MARTIAN METEORITES QUE 94201, AN UNUSUAL BASALT, AND GOVERNADOR VALADAレス, A TYPICAL CLINOPYROXENITE: GEOCHEMISTRY; David W. Mittlefehldt1 and Marilyn M. Lindstrom2

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We have begun a geochemical study of the martian meteorites Governor Valadares and QUE 94201. As expected based on petrology [1], Governor Valadares is a typical martian clinopyroxenite, very similar in composition to Lafayette and Nakhla. Quite unexpectedly, the new martian meteorite QUE 94201 is unusual in composition. In general geochemical characteristics, it is most similar to EETA79001 lithology B. However, QUE 94201 exhibits more extreme geochemical fractionations. QUE 94201 is extremely LREE depleted, with La/Sm ~0.1 times CI, but shows little fractionation in the MREE to HREE (Sm/Yb ~0.7 times CI). QUE 94201 is enriched in the high field strength elements (HFSE), and has higher contents of P, Ti and Hf than any other martian meteorite yet found. paradoxically, QUE 94201 is highly depleted in two other HFSE, Ta and Th. The extreme geochemical variations exhibited by martian basalts (EETA79001 lithologies A and B, QUE 94201, Shergotty and Zagami) are unusual by terrestrial standards, and suggest unusual petrogenetic processes on Mars.

**Geochemistry:** We have determined our normal suite of major, minor and trace elements by INAA on Governor Valadares and QUE 94201, and major elements by EMPA of a fused bead of QUE 94201. Here we present our preliminary data.

Governor Valadares is a clinopyroxenite petrologically very similar to Lafayette and Nakhla [1], and our INAA data for Governor Valadares are virtually identical to data on the latter. One statistically significant distinction is an approximately 10% lower FeO content in Governor Valadares compared to Lafayette or Nakhla. This difference is not reflected in core compositions of mafic minerals in the clinopyroxenites [1]. A second difference is in Br; the Br content of Governor Valadares is intermediate between those of Lafayette and Nakhla. Halogens are in part contributed by martian weathering products [2,3], and the approximate order of magnitude variation in Br amongst the martian clinopyroxenites may be indicative of variations in the amount of alteration each meteorite suffered.

QUE 94201 is geochemically more interesting. QUE 94201 is most similar to EETA79001, especially lithology B, amongst the martian meteorites, but it exhibits the most extreme geochemical fractionations of any Mars rock yet studied. QUE 94201 has the highest abundances of the modestly incompatible elements, MREE through HREE, P, Hf, Zr and Ti, yet has amongst the lowest contents of the extremely incompatible elements; Cs, Th, K, Ta La and Ce (Fig. 1). The depletion of the extremely incompatible elements is not a sampling problem. The LREE are typically hosted in phosphates in basalts, and QUE 94201 has the highest P content (Fig. 1) and a high modal abundance of phosphates [4]. Hence, the extreme geochemical fractionation observed (Fig. 1) is characteristic of the melt. QUE 94201 is also the most ferroan of the martian basalts, with mg# ~36 compared to 42-61 for EETA79001 lithologies A and B, Shergotty and Zagami.

**Discussion:** Because Governor Valadares is unexceptional compared to Lafayette and Nakhla, we will focus our discussion on QUE 94201. For simplicity, we divide martian meteorites into six lithological types: dunite (Chassigny), orthopyroxenite (ALH 84001), clinopyroxenite (Governor Valadares, Lafayette, Nakhla), lherzolite (ALH 77005, LEW 88518, Y-793605), basalt (Shergotty, Zagami) and depleted basalt (EETA79001 lithologies A and B, QUE 94201). Figure 2 compares martian basalts and depleted basalts to a terrestrial depleted basalt; average normal MORBs from the Reykjanes Ridge [5]. Normal MORBs exhibit a characteristic incompatible trace element pattern of increasing contents with decreasing incompatibility caused by separation of the continental crust from the primitive mantle, resulting in a depleted mantle composition as the source for current mid-ocean ridge magmatism. The age of QUE 94201 is not yet known (but search around this volume, maybe someone sent in an abstract), but EETA79001 is quite young and likely formed from depleted martian mantle [6]. Hence, in the broadest sense, the martian depleted basalts might be considered somewhat analogous to MORBs. Based on the mg# of QUE 94201, this martian depleted basalt may not be a primary melt of its source region. However, the incompatible trace element pattern will not be greatly affected by crystallization as long as fractionation of accessory trace element-rich phases has not been important.

On Fig. 2, MORBs exhibit a smooth pattern; a consequence of the partitioning behavior of the trace elements in the depleted source region between the residual minerals, olivine and orthopyroxene and melt. This is not what is observed for the martian depleted basalts. On the grossest scale, an
average of EETA79001 lithologies A and B shows a low and fairly constant abundance for the most incompatible elements Cs through Ce; a sharp increase in content between Sr and Nd, and a fairly constant and high abundance of the lesser incompatible elements P through Lu. This same basic pattern, but in more extreme form, is shown by QUE 94201. Scandium is compatible in pyroxene, and the slight drop-off in Sc in the patterns for N-MORB and QUE 94201 may reflect retention in the source regions, or early pyroxene crystallization. This characteristic trace element pattern for the martian depleted basalts cannot be imposed by a depleted harzburgitic residual source region as is the case for N-MORBs.

Undepleted martian mantle is estimated to contain a thick zone garnet lherzolite overlying a thick zone of β-spinel plus majorite; perovskite structure is not anticipated to be important [7]. The relevant phase boundaries for a depleted martian mantle are not known, but for discussion, we will assume that depleted martian mantle source regions could be either in the garnet lherzolite or β-spinel-majorite phase fields. Can either a depleted garnet lherzolite or depleted β-spinel-majorite source yield melts with trace element patterns as determined for martian depleted basalts? Based on the meager partitioning data available for majorite, it seems that a depleted β-spinel-majorite source region is not a likely source for martian depleted basalts. For example, majorite/melt partition coefficients for La and Sm differ by less than about a factor of two [8], and cannot explain the order of magnitude difference observed in QUE 94201. Partitioning data for garnet, however, suggest that a depleted garnet lherzolite source region might cause the extreme variations in incompatible trace elements. Garnet/melt partition coefficients for Ce and Th on one hand and Sm and Hf on the other are different by about an order of magnitude or more [e.g., see 9]. Hence, a previously depleted garnet lherzolite is a potential candidate source region for the depleted martian basalts. However, it seems likely clinopyroxene in the source region will tend to reduce the difference in rock/melt bulk distribution coefficients for La and Sm, making this scenario untenable. We will more fully explore this and other possible causes of the unusual trace element patterns of martian depleted basalts and their petrogenetic implications in more detail between now and March. (Hey, we only got these data two days ago.)


Figure 1. Incompatible elements in martian meteorites normalized to estimated primitive martian mantle composition [7]. Elements are arranged in order of decreasing incompatibility as judged from MORBs [10]. QUE 94201 Cs and Th data are 2σ upper limits.

Figure 2. Incompatible elements in martian basalts normalized to estimated primitive martian mantle composition [7], and compared to normal MORBs [5] normalized to estimated primitive terrestrial mantle composition [11]. Elements arranged as in Fig. 1.