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1 **Consolidated Chemical Provinces on Mars: Implications for Geologic**

2 **Interpretations**

3

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14

15 **Key Points:**

- 16 • We have consolidated three key multivariate methods, yielding the first unified set of
- 17 chemical provinces of Mars
- 18 • Igneous geochemistry pervades volatile-rich regions, consistent with water-limited
- 19 isochemical weathering throughout Mars's geologic history
- 20 • Secular chemical trends suggest complex processes of mantle melting for highlands,
- 21 which differs from a possibly garnet-rich lowland source

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30 **Abstract**

31 Chemical provinces were defined on Mars a decade ago using orbital nuclear
32 spectroscopy of K, Th, Fe, Si, Ca, Cl, and H₂O. However, past multivariate analyses yielded
33 three sets of provinces, suggesting methodologic variability. Province-stability to the
34 inclusion of Al and S is also unknown, presenting additional uncertainties for geologic
35 insight. Here we consolidate key multivariate methods to define the first cross-validated
36 provinces. In southern highlands, the highly incompatible K and Th show non-uniform
37 distribution with higher values in mid Noachian and Hesperian than late Noachian – early
38 Hesperian volcanic terrains. Silica- and Al-depletion trends from Noachian to Amazonian
39 indicate highly differentiated mantle with variable degree of melting. Late Hesperian
40 lowlands are highly depleted in Al and enriched in K and Th, consistent with volcanic
41 resurfacing from a low-degree partially melted, garnet-rich mantle. Furthermore, older
42 volatile-rich regions such as Medusae Fossae Formation exhibit igneous geochemistry,
43 consistent with water-limited isochemical weathering throughout Mars's history.

44

45 **Plain Language Summary**

46 Topographically Mars can be divided into two large regions: southern highlands and
47 northern lowlands. However, the compositional evolution of these two landforms and their
48 source characteristics remains unclear. Therefore, using enhanced satellite nuclear
49 spectroscopic data, we develop a set of consolidated geochemical provinces of Mars using
50 three multivariate analysis techniques. We identified the correlation of distinct geochemical
51 provinces with mapped geologic units, which demonstrates the effect of bedrock composition
52 over bulk soil composition. Our study depicts discrete igneous provinces within the southern
53 highlands, which follow a secular chemical pattern, indicating a highly differentiated mantle

54 source with an evolving formation pressure and degree of melting. The northern lowlands, on
55 the other hand, are uncorrelated with the chemical trend of southern highland provinces,
56 suggesting a distinct evolution. Our findings further reveal that regardless of volatile
57 enrichment, igneous crustal composition dominates over chemical alteration signatures
58 indicating a limited role of liquid water on the martian landscape.

59

60 **1. Introduction**

61 *A trilogy* of multivariate cluster analysis methods applied to the chemical maps
62 derived from Mars Odyssey gamma-ray and neutron spectroscopy (GRS) initially identified
63 chemical provinces and supported interpretations of regional-scale geology ([Karunatillake et al., 2009](#);
64 [Gasnault et al., 2010](#); [Taylor et al., 2010](#)). However, the lack of an inter-
65 methodological synthesis to characterize geological processes has hindered subsequent works
66 and stymied advances with other datasets (cf., [Rogers & Hamilton 2015](#)). Furthermore, key
67 chemical maps used in subsequent papers ([Baratoux et al., 2014](#); [Ojha et al., 2018](#); [Plesa et al., 2018](#))
68 were unavailable or only in a preliminary state for the original trilogy: Aluminium
69 (Al), sensitive to both igneous evolution and secondary mineralogy (cf., [Nimmo & Tanaka,](#)
70 [2005](#); [Ehlmann et al., 2011](#); [McLennan, 2012](#)); and Sulfur (S), sensitive to cycling processes
71 within the martian critical zone across the atmosphere and crust ([Halevy et al., 2007](#); [King &](#)
72 [McLennan, 2010](#)).

73 Here we use nine elemental mass fraction maps from the GRS: key rock-forming
74 elements (Fe, Si, Ca, and Al) with large ion lithophiles (K and Th) and volatiles
75 (stoichiometrically equivalent H₂O, Cl, and S) to resolve the aforementioned challenges. We
76 synthesize and advance prior multivariate methods ([Karunatillake et al., 2009](#); [Gasnault et al.,](#)
77 [2010](#); [Taylor et al., 2010](#)) to derive the first consolidated chemical provinces of Mars. We

78 consider three of the provinces as case studies on geologic insight, revealing diverse mantle
79 sources and magmatic processes in volcanic areas, characterizing possible global ashfall
80 units, and evaluating the relative roles of igneous versus aqueous environments.

81

82 **2. Data and Methods**

83 We use chemical maps derived from GRS spectra to delineate the chemically distinct
84 provinces. The average decimetre sampling depth and coarse spatial resolution of GRS
85 overcome the effects of fine dust mantles making GRS elemental analysis ideal for primary
86 and secondary geological process studies on broad scales. GRS measures the energy
87 spectrum of gamma photons emitted from the martian surface and characteristic spectral
88 peaks allow us to measure the abundance and distribution of most major rock-forming
89 elements, along with some minor elements present on the martian surface. There are two
90 main processes on the martian surface that give rise to gamma-photon emission. Gamma
91 photons can be emitted from the decay of natural radioactive elements (K and Th) or
92 emissions induced by cosmic particle interactions with the martian atmosphere and non-
93 radioactive elements of the martian surface. However, due to increasing H (reported as
94 stoichiometric H₂O mass fractions) towards the poles causing mass dilution for radioactive
95 elements and compositional modelling issues for others due to neutron moderation, derived
96 chemical maps are restricted to the mid-to-low latitudes, roughly within $\pm 50^\circ$. Furthermore,
97 chemical maps are generated at a resolution of $5^\circ \times 5^\circ$ due to broad footprint of the GRS
98 instrument (Boynton et al., 2007). We use the latest refined datasets of GRS, including Al
99 and S used in the literature (cf., Hood et al., 2016, 2019; Ojha et al., 2018, 2021), and
100 compare them with GRS data used a decade ago (Boynton et al., 2007; Karunatillake et al.,
101 2009; Gasnault et al., 2010; Taylor et al., 2010), including the archived data at the NASA

102 Planetary Database System (<https://pds-geosciences.wustl.edu/ody/ody-m-grs-5-elements>
103 [v1/odgm_xxxx/data/smoothed/](#)). The delineation of provinces also mitigates the substantial
104 spatial autocorrelation inherent in the GRS data by associating large chemical deviations with
105 multi-pixel regions rather which are larger than the GRS instrument footprint ([Karunatillake](#)
106 [et al., 2009](#)). The detailed description and comparison of old versus latest refined datasets of
107 GRS are described in Supplementary Information S1.

108

109 **2.1. Multivariate Cluster Analysis**

110 We apply three multivariate cluster analyses to discern a set of internally uniform
111 chemical provinces that reflect the compositional variability of the martian crust. The three
112 methods (**Supporting Information S1.2** provides more details) consist of non-hierarchical
113 clustering with principal component analysis (NHC-PCA: [Taylor et al., 2010](#)), hierarchical
114 clustering with principal component analysis (HC-PCA: [Gasnault et al., 2010](#)), and modified
115 student's t-test to distinguish spatially overlapping Gaussian tail clusters (t-GTC:
116 [Karunatillake et al., 2009](#)).

117 The three methods optimize clustering differently but still present spatially
118 overlapping trends suggestive of distinct provinces. NHC-PCA optimizes Euclidian distances
119 between cluster centers, where the number of clusters is specified a priori. In comparison,
120 HC-PCA builds a hierarchy of clusters using a top-down clustering approach based on a
121 divisive algorithm ([Kaufman & Rousseeuw, 2005](#)), where the complete martian landscape
122 mapped by GRS belongs to one cluster and is split iteratively, moving down the hierarchy to
123 highlight the differences between the sub-clusters. The modified t-GTC method identifies
124 spatially contiguous areas where two or more elements deviate from their respective average
125 mid-to-low latitude crustal abundances by one standard deviation or greater. The t-GTCs and

126 HC-PCA-derived provinces reduce spatial autocorrelation biases by using unclassified
127 (boundary) pixels to separate provinces from each other. Complementarily, the NHC-PCA
128 method delineates border-sharing provinces.

129 We combine the intermediate provinces from the NHC-PCA, HC-PCA, and t-GTC
130 methods into a consolidated map using a spatial contouring approach. A contour map of
131 provinces is made by categorizing the regions into three levels: provinces derived from all
132 three-methods overlapping, provinces with any two-methods overlapping, and provinces with
133 no overlap (**Figure S1**). We demarcate the boundaries of final provinces resulting from at
134 least two-methods overlapping, reducing the spatial uncertainty in any method (**Supporting**
135 **Information S2** provides more details). Provinces that deviate minimally from the average
136 martian crust (AMC) composition (**Supporting Information S2.1** and **S2.2**) are omitted so
137 that the consolidated chemical province map highlights crustally distinct regions. In addition,
138 we use mapped geology ([Tanaka et al., 2014](#)) for context on chemical trends.

139

140 **3. Results**

141 All three methods lead to large chemically uniform provinces, with minimal intra-
142 province compositional variance, reinforcing the subdued variability in chemical maps of
143 Mars. The intermediate chemical province sets resulting from the three underlying methods
144 (**Supporting Information S2** provides more details) are labeled numerically (Province-1 to
145 Province-6; **Figures 1a-c** and **Tables S1** and **S2**). Province-2 from NHC-PCA and HC-PCA
146 methods lacks the minimum criterion of at least two methods overlapping (**Figure S1**;
147 **Supporting Information S2** provides more details), and Province-4 is compositionally
148 identical to the AMC within statistical uncertainty. Therefore, Province-2 and 4 are de-
149 prioritized in the consolidated chemical province map (**Figure 1d**). Moreover, provinces that

150 overlap spatially across the methods are compositionally similar even if driven by different
151 multivariate methods (**Tables S2, S3**). This further justifies our contour-consolidation method
152 yielding the merged chemical province map (**Figure 1** and **Tables 1** and **S3**). Overall,
153 overlapping areas labeled as ‘Province-1’ in **Figures 1a-c** have been combined into
154 ‘Province-A’, ‘Province-3’ into ‘Province-B’, ‘Province-5’ into ‘Province-C’, and ‘Province-
155 6’ into ‘Province-D’, resulting in four consolidated provinces (**Figure 1d** and **Tables 1** and
156 **S1**). Compositional consistency across the numeric intermediate provinces enables this
157 synthesis (**Supporting Information S2**). While geographically widely separated areas may
158 constitute a single province, such regions show some compositional heterogeneity.

159

160 **3.1. Distinct Geochemical Provinces**

161 Four geographically distributed regions in the southern highlands constitute Province-
162 A (**Figure 1d**). This province broadly represents mid and late Noachian highlands (> 30%) to
163 early Hesperian aged volcanic units (> 20%) (**Figures 2a** and **S2**), containing many of the
164 large Hesperian volcanic provinces. This province is enriched in Al and depleted in K, Th,
165 and volatiles (H₂O, S, Cl) relative to the AMC (**Figure 2b** and **Tables 1, S3, and S4**;
166 **Supporting Information S2.2**). The K/Th and S/Cl ratios are above average, while the Fe/Si
167 ratio is consistent with the AMC.

168 Province-B comprises Amazonian and Amazonian-Hesperian aged volcanic units (>
169 30%) with Amazonian to Hesperian transitional geological units (~ 18%) (**Figures 2a** and
170 **S2**). The distribution of K and Th is consistent with the AMC ([Taylor et al., 2006](#)); however,
171 the K/Th ratio is slightly low compared to the AMC (**Figure 2b** and **Tables 1, S3** and **S4**;
172 **Supporting Information S2.2**). This province is moderately depleted in Si, Ca, and Fe and
173 highly depleted in Al, while the volatiles (especially Cl and S) are highly enriched relative to

174 the AMC. The S/Cl ratio is depleted from preferential Cl enrichment. Compared to the AMC,
175 the Fe/Si ratio is below average.

176 Province-C consists of two geographic regions: Sinus Meridiani (SM) and the
177 Medusae Fossae Formation (MFF), dominated by mid-Noachian highlands (~ 40 %) (**Figures**
178 **1d, 2a, and S2** and **Table S1**). These regions are enriched in volatiles (H₂O, Cl, and S) (cf.
179 [Diez et al. 2008](#); [Feldman et al., 2011](#); [Maurice et al., 2011](#)), while Fe, Ca are slightly
180 enriched relative to the AMC (**Figure 2b** and **Tables 1, S3 and S4; Supporting Information**
181 **S2.2**). The ratio of S/Cl and K/Th is consistent with the AMC. However, Fe enrichments
182 make the Fe/Si ratio higher relative to the AMC.

183 Two regions of broadly late Hesperian lowlands form Province-D (> 60%) (**Figures**
184 **2a and S2**). It is confined to Southern Acidalia Planitia and Utopia Planitia of the Northern
185 lowland near the dichotomy boundary (**Figure 1d** and **Table S1**). Since both these regions
186 are found within the northern lowlands and the northern extent of each is obscured by the
187 chemical mapping boundary (**Supporting Information S1**), they may constitute a larger,
188 contiguous region. The broader extent of Province-D, which includes the western and eastern
189 part of this province, spatially overlaps with the TES-derived Surface Type 2 mineralogy in
190 the martian northern lowlands ([Bandfield et al., 2000](#); [Rogers et al., 2007](#); [Rogers &](#)
191 [Hamilton 2015](#)). This province is highly depleted in Al, enriched in Si, Fe, K, and Th relative
192 to the AMC (**Figure 2b** and **Tables 1, S3 and S4**), contrasting with other provinces. The
193 K/Th and S/Cl ratio is consistent with the AMC, whereas Fe/Si is higher.

194

195 **4. Discussion**

196 **4.1. Extent of aqueous alteration and K/Th trends**

197 We first evaluate the extent of aqueous alteration evident at regional scales to
198 decimeter depths. The Chemical Index of Alteration
199 ($CIA = Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O) \times 100$) in standard molar abundances of oxides
200 corresponding to the provinces A-D is < 50 , which indicates no signature of weathering
201 (**Figure 2c**) at these broad scales. The K/Th ratio is similar across all the provinces, and with
202 the AMC within statistical uncertainty (**Figure 2b**). Specifically, K/Th ratio is effectively
203 invariant with the abundance of the volatiles (H_2O , SO_3 , and Cl) even across the maximum in
204 Province-C to a minimum in Province-A (**Figure 3a**). The most incompatible mapped
205 elements, K and Th (partition coefficient $\ll 1$; [Borg & Draper, 2003](#)) do not fractionate in the
206 solid phases during magmatic processes. Collectively, our study shows that even the volatile-
207 rich regions are compositionally consistent with water-limited isochemical weathering
208 throughout Mars's geologic history ([Hurowitz & McLennan, 2007](#); [Tosca et al., 2008](#)).
209 Consequently, the provinces are broadly representative of well-preserved igneous processes
210 at least to decimeter depth scales and averaged over a few hundred kilometres horizontally.

211

212 4.2. Secular chemical trends on Mars

213 Earlier work by [Taylor et al. \(2010\)](#) grouped all volcanic landscapes into a single
214 province irrespective of age. However, our study supports the findings ([Karunatillake et al.,](#)
215 [2009](#); [Gasnault et al., 2010](#)) that volcanic regions form separate provinces by age (**Figure**
216 **2a**), as shown by [Baratoux et al. \(2011\)](#). Moreover, the minimally weathered secular volcanic
217 composition of provinces A-C in the southern highlands of Mars shows distinct geochemical
218 trends. Unlike southern highlands, Province-D, the late Hesperian lowland unit, deviates from
219 the secular chemical trend (**Figure 3b-d**), indicating distinct lithology. The provinces A-C
220 from mid-Noachian to Amazonian show Al-, Fe-, Si- and Ca-depletion (**Figure 3b-d**). As

221 hypothesized by [Balta & McSween \(2013\)](#), higher SiO₂ in older regions of Mars may indicate
222 dehydration melting of the mantle with hundreds of mg/kg water, similar to that of Province-
223 A and -C of our study, in contrast to the relatively silica-depleted younger Province-B. Unlike
224 Earth, considering a stagnant-lid regime of Mars ([Golombek & Phillips, 2009](#); [Grott et al.,](#)
225 [2013](#)), the decrease of SiO₂ and concomitant increase in olivine component in the parent
226 magma from the oldest to youngest volcanic terrains of southern highlands could be
227 explained by the growth of lithospheric thickness, which would increase the formation
228 pressure, supporting the results of [Baratoux et al. \(2013\)](#). This contrasts with the topmost
229 micron-layer observation by Thermal Emission Spectrometer (TES), suggestive of
230 weathering reflected by the non-detection of olivine in the Hesperian highland terrains, at the
231 spatial resolution of 1 pixel per degree ([Rogers & Hamilton, 2015](#)). GRS-scale footprints in
232 this study consistently reveal the igneous crustal composition albeit weathering processes was
233 prevalent during martian surface evolution. In addition, high Ca/Al for Province-B and -D
234 could indicate a path for sampling a high-pressure, garnet-rich source ([Treiman, 2005](#);
235 [Dasgupta & Hirschmann, 2007](#); [Balta & McSween, 2013](#)). The abundances of K and Th are
236 relatively low in late Noachian – early Hesperian Province-A as compared to Hesperian-
237 Amazonian Province-B and mid-Noachian Province-C in the highland volcanic terrains
238 (**Figure 3e**). Earlier studies advocated the early Noachian crust building phenomenon for the
239 enrichment of these large ion lithophile elements (LILEs: K and Th) in Noachian than
240 Hesperian terrains ([Rogers & Hamilton, 2015](#)). However, our study shows that the youngest
241 volcanic province also contains a high relative abundance of those LILEs, which contradicts
242 the hypothesis of LILE fractionation during the early Noachian crust formation. Moreover,
243 the non-systematic trend of the abundances of LILEs and other secular chemical trends may
244 necessitate complex melting processes in a highly differentiated mantle source on a regional

245 to global scale (cf. [Basu Sarbadhikari et al., 2016; 2017; Udry et al., 2020](#)) that existed from
246 the early-stage evolution of Mars.

247 Compared to prior works, the emergence of distinct regions as well as the exclusion
248 of previously suggested provinces (**Figure 1d**) reflects our methodological advances along
249 with the use of Al and S. Given the collective distinctness among the consolidated chemical
250 provinces, we consider three regions for detailed case studies: Lunae Planum, Medusae
251 Fossae Formation, and Southern Acidalia Planitia (**Figure 1d**).

252

253 **4.3. Lunae Planum (LP) in Province-A**

254 LP region is a geologically distinct plateau of early Hesperian-aged highland material
255 ([Tanaka et al., 2014](#)), which lies between Chryse Planitia and Olympus Mons in Province-A
256 (**Figure 1d**). Geochemically, the LP is depleted in K, Th, and H₂O relative to the AMC. LP
257 follows the general K and Th crustal correlation on Mars and substantially overlaps with the
258 K and Th distribution in Hesperia and Thaumasia Planum (**Figures 3e** and **S3**).
259 Consequently, LP's K and Th depletion likely reflects volcanic resurfacing, not aqueous
260 weathering ([Taylor et al., 2006](#)). H₂O depletion in the LP is also comparable in magnitude to
261 that in the vicinity of Greater Thaumasia ([Hood et al., 2016](#)). Given minimal chemical
262 weathering across the provinces (Section 4.1), the H₂O depletion is likely volcanic and could
263 suggest a dry mantle source as predicted for Hesperian volcanism (cf., [Balta & McSween,](#)
264 [2013](#)). However, that mantle evolution model also predicts high Th abundances, not seen in
265 our study. Overall, the LP likely follows the same volcanic evolution trends as identified in
266 the Greater Thaumasia area, i.e., low H₂O abundance and temporally decreasing K and Th,
267 maybe a part of the same evolving volcanic province ([Hood et al., 2016](#)). Furthermore, higher

268 K and Th abundance within LP relative to Greater Thaumasia could place it as the oldest
269 member of an underlying volcanic series.

270

271 **4.4. Medusae Fossae Formation (MFF) in Province-C**

272 The discrete wind-sculpted outcrops of the mid-Noachian MFF extend along the
273 martian equator (**Figure 1d**) and their origin remains uncertain (c.f., [Kerber & Head, 2010](#);
274 [Zimbelman & Scheidt, 2012](#); [Wilson et al., 2018](#)). Geochemically, the MFF region is highly
275 enriched in Fe, Ca, and volatiles (SO₃, Cl, and H₂O) relative to the AMC (**Figure S4**) ([Keller
276 et al., 2006](#)). However, the abundance of K, Th, Al, Si, and the value of K/Th is consistent
277 with the martian crust. As highly incompatible elements in igneous processes, the ratio of
278 Cl/K would inherit the initial mantle abundance ([Taylor et al., 2010](#)). Although the ratio is
279 globally maintained, the MFF region shows significantly different Cl/K than the rest of Mars.
280 Chlorine is highly abundant, and K is generally lower than that in AMC (**Figures 3e and S4**),
281 consistent with Cl enrichment in airborne dust and volcanic aerosol in the MFF ([Newsom &
282 Hagerty, 1997](#); [Goetz et al., 2005](#)). Meanwhile, high S and Cl content, moderately high H₂O
283 (**Figure S5**), fine-grained nature, preserved primary mineralogy, and extensive erosional
284 features suggest that MFF is the source of the global dust reservoirs of Mars ([Ojha et al.,
285 2018](#)). Thus, our work supports the provenance of martian dust from mostly mechanical
286 weathering and transport of a pyroclastic ashfall unit, which possibly arose from SW-oriented
287 paleo-winds during Tharsis volcanic eruptions ([Keller et al., 2006](#); [Diez et al., 2009](#)). Our
288 results don't support the hypothesis of water-ice existence in polar layer-like deposits to
289 explain the volatile enrichment in the equatorial MFF ([Wilson et al., 2018](#)). Summarily, the
290 voluminous pyroclasts of MFF are most likely the product of low-moderate degree partial

291 melting of a distinct volatile-rich mantle source during mid-Noachian age in comparison to
292 the late Noachian - Amazonian volcanic provinces of the martian highlands.

293

294 **4.5. Southern Acidalia Planitia (SAP) in Province-D**

295 SAP is a late Hesperian plain area (Tanaka et al., 2014) in the northern lowlands that
296 geographically lies between Tharsis and Arabia Terra and is part of Province-D (Figure 1d).
297 Geochemically, SAP is enriched in K, Th, Fe, Si and depleted in Al relative to the rest of the
298 AMC (Figure S6). Despite K and Th enrichment, the K/Th ratio of SAP is consistent with
299 the martian crust (Figures 3e and S6), which suggests primary rock composition
300 (Karunatillake et al., 2006; Taylor et al., 2006), diverging from the extensive alteration
301 posited by Bouley et al. (2020). Al/Si versus Mg/Si plots of SAP (Figure S7a) show a slope
302 different from the martian crust but resembling that of younger martian meteorites (after,
303 McSween et al., 2009). The Al depletion in SAP best correlates with that of the mean basaltic
304 shergottite composition (Nimmo & Tanaka, 2005), and given the K, Th, and K/Th ratio
305 signatures, it is more likely to be related to mantle composition than chemical weathering
306 (Taylor et al., 2006) at least at the scales of our observations. Further, mineralogical
307 observations by Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) reveal
308 mafic mineral signatures in outcrops, crater ejecta, and central peaks of the craters in SAP
309 (Pan et al., 2017) resembling Hesperian-aged volcanism (Salvatore et al., 2010). Also, the
310 non-detection of Al-bearing sulfates (Figure S7b) that would result from low-pH aqueous
311 alteration (McLennan, 2012) supports an igneous origin for the apparent depletion of Al. The
312 collective K and Th enrichment and Al-depletion can best be explained by a low degree of
313 partial melting at high pressure derived from a garnet-rich mantle source for SAP.

314

315 **5. Summary and Conclusion**

316 The first consolidated chemical provinces of Mars reveal several geochemical
317 signatures of broad geologic import. Our findings demonstrate secular chemical trends among
318 the southern highland provinces A-C may indicate complex processes of an evolving degree
319 of partial melting within a highly differentiated mantle source. Distinct lithology of the late
320 Hesperian lowland unit, Province-D, does not follow the secular chemical trends like
321 highland provinces. This could provide a mechanism for sampling a high-pressure, garnet-
322 rich source for Province-D. We also find that even older volatile-rich regions preserve
323 igneous geochemistry, indicating how throughout Mars's geologic history, water-limited
324 isochemical weathering dominated regionally to decimeter depths scales. Specifically, as a
325 distinct plateau of early Hesperian-aged highlands, the Lunae Planum region shows
326 compositional links – and possibly shared provenance - with Province-A, much like Hesperia
327 Planum, Syrtis Major, and part of Greater Thaumasia. The similarity of Province-C's K/Th
328 trend with the average crust and enrichment of volatiles (especially S and Cl) supports mostly
329 regional volcanic materials (e.g., ashfall pyroclastic deposits), especially for the Medusae
330 Fossae Formation, despite volatiles' enrichment. In contrast to the provinces A-C, Southern
331 Acidalia Planitia of Province-D in the northern lowlands is lithologically distinct with the
332 highest abundance of K and Th of the provinces. However, the similarity of K/Th and
333 depletion of Al relative to the average crust argues against sedimentary signatures of putative
334 paleo-ocean(s). The northern lowlands may mostly represent the mafic crust of Mars, which
335 might have originated by a low degree of partial melting at high pressure as suggested by
336 high abundances of incompatible elements (K, Th) and Al- depletion rather than the
337 conventional thought that the northern lowlands are highly fractionated. These findings also
338 demonstrate the overall utility of the integrative multivariate methodology we have

339 developed for martian geochemical data, motivating possible applications to other planetary
340 bodies (e.g., Mercury, Moon, and Vesta) with comparable datasets.

341

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350

351 **Data Availability Statement:** Data in support of this work can be found through Mendeley
352 data (doi: [10.17632/3jd9whd78m.1](https://doi.org/10.17632/3jd9whd78m.1)). Archival GRS-derived chemical maps are from NASA
353 Planetary Database System (PDS, [https://pds-
354 geosciences.wustl.edu/missions/odyssey/grs_egs.html](https://pds-geosciences.wustl.edu/missions/odyssey/grs_egs.html)). Mars geology map taken from
355 USGS-310 archive (<https://pubs.usgs.gov/sim/3292/>), and topographic data from MOLA-
356 HRSC blended DEM data by [Ferguson et al. \(2018\)](#).

357

358

359 **Figure Caption**

360 **Figure 1:** Results obtained from multivariate analysis by NHC-PCA (**a**), HC-PCA (**b**), and t-
361 GTC (**c**) methods, overlaid on the Mars Orbiter Laser Altimeter and High-Resolution Stereo
362 Camera (MOLA-HRSC) data map ([Smith et al., 2001](#)) to delineate the geochemical
363 provinces. Provinces-2 and -4 do not appear in the t-GTC method (**c**) as they are
364 compositionally similar to the average crustal composition (**Tables S2 and S3**). (**d**) The
365 consolidated geochemical provinces on Mars are derived by integrating provinces from three
366 different multivariate techniques and overlaid onto mapped geology ([Tanaka et al., 2014](#);

367 different colors indicate different geologic units with major units in legend). The white
368 dashed outline areas delineate our regional (LP, SAP, and MFF) case studies.

369

370 **Figure 2: (a)** The relative areal fractions of secular, transitional, and volcanic units within
371 each chemical province corresponding to the consolidated geochemical map. The prefix “N”
372 indicates Noachian, “H” indicates Hesperian, and “A” indicates Amazonian, and suffix “v”
373 indicates the associated volcanic units (after, [Tanaka et al., 2014](#)). A detailed version of
374 Figure 2a is given in Figure S2, both as per [Tanaka et al. \(2014\)](#) geology map. **(b)** Modified
375 box-and-whiskers diagram to compare the distribution of elements for all provinces to the
376 global geochemistry of the AMC. The top of the upper box represents 75th percentile/25th
377 percentile ratio, the bottom of the lower box represents the 25th/75th percentile ratio, and the
378 ratio of the medians by the boundary between them. The whiskers here represent the
379 uncertainty on the ratio of medians using the Median Absolute Deviation (MAD)
380 ([Karunatillake et al., 2011](#)). **(c)** The Chemical Index of Alteration
381 ($CIA=100*[Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)]$) diagram is used to assess the extent of
382 chemical weathering in the provinces A-D. For CIA, we are using standard molar abundances
383 of oxides. Non-GRS Na₂O is calculated using [Baratoux et al. \(2014\)](#).

384

385 **Figure 3:** Diagrams of K/Th normalized to the bulk silicate Mars (~ 5300) versus GRS
386 derived total volatile concentration **(a)**, Fe versus Si **(b)**, Al versus Fe **(c)**, and Ca versus Si
387 **(d)** of the provinces A-D are represented by colored boxes (southern highland provinces A-C)
388 and ellipse (northern lowland Province-D). The modest variation in K/Th is consistent with
389 the bulk Mars, implies to low or no alteration at decimeter depths in the consolidated
390 provinces. The regional uncertainty is shown at the right corner of each plot, represented by

391 the average of standard error of mean (1σ) from all provinces (**Table 1**). From Noachian to
392 Amazonian, all the three plots (**b-d**) exhibit a compositional trend, marked by a dashed
393 arrow, except Province-D (**Figure S2**). The prefix “N” indicates Noachian, “H” indicates
394 Hesperian, and “A” indicates Amazonian, and the suffix “v” indicates associated volcanic
395 units, “h” indicates highland, “m” indicates middle and “lHI” indicates late Hesperian
396 lowland. **(e)** The scatter values of K (wt. %) versus Th (mg/kg) in Southern Acidalia Planitia
397 (SAP), Lunae Planum (LP), Medusae Fossae Formation (MFF), consolidated provinces A-D,
398 and AMC. SAP, LP, and MFF generally follow the same trend of K/Th as the AMC.

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412 **References**

- 413 Balta, J. B., & McSween Jr, H. Y. (2013). Water and the composition of Martian magmas.
414 *Geology*, *41*, 1115-1118. <https://doi.org/10.1130/G34714.1>.
- 415 Bandfield, J. L., Hamilton, V. E., & Christensen, P. R. (2000). A global view of Martian
416 surface compositions from MGS-TES: *Science*, *287*, 1626-1630,
417 <https://doi.org/10.1126/science.287.5458.1626>.
- 418 Baratoux, D., Toplis, M. J., Monnereau, M., & Gasnault, O. (2011). Thermal history of Mars
419 inferred from orbital geochemistry of volcanic provinces. *Nature*, *472*, 338–341.
420 <https://doi.org/10.1038/nature09903>
- 421 Baratoux, D., Toplis, M. J., Monnereau, M., & Sautter, V. (2013). The petrological
422 expression of early Mars volcanism. *Journal of Geophysical Research: Planets*, *118*(1),
423 59-64. <https://doi.org/10.1029/2012JE004234>
- 424 Baratoux, D., Samuel, H., Michaut, C., Toplis, M. J., Monnereau, M., Wieczorek, M., et al.
425 (2014). Petrological constraints on the density of the Martian crust. *Journal of*
426 *Geophysical Research: Planets*. *119*, 1707-1727.
427 <https://doi.org/10.1002/2014JE004642>
- 428 Basu Sarbadhikari, A., Babu, E. V. S. S. K., Vijaya Kumar, T., & Aoudjehane, H. C. (2016).
429 Martian meteorite Tissint records unique petrogenesis among the depleted shergottites.
430 *Meteoritics and Planetary Science*, *51*:1588–1610. <https://doi.org/10.1111/maps.12684>
- 431 Basu Sarbadhikari, A., Babu, E. V. S. S. K., & Vijaya Kumar, T. (2017). Chemical layering
432 in the upper mantle of Mars: Evidence from olivine-hosted melt inclusions in Tissint.
433 *Meteoritics and Planetary Science*, *52*, 251-267. <https://doi.org/10.1111/maps.12790>
- 434 Bevington, P. R., & Robinson, D. K. (2003). Data reduction and error analysis. *McGraw-Hill*,

435 New York.

436 Borg, L. E., & D. S. Draper (2003). A petrogenetic model for the origin and compositional
437 variation of the Martian basaltic meteorites, *Meteoritics & Planetary Science*, 38,
438 1713–1731. <https://doi.org/10.1111/j.1945-5100.2003.tb00011.x>

439 Bouley, S., Keane, J.T., Baratoux, D., Langlais, B., Matsuyama, I., et al. (2020). A thick
440 crustal block revealed by reconstructions of early Mars highlands. *Nature Geoscience*.
441 13, 105–109. <https://doi.org/10.1038/s41561-019-0512-6>

442 Boynton, W. V, Taylor, G. J., Evans, L. G., Reedy, R. C., Starr, R., Janes, D. M., et al.
443 (2007). Concentration of H, Si, Cl, K, Fe, and Th in the low- and mid-latitude regions
444 of Mars. *Journal of Geophysical Research: Planets*, 112, 1–15,
445 <https://doi.org/10.1029/2007JE002887>

446 Charrad M., Ghazzali N., Boiteau V., & Niknafs A. (2014). NbClust: An R Package for
447 Determining the Relevant Number of Clusters in a Data Set. *Journal of Statistical*
448 *Software*, 61, 1-36. <http://www.jstatsoft.org/v61/i06/>.

449 Cormack, R. M. (1971). A review of classification. *Journal of the Royal Statistical Society:*
450 *Series A (General)*, 134, 321-353.

451 Dasgupta, R., & Hirschmann, M.M. (2007). A modified iterative sandwich method for
452 determination of near-solidus partial melt compositions. II. Application to
453 determination of near-solidus melt compositions of carbonated peridotite, *Contributions*
454 *to Mineralogy and Petrology*, 154, 647–661, [https://doi.org/10.1007/s00410-007-0214-](https://doi.org/10.1007/s00410-007-0214-8)
455 8.

456 Diez, B., Feldman, W. C., Maurice, S., Gasnault, O., Prettyman, T. H., & Mellon, M. T.
457 (2008). H layering in the top meter of Mars. *Icarus*, 196, 409–421.
458 <https://doi.org/10.1016/j.icarus.2008.02.006>

459 Diez, B., Feldman, W. C., Mangold, N., Baratoux, D., Maurice, S., Gasnault, O., et al.
460 (2009). Contribution of Mars Odyssey GRS at central Elysium Planitia. *Icarus*, 2001, 19-
461 29. <https://doi.org/10.1016/j.icarus.2008.11.011>

462 Ehlmann, B. L., Mustard, J. F., Murchie, S. L., Bibring, J. P., Meunier, A., Fraeman, A. A., &
463 Langevin, Y. (2011). Subsurface water and clay mineral formation during the early
464 history of Mars. *Nature*, 479, 53–60. <https://doi.org/10.1038/nature10582>

465 Feldman, W. C., Head, J. W., Maurice, S., Prettyman, T. H., Elphic, R. C., Funsten, H. O., et
466 al. (2004). Recharge mechanism of near-equatorial hydrogen on Mars: Atmospheric
467 redistribution or sub-surface aquifer. *Geophysical Research Letters*, 31, 2–5.
468 <https://doi.org/10.1029/2004GL020661>

469 Feldman, W. C., Pathare, A., Maurice, S., Prettyman, T. H., Lawrence, D. J., Milliken, R. E.,
470 & Travis, B. J. (2011). Mars Odyssey neutron data: 2. Search for buried excess water
471 ice deposits at nonpolar latitudes on Mars. *Journal of Geophysical Research: Planets*,
472 116, E11009. <https://doi.org/10.1029/2011JE003806>

473 Ferguson, R. L., Hare, T. M., & Laura, J. (2018). HRSC and MOLA blended digital elevation
474 Model at 200m v2. *Astrogeology PDS annex*. U.S. Geological Survey. Retrieved from
475 http://bit.ly/HRSC_MOLA_Blend_v0.

476 Gasnault, O., Taylor, J. G., Karunatillake, S., Dohm, J., Newsom, H., Forni, O., et al. (2010).
477 Quantitative geochemical mapping of martian elemental provinces. *Icarus*, 207, 226–
478 247. <https://doi.org/10.1016/j.icarus.2009.11.010>

479 Goetz, W., Bertelsen, P., Binau, C. S., Gunnlaugsson, H. P., Hviid, S. F., Kinch, K. M., et al.
480 (2005). Indication of drier periods on Mars from the chemistry and mineralogy of
481 atmospheric dust. *Nature*. 436, 62–65. <https://doi.org/10.1038/nature03807>

- 482 Golombek, M.P., & Phillips, R.J. (2009) Mars tectonics, *Planetary tectonics*. Cambridge
483 University Press, 11, 180–232.
- 484 Grott, M., Baratoux, D., Hauber, E., Sautter, V., Mustard, J., Gasnault, O., et al. (2013).
485 Long-term evolution of the Martian crust-mantle system, *Space Science Reviews*,
486 174(1), 49-111. <https://doi.org/10.1007/s11214-012-9948-3>
- 487 Halevy, I., Zuber, M. T., & Schrag, D. P. (2007). A Sulfur Dioxide Climate Feedback on
488 Early Mars, *Science*, 318, 1903–1908. <https://doi.org/10.5040/9780755621101.0007>
- 489 Hood, D. R., Judice, T., Karunatillake, S., Rogers, D., Dohm, J. M., Susko, D., & Carnes, L.
490 K. (2016). Assessing the geologic evolution of Greater Thaumasia, Mars. *Journal of*
491 *Geophysical Research: Planets*. 121, 1753–1769,
492 <https://doi.org/10.1002/2016JE005046>
- 493 Hood, D. R., Karunatillake, S., Gasnault, O., Williams, A. J., Dutrow, B., Ojha, L., Kobs, S.,
494 Kim, K., Heldmann, J., & Fralick, C. (2019). Contrasting regional soil alteration across
495 the topographic dichotomy of Mars. *Geophysical Research Letters*, 46, 13668-13677.
496 <https://doi.org/10.1029/2019GL084483>
- 497 Hurowitz, J. A., & McLennan, S. M. (2007). A ~3.5 Ga record of water-limited, acidic
498 weathering conditions on Mars, *Earth and Planetary Science Letters*, 260 (3–4), 432–
499 443, <https://doi.org/10.1016/j.epsl.2007.05.043>.
- 500 Karunatillake, S., Squyres, S. W., Taylor, G. J., Keller, J. M., Gasnault, O., Evans, L. G., et
501 al. (2006). Composition of northern low-albedo regions of Mars: Insights from the
502 Mars Odyssey Gamma Ray Spectrometer. *Journal of Geophysical Research*, 111.
503 <https://doi.org/10.1029/2006JE002675>

504 Karunatillake, S., Wray, J. J., Squyres, S. W., Taylor, G. J., Gasnault, O., McLennan, S. M., et
505 al. (2009). Chemically striking regions on Mars and Stealth revisited, *Journal of*
506 *Geophysical Research: Planets*, 114, 1–35. <https://doi.org/10.1029/2008JE003303>

507 Karunatillake, S., Squyres, S. W., Gasnault, O., Keller, J. M., Janes, D. M., Boynton, W. V.,
508 et al. (2011). Recipes for spatial statistics with global datasets: a martian case study.
509 *Journal of Scientific Computing*, 46, 439-451. [https://doi.org/10.1007/s10915-010-](https://doi.org/10.1007/s10915-010-9412-z)
510 9412-z

511 Kaufman, L., & Rousseeuw, P.J. (2005). Finding Groups in Data: An Introduction to Cluster
512 Analysis. *John Wiley & Sons*, New York.

513 Keller, J. M., Boynton, W. V., Karunatillake, S., Baker, V. R., Dohm, J. M., Evans, L. G., et
514 al. (2006). Equatorial and midlatitude distribution of chlorine measured by Mars
515 Odyssey GRS. *Journal of Geophysical Research: Planets*, 111, 1–18.
516 <https://doi.org/10.1029/2006JE002679>

517 Kerber, L., & Head, J. W. (2010). The age of the Medusae Fossae Formation: Evidence of
518 Hesperian emplacement from crater morphology, stratigraphy, and ancient lava
519 contacts. *Icarus*, 206 (2), 669–684. <https://doi.org/10.1016/j.icarus.2009.10.001>

520 King, P.L., & McLennan, S.M. (2010). Sulfur on Mars. *Elements* 6, 107-112.

521 Maurice, S., Feldman, W., Diez, B., Gasnault, O., Lawrence, D. J., Pathare, A., & Prettyman,
522 T. (2011). Mars Odyssey neutron data: 1. Data processing and models of water-
523 equivalent-hydrogen distribution. *Journal of Geophysical Research: Planets*, 116.
524 <https://doi.org/10.1029/2011JE003810>

525 McLennan, S. M. (2012). Geochemistry of Sedimentary Processes on Mars, Sedimentary
526 Geology of Mars. *Sedimentary Geology of Mars*. Special Publication 102, 119–138,
527 <https://doi.org/10.2110/pec.12.102.0119>

- 528 McSween Jr, H. Y., Taylor, G. J., & Wyatt, M. B. (2009). Elemental Composition of the
529 Martian Crust. *Science*, 324(5928), 736-739. <https://doi.org/10.1126/science.1165871>
- 530 Newsom, H. E., & Hagerty, J. J. (1997). Chemical components of the Martian soil: Melt
531 degassing, hydrothermal alteration, and chondritic debris. *Journal of Geophysical*
532 *Research: Planets*, 102, 19345-19355. <https://doi.org/10.1029/97JE01687>
- 533 Nimmo, F., & Tanaka, K. (2005). Early crustal evolution of Mars. *Annual Review of Earth*
534 *and Planetary Sciences*, 33, 133–161.
535 <https://doi.org/10.1146/annurev.earth.33.092203.122637>
- 536 Ojha, L., Lewis, K., Karunatillake, S., & Schmidt, M. (2018). The Medusae Fossae
537 Formation as the single largest source of dust on Mars. *Nature Communications*, 9, 1–
538 7. <https://doi.org/10.1038/s41467-018-05291-5>
- 539 Ojha, L., Karunatillake, S., Karimi, S., & Buffo, J. (2021). Amagmatic hydrothermal systems
540 on Mars from radiogenic heat. *Nature Communications*, 12, 1-11.
541 <https://doi.org/10.1038/s41467-021-21762-8>
- 542 Pan, L., Ehlmann, B. L., Carter, J., & Ernst, C. M. (2017). The stratigraphy and history of
543 Mars' northern lowlands through mineralogy of impact craters. A comprehensive
544 survey. *Journal of Geophysical Research: Planets*, 122, 1824–1854.
545 <https://doi.org/10.1002/2017JE005276>
- 546 Plesa, A.C., Padovan, S., Tosi, N., Breuer, D., Grott, M., Wieczorek, M. A., et al. (2018). The
547 thermal state and interior structure of Mars. *Geophysical Research Letters*, 45, 198–12.
548 <https://doi.org/10.1029/2018GL080728>

549 Rogers, A. D., Bandfield, J. L., & Christensen, P. R. (2007). Global spectral classification of
550 Martian low-albedo regions with Mars Global Surveyor Thermal Emission
551 Spectrometer (MGS-TES) data. *112*, 1–29. <https://doi.org/10.1029/2006JE002726>

552 Rogers, A. D., & Hamilton, V. E. (2015). Compositional provinces of Mars from statistical
553 analyses of TES, GRS, OMEGA and CRISM data. *Journal of Geophysical Research:*
554 *Planets*, *120*, 62–91. <https://doi.org/10.1002/2014JE004690>

555 Rousseeuw, P.J. (1987). Silhouettes: A graphical aid to the interpretation and validation of
556 cluster analysis. *Journal of Computational and Applied Mathematics*, *20*, 53–65.

557 Salvatore, M. R., Mustard, J. F., Wyatt, M. B., & Murchie, S. L. (2010). Definitive evidence
558 of Hesperian basalt in Acidalia and Chryse Planitiae. *Journal of Geophysical Research*,
559 *115*, E07005. <https://doi.org/10.1029/2009JE003519>

560 Smith, D. E., Zuber, M. T., Frey, H. V., Garvin, J. B., Head, J. W., Muhleman, D. O., et al.
561 (2001). Mars Orbiter Laser Altimeter: Experiment summary after the first year of
562 global mapping of Mars. *Journal of Geophysical Research: Planets*, *106*, 23689–23722.
563 <https://doi.org/10.1029/2000JE001364>

564 Tanaka, K. L., Skinner, J. A., Dohm, J. M., Irwin, R. P., I., Kolb, E. J., Fortezzo, C. M., et al.
565 (2014). Description of Map Units, p. 1–43, <https://doi.org/10.133/sim3292>

566 Taylor, G. J. (2013). The bulk composition of Mars. *Geochemistry*. *73*, 401–420.
567 <https://doi.org/10.1016/j.chemer.2013.09.006>

568 Taylor, G. J., Stopar, J. D., Boynton, W. V., Karunatillake, S., Keller, J. M., Brückner, J., et
569 al. (2006). Variations in K/Th on Mars. *Journal of Geophysical Research*, *112*,
570 E03S06. <https://doi.org/10.1029/2006JE002676>

571 Taylor, G. J., Martel, L. M. V., Karunatillake, S., Gasnault, O., & Boynton, W. V. (2010).
572 Mapping Mars geochemically. *Geology*, 38, 183–186.
573 <https://doi.org/10.1130/G30470.1>

574 Tosca, N. J., McLennan, S. M., Dyar, M. D., Sklute, E. C., & Michel, F. M. (2008). Fe
575 oxidation processes at Meridiani Planum and implications for secondary Fe mineralogy
576 on Mars. *Journal of Geophysical Research: Planets*, 113(E5).
577 <https://doi.org/10.1029/2007JE003019>

578 Treiman, A.H., (2005). The nakhlite meteorites: Augite-rich igneous rocks from Mars:
579 *Chemie der Erde Geochemistry*, 65, 203–270,
580 <https://doi.org/10.1016/j.chemer.2005.01.004>.

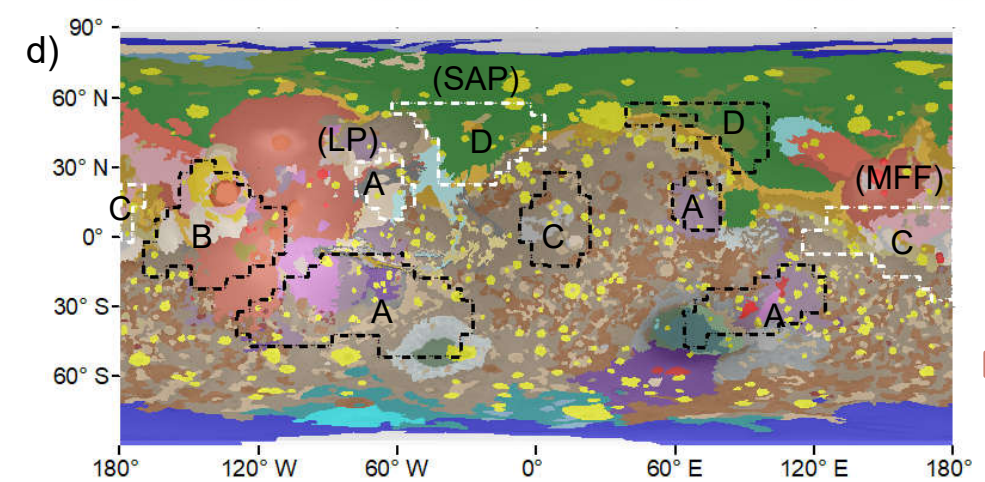
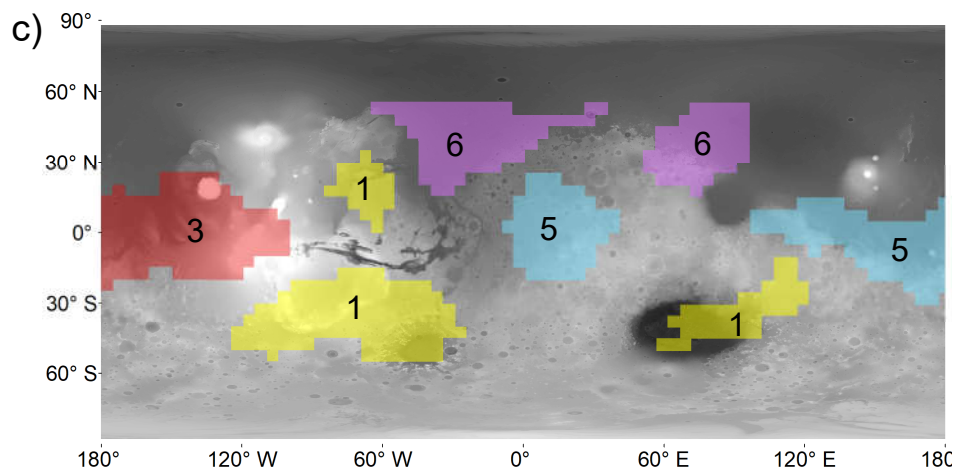
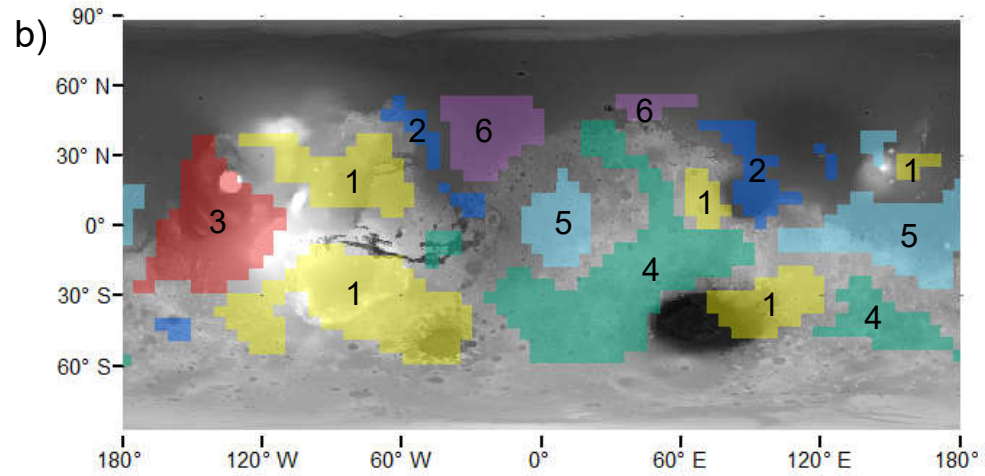
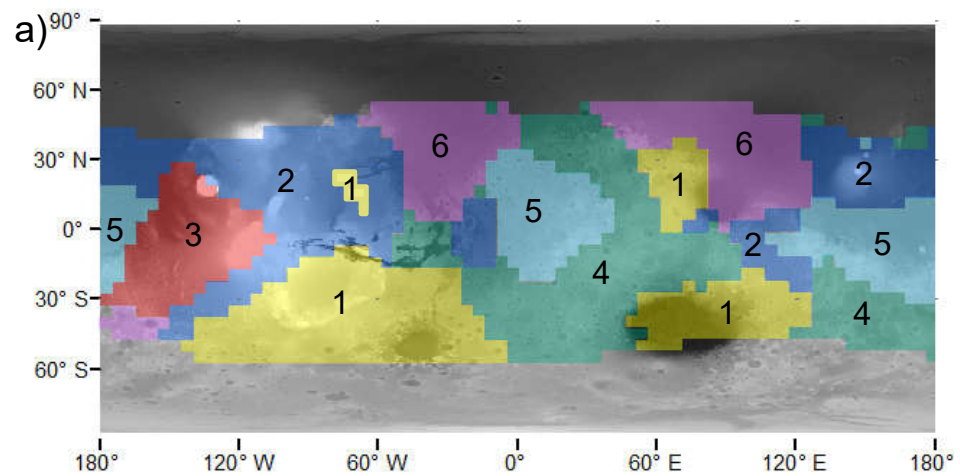
581 Udry, A., Howarth, G. H., Herd, C. D. K., Day, J. M., Lapen, T. J., & Filiberto, J. (2020).
582 What martian meteorites reveal about the interior and surface of Mars, *Earth Space*
583 *Science Open Archive* 55, <https://doi.org/10.1002/essoar.10503123.1>.

584 Wilson, J. T., Eke, V. R., Massey, R. J., Elphic, R. C., Feldman, W. C., Maurice, S., &
585 Teodoro, L. F. A. (2018). Equatorial locations of water on Mars: Improved resolution
586 maps based on Mars Odyssey Neutron Spectrometer data. *Icarus*, 299, 148–160.
587 <https://doi.org/10.1016/j.icarus.2017.07.028>

588 Zimbelman, J. R., & Scheidt, S. P. (2012). Hesperian Age for Western Medusae, Mars,
589 *Science*, 336(6089), 1683-1683. <https://doi.org/10.1126/science.1221094>

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Figure 1.



Major Geologic units
after Tanaka et al.
(2014) for Figure 1d

- Middle Noachian highland
- Early Hesperian volcanic
- Late Hesperian lowland
- Amazonian Hesperian volcanism

Figure 2.

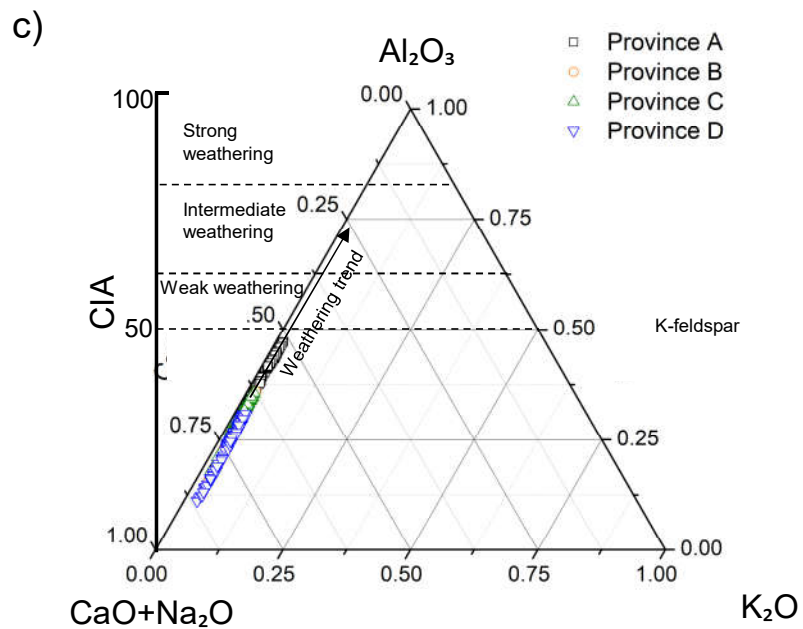
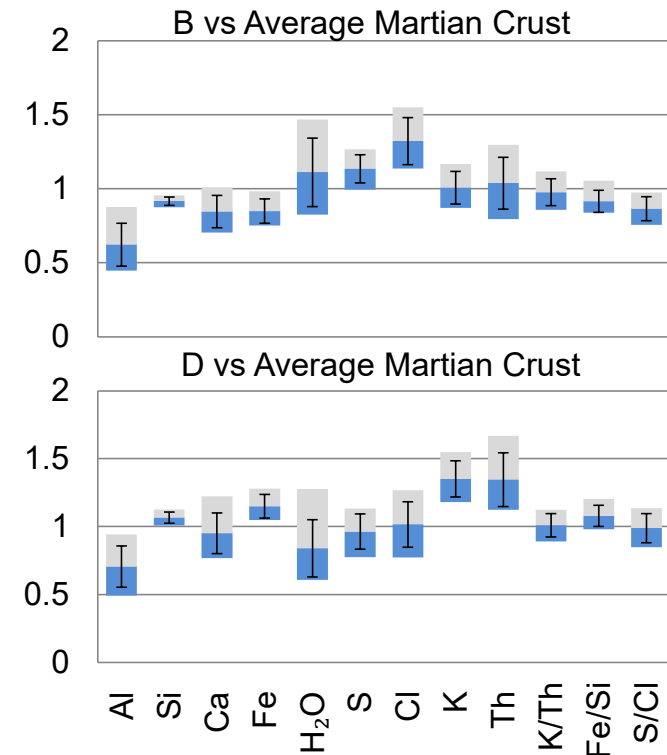
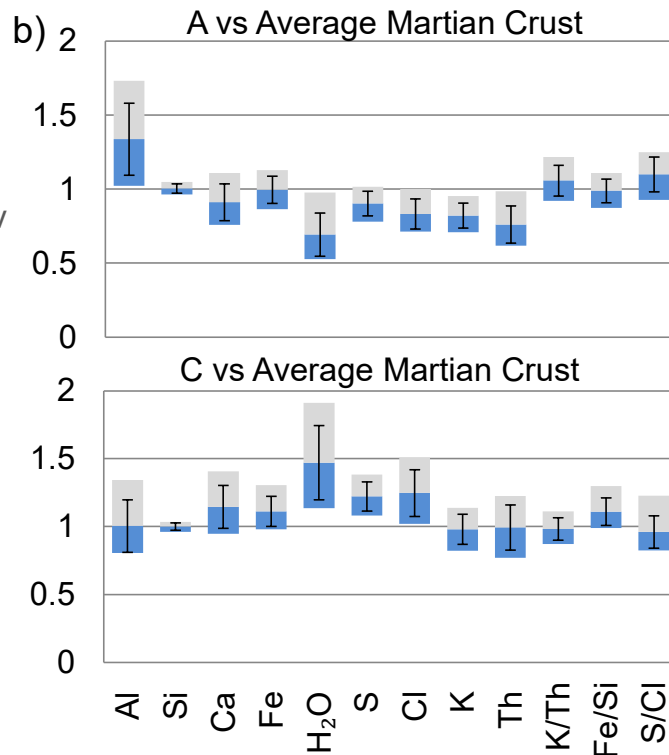
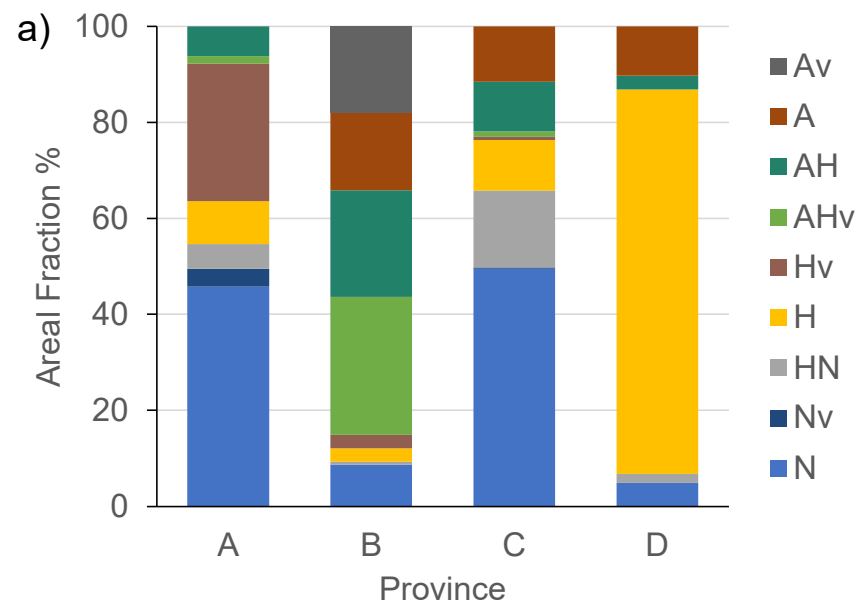


Figure 3.

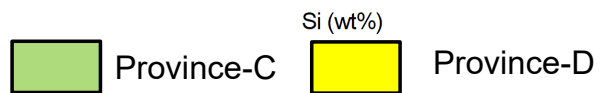
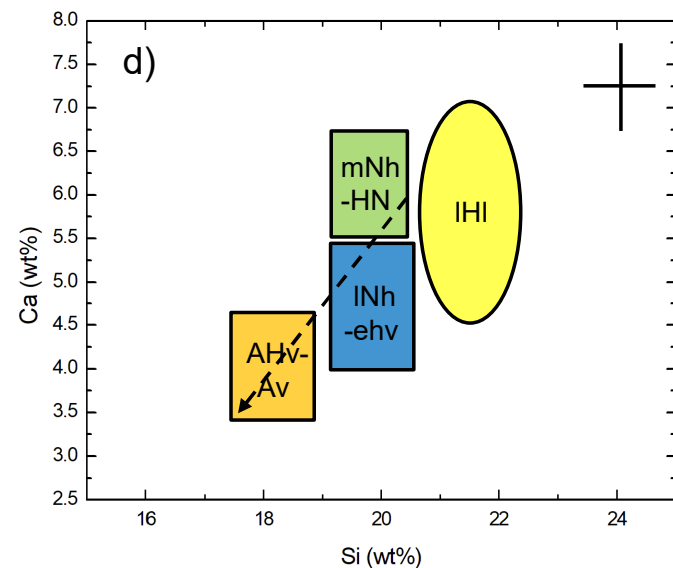
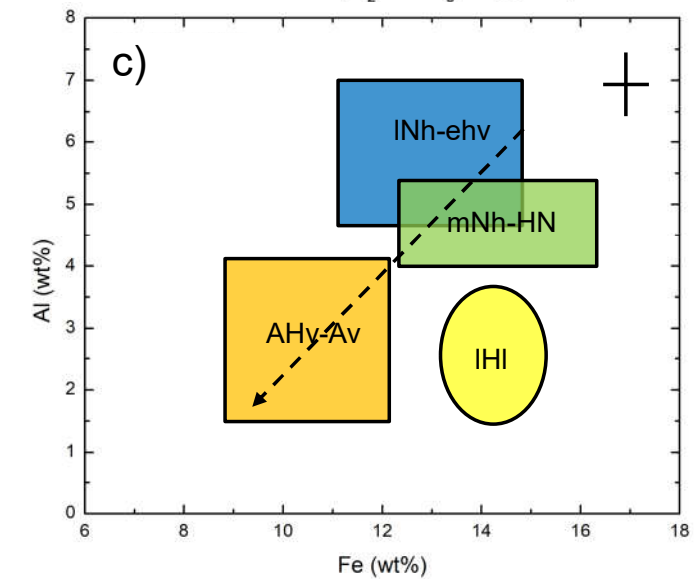
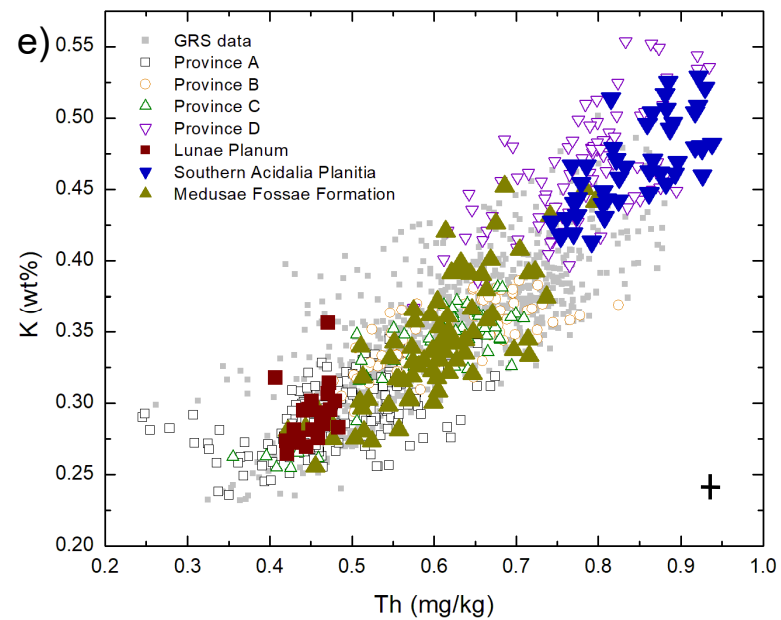
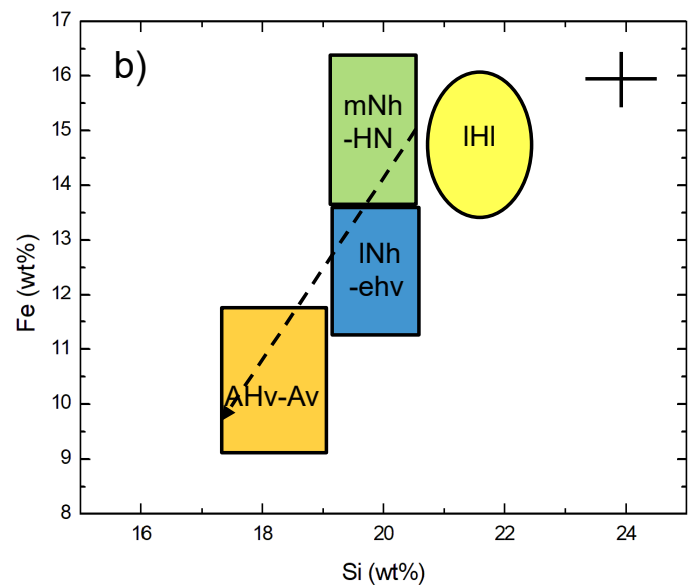
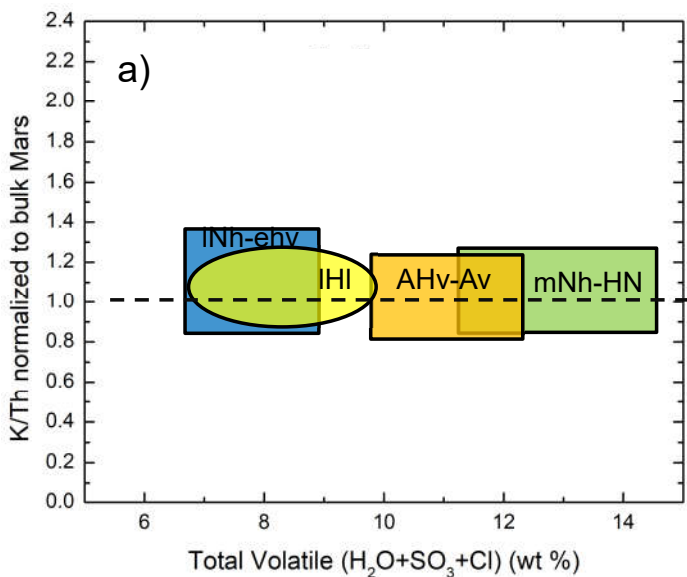


Table 1: Arithmetic mean stoichiometric oxide mass fraction as a percentage (wt%, if not mentioned otherwise), elemental ratio, and its corresponding root means square uncertainty (σ) are calculated from mean measurement uncertainties for the grid points composing a geochemical province. Whereas, K/Th ratio uncertainty is calculated from $[(K/Th)*((\sigma_K/K)^2+(\sigma_{Th}/Th)^2)]^{1/2}$ (GRS derived) of the consolidated chemical provinces.

	Province-A	Province-B	Province-C	Province-D	Mid-latitudinal Average Martian Crust (AMC)
K₂O	0.35±0.01	0.42±0.01	0.40±0.01	0.56±0.02	0.43±0.01
FeO	16.1±0.9	14.0±0.8	18.2±1.1	18.4±1.2	16.3±1.0
SiO₂	42.7±2.3	39.1±2.1	42.4±2.6	44.9±3.0	42.5±2.5
CaO	6.6±1.2	5.9±1.1	7.9±1.4	6.9±1.7	7.0±1.3
Th mg/kg	0.48±0.04	0.62±0.05	0.59±0.05	0.80±0.06	0.61±0.05
Al₂O₃	10.6±2.1	5.5±1.8	8.6±2.2	6.2±2.6	8.5±2.2
H₂O	2.9±0.4	4.2±0.4	5.5±0.5	3.5±0.6	3.9±0.5
Cl	0.41±0.03	0.61±0.03	0.57±0.04	0.46±0.04	0.47±0.03
SO₃	4.9±0.5	6.0±0.5	6.5±0.6	5.2±0.7	5.4±0.6
K/Th	6060±580	5600±430	5680±520	5800±440	5760±470