ALH 84001: TRACE ELEMENT GEOCHEMICAL SIMILARITIES OF ITS TRAPPED MELT COMPONENT TO NAKHLA, LAFAYETTE AND CHASSIGNY; David W. Mittlefehldt¹, Marilyn M. Lindstrom² and Everett K. Gibson³ ¹C23, Lockheed ESC, 2400 Nasa Rd. 1, Houston, TX 77058, ²SN2 Planetary Missions & Materials, ³SN4 Planetary Science, NASA/Johnson Space Center, Houston, TX 77058.

Based on a reconnaissance study of one thin section and a whole rock sample, ALH 84001 was described as having some petrologic similarities with the martian basalt-hexorolite suite on the one hand, and some geochemical similarities with the martian clinopyroxenite-dunite suite on the other [1]. In particular, it was suggested that while the major cumulus mineralogy of ALH 84001 seemed to more closely resemble the petrologic features of the basalt-hexorolite suite, the trapped melt component appeared to have a trace element signature more closely akin to that of the clinopyroxenite-dunite suite [1,2]. Preliminary ion probe measurements suggested that the orthopyroxene in ALH 84001 was not in equilibrium with the interstitial melt component as inferred from measurements on apatite and feldspar-rich glass, and this interstitial melt was suggested to be a foreign melt that infiltrated the cumulus minerals [3]. Here we report on continued petrologic and geochemical characterization of ALH 84001, along with geochemical studies of Chassigny, Lafayette, Nakhla, Shergotty and Zagami. We find a strong incompatible element geochemical affinity of the ALH 84001 trapped melt component with those in the martian clinopyroxenites and dunite. The trapped melt component in ALH 84001 is clearly distinct from melts exemplified by the martian basalts. We find no strong petrologic support for the suggestion that the trapped melt component in ALH 84001 was a later addition [3], however, neither can we rigorously exclude it. Zoning in TiO₂ in pyroxene near the trapped melt material is compatible with igneous zoning associated with the crystallization of a co-genetic trapped melt. Based on the evidence at hand, we believe it is more likely that the trapped melt component in ALH 84001 is co-genetic with the cumulus minerals.

Petrology: Orthopyroxene in ALH 84001 is relatively uniform in major and minor element content [1]. One would expect, however, that there might be zonation near the trapped melt component. In diogenites, the minor elements TiO₂ and Al₂O₃ still preserve evidence of igneous fractionation even though the major elements, MgO, FeO and CaO, have been nearly completely re-equilibrated [4]. We have therefore begun more detailed EMPA in the regions around apatite and the feldspar-rich glass, vestiges of the trapped melt component, concentrating especially on the minor elements. Within about 200-300 µm of apatite grains, there is a slight increase in TiO₂ content, up to about 1.5 times the content far from the apatite (Fig. 1). The TiO₂ zoning trends are continuous with the homogeneous centers of pyroxenes, at least up to 1000 µm away, and are consistent with igneous crystallization of an associated trapped melt. There is no commensurate increase in Al₂O₃ content along the zoning profile, and Cr₂O₃ shows a slight decrease. A decrease in Cr₂O₃ likely indicates that Cr was a compatible element during crystallization of ALH 84001 as suggested by the euhedral chromite grains in the rock. We had a priori expected to see breaks in the minor element trends with distance from the apatite, especially in TiO₂ content, if the apatite was formed from a foreign melt. Parent magmas for the clinopyroxenites are thought to have had generally low high-field-strength element to trivalent element ratios (HFSE/R³⁺) as compared to those of martian basalts [5]. At first blush then, the increase in TiO₂ near the trapped melt material seems at odds with addition of a foreign melt like that parental to martian clinopyroxenites to a cumulate formed from a parent melt related to those of the martian basalts and lherzolites [3]. However, we cannot exclude the possibility that the zoning profiles are the result of diffusive interaction between a foreign melt and the cumulus orthopyroxene.

Geochemistry: We have determined our normal suite of major, minor and trace elements by INAA on a total of five samples of ALH 84001, two of Zagami, and one each of Chassigny, Lafayette, Nakhla and Shergotty. These new analyses confirm our earlier conclusions using literature data, which were very sparse for the diagnostic HFSE contents of the clinopyroxenites and Chassigny, that with increasing trace element content, the HFSE/R³⁺ (Fig. 2) and LREE/HREE ratios of ALH 84001 approach those of the martian clinopyroxenites and dunite. For highly incompatible elements such as the LREE and HFSE, the trace element ratios of whole rock cumulate samples will be those of the trapped melt even when the trapped melt is only a few percent of the total sample. Hence, the trapped melt component is confirmed to have geochemical similarities with the 1.3 Ga old martian magmatism, and be distinct from the magmatism that produced the basalts and lherzolites. This is in accord with conclusions based on ion
probe analysis of the interstitial apatites [3]. The trace element signature of the incompatible element-poor samples is similar to those of the martian basalts and lherzolites. The trace element signature of these incompatible element-poor samples more closely approximates that of the cumulus mineralogy, and hence, don't directly yield information on their parent melt. At present, partition coefficients for the HFSE are not well enough known to be able to model the geochemical characteristics of the parent melt of the cumulus minerals.

**Discussion:** At present, there is no way to ascertain whether all martian meteorites were launched by a single or by multiple cratering events [6]. For the sake of discussion only, we will assume that all originated in a single impact event, and that they represent the bedrock of the impact locality (as opposed to material juxtaposed by faulting, surface mass wasting, cratering, etc.). There is increasingly strong evidence that ALH 84001 may be much older than any of the other martian meteorites [7-9]. Hence, comparison with the other martian meteorites may be moot. However, the strong trace element similarities between the ALH 84001 trapped melt and the clinopyroxenites and dunite suggest there is a connection; either melts with this trace element signature were formed on Mars over an extended time period, perhaps as much as 3 Ga, or the ALH 84001 protolith was infiltrated by 1.3 Ga melts like those parental to the clinopyroxenites and dunite. The latter case would support the petrogenetic model of [3], as well as a single launch event for the martian meteorites assuming the 1.3 Ga magmatism was not very widespread. The former case is more in accord with geochronological studies which show that ALH 84001 is old [7,9], and which seem to preclude mixing of an old ALH 84001 protolith with 1.3 Ga magmas. Only if the foreign melt was nearly contemporaneous with the ALH 84001 protolith, and had similar isotopic characteristics, could the petrogenetic model of [3] be consistent with the geochronological evidence.

The textures and minor element zoning do not lend support to the petrogenetic model of [3], but neither do they absolutely exclude it. The trapped melt, as exemplified by the feldspar-rich glass, does not appear to be a late addition based on texture. It neatly occupies the elongate, angular spaces between orthopyroxene grains as though it represents melt trapped between cumulus grains. Likely, an infiltrating fluid would not have been in equilibrium with the cumulus grains, and we would observe evidence for reaction between the orthopyroxene and the foreign melt. Lack of such evidence favors an origin of the feldspar-rich glass as trapped melt co-genetic with the cumulus grains. Strontium and Nd isotopic evidence further support a co-genetic origin for the cumulus minerals and trapped melt [9]. As mentioned above, the lack of evidence for disruption in the minor element zoning profiles near the apatite also favors a co-genetic origin.


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**Figure 1.** TiO$_2$ zoning away from apatite in ALH 84001 orthopyroxene.

**Figure 2.** CI-normalized HFSE/LREE ratios for martian meteorites, and estimated parent magmas for nakhlites (circled n) and shergottites (circles s) from [5].