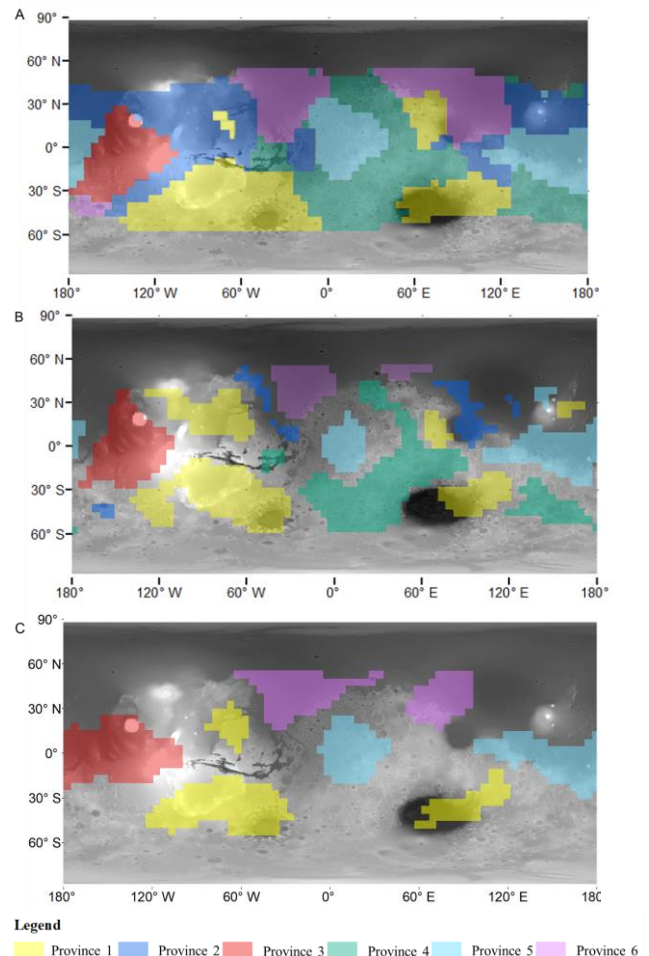
Figure 1: Geochemical provinces from integrated multivariate statistical analysis. Underlain by latitude-longitude (Lat-Long) grid and the Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) topography [6]. A) N-HC B) HC-PCA and C) t-GTCs.

other two chemical province sets also indicates the distinctness between multivariate clustering versus deviation methods. For example, Province 2 derived from the N-HC (Fig. 1A) method does not show any deviation at one sigma level (Fig. 1C); however, its HC-PCA portion depicts significant deviation (Fig. 1B compared with 1C). Collectively, Fig 1C highlights the broadest scale at which the Martian landscape can be categorized compositionally, while 1B shows the spatially most significant compositional clustering. Meanwhile, 1C helps identify the most compositionally contrasting regions of Mars. Consequently, areas of

convergence across the three figures can effectively represent the most compelling provinces for interpreting mapped geology.

Discussion: We consider Southern Acidalia Planitia (SAP) to show how the mapped geology and chemical provinces advance mutually when used together [5]. SAP is consistently identified across all three province maps (Fig. 1). SAP's compositional distinctness results from high enrichment in K, Th, Fe, Si and depletion in Al relative to the rest of the global Martian crust. The geochemical area of SAP reinforces mapped geological boundaries, areally dominated by late Hesperian lowland units (~ 59% , lHl) [5] (Fig. 2). The bulk composition of SAP is given in Table 1.
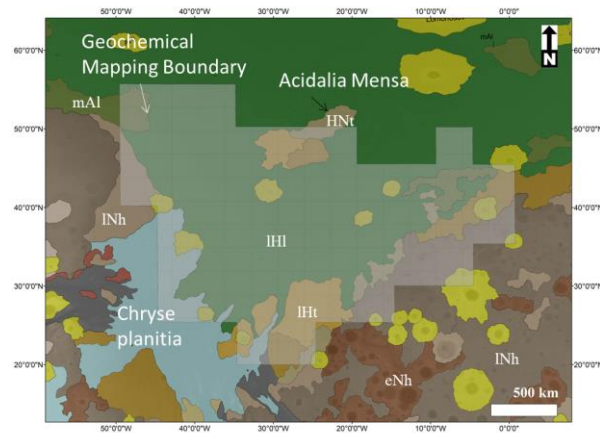

Figure 2: Geochemical province SAP overlay over geologic map [5].

Earlier studies proposed various hypotheses for the formation of this region, which were difficult to disentangle whether the distinct chemical signature in this province is caused by genetic processes related to the lHl unit or if aqueous alteration in this area caused the chemical distinctness. Therefore, we used the fractionation of incompatible elements (K and Th) as a geological signature. They do not fractionate significantly, mostly following the linear trend oof the Martian crust (Fig. 3). Enrichment of large ion lithophiles could be plausible with a lower degree of partial melting of the undepleted mantle [6-8]. Mineralogical observations also support SAP's igneous origin hypothesis [9]. Summarily, this study shows significant chemical variation, especially in large ion lithophile elements (K, Th), from early to late Hesperian geologic provinces (Fig. 3). Specifically, early Hesperian volcanic provinces are depleted in K and Th, K/Th for both is consistent with the average Martian crust. The difference between early and late Hesperian could result from different mantle source compositions or subsequent magmatic processes or both. This further

motivates incorporating chemical province classification into geologic mapping, such as denoting the chemical signature of mapped geologic units that dominate SAP.
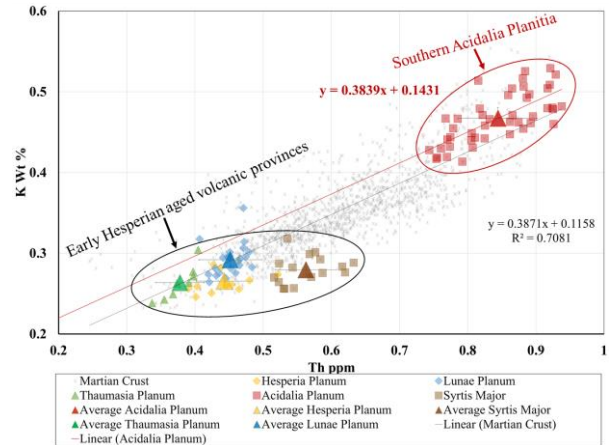

Figure 3: K wt% vs. Th ppm in various Hesperian aged volcanic regions, SAP and the Martian surface derived from geochemical mapping.

Table 1: Bulk composition of SAP region derived using GRS.

Element oxide (wt %)	Average	SD
Al_2O_3	7.1	1.4
SiO_2	46.4	0.9
CaO	7.6	1
FeO	19.6	0.7
H_2O	3.9	0.8
SO_3	5.7	0.2
Cl	0.4	0.04
K_2O	0.5	0.03
Th ppm	0.84	0.06

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[1] Taylor et al., (2010), *Geology, 38,* 183-186. [2] Gasnault et al., (2010), *Icarus*, 226-247. [3] Karunatillake et al., (2009), *JGR, 114*. [4] Haining, (2003), *Cambridge University Press, 432*. [5] Tanaka, et al., (2014), *Geologic map of Mars: U.S. Geological Survey Scientific Investigations Map 3292.* [*6*] Smith et al., (2001), *JGR, 106*. [6] Taylor et al., (2006), *JGR, 111*. [7] Karunatillake et al., (2006), *JGR-Planets, 111*. [8] Tanaka et al., (2013), *PSS, 95, 11-24*. [9] Pan et al., (2017), *JGR-Planets, 122*.