THE CONUNDRUM OF THE AGE OF SHERGOTTITES.

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Introduction: The young ages (160-650 Ma) obtained for Martian shergottites by the Ar-Ar, U-Pb, Rb-Sr, Sm-Nd, and Lu-Hf chronometers combined with the multiple cosmic-ray exposure ages of shergottites [1] are difficult to reconcile with the small proportion of large uncratered areas on Mars. In addition, the ^{142}Nd and ^{182}W anomalies associated with extinct radioactivities found in the SNC meteorites argue against a strongly convective mantle over most of Mars' history [2], again difficult to reconcile with the existence of young magmatism on this planet.

Early Pb-Pb studies (e.g., [3-5]) actually did identify this issue and it was suggested that basaltic shergottites may be fairly old and that the young ages <650 Ma [1] were related to impacts [6]. Upon reanalysis of Pb-Pb in Zagami, Bouvier et al. [7] rediscovered that the shergottite Pb-Pb data from different laboratories [3, 5, 7-10] are far more consistent with a shergottite crystallization age of ~4 Ga (Fig.1) than with one of only a few hundred Ma.

An alternative interpretation of apparently old shergottite ages was put forward by Borg et al. [10] on the basis that these samples were contaminated first on Mars during impact and then on Earth during handling and curation. The present work re-examines the contamination issue and discusses some recent data, notably new Ar-Ar ages produced by Walton et al. [11].

Discussion: It is well understood that shergottites contain a labile component dominated by phosphates and regardless of the chronometer used the consensus is that this component is young (as recent as 180 Ma). In order to see through the isotopic characteristics of the labile phase, it has to first be eliminated, or at least greatly diminished, by acid leaching. An incomparable advantage of the Pb-Pb technique over other methods is that it does not rely on measured parent/daughter ratios, which are invariably fractionated by leaching, while isotopic fractionation in the process remains minimal.

There are two separate issues relevant to the Pb isotope results on shergottites and this is the number and nature of Pb components involved. Borg et al. [10] contend that shergottites contain several Pb components: (i) Pb from the sample, which for convenience can always be broken down into primordial (Canyon Diablo) and radiogenic Pb accumulated since the formation of the planet; (ii) a terrestrial contaminant added to the meteorite during handling, curation, or sawing; and (iii) a Martian component, which would have been added during the shock process.

A critical observation made by Bouvier et al. [7] is that some shergottites, notably Zagami, form a statistically significant isochron in the ^{207}Pb/^{206}Pb vs ^{204}Pb/^{206}Pb diagram (preferred for minimal correlation of errors; Fig. 1). Regardless of the isochron age, this observation requires that two and only two end-members participate in the multi-component mixture. In effect, the four components mentioned above must have been homogenized to the extent that they merged into the two observed end-members.

It is totally unlikely that terrestrial Pb introduced during handling and curation (conveniently represented by the crustal Pb of Stacey and Kramers [12] SKE or the laboratory blank of Bouvier et al. [7]; Fig. 1) could have been homogenized with the original sample Pb. Some event (shock) should have affected Martian Pb to the extent that it was isotopically homogenized between the coexisting mineral phases. This model can safely be exluded for two reasons. First, terrestrial Pb is more radiogenic (lower ^{204}Pb/^{206}Pb) than Pb from the shergottite samples themselves. This implies that the uncontaminated Pb from shergottites prior to their arrival on Earth should have been very unradiogenic. Although the ^{238}U/^{204}Pb ratio of the mantle source of shergottites is undoubtedly very low [13], this is not the case for the rocks themselves, even after removal of phosphate.

Second, the Pb-Pb data on nakhlites, which comprise whole-rocks and mineral separates from Nakhla [7, 8, 14] and apatites from Yamato 000593 [15] (Fig. 1), are very informative. The two nakhlites present a common alignment significantly distinct from the shergottite trend. We obtain an internal isochron age of ~1.3 Ga for Nakhla (data from [7, 9, 14]), in agreement with the Ar-Ar, Rb-Sr, and Sm-Nd ages found in the literature for the nakhlite group. In spite of their very low Pb concentrations and whether they are falls or finds, the nakhlite isochron plots well off the isotope composition of terrestrial Pb. We therefore conclude that, as long as leaching residues are considered, contamination of shergottites by terrestrial Pb can be neglected.

We are hereafter left with three potential Pb components: primordial, radiogenic and a contaminant from the Martian surface. It is unlikely that the Martian contaminant (soil) could have been fully homogenized with either radiogenic or primordial Pb while leaving the third component so clearly identifiable. The linear array formed by the Pb isotope compositions of shergottites in isochron diagrams therefore

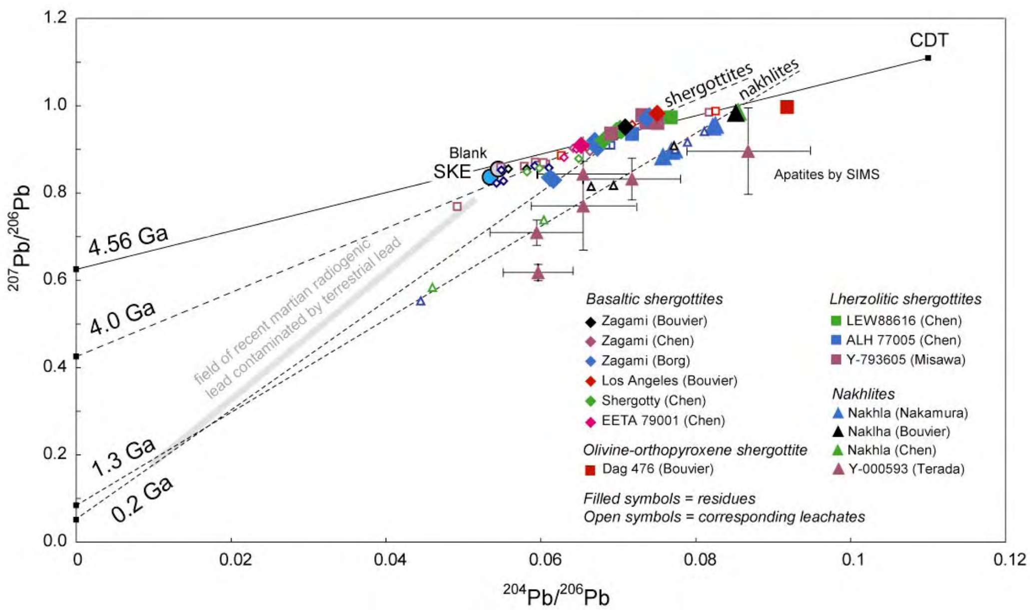

Figure 1: $^{207}Pb/^{206}Pb$ vs $^{204}Pb/^{206}Pb$ of shergottites and nakhlites with respective isochrons at 4.0 Ga and 1.3 Ga. Data from [3, 5, 7-10, 14, 15]. Canyon Diablo troilite (CDT) and a 4.56 Ga geochron are represented as references for Pb isotopic evolution.

requires that some event fully homogenized primordial (or initial in general) and radiogenic Pb. Given a Pb closure of 1100 K in pyroxene [16], such an event should have changed the original mineralogy of the rock beyond recognition.

We thus conclude that the alignment observed in the $^{207}Pb/^{206}Pb$ vs $^{204}Pb/^{206}Pb$ diagram represents a true isochron, which in essence is a binary mixture between radiogenic Pb and initial Pb, and that the age of basaltic shergottites is ~4.0 Ga as proposed by Bouvier et al. [7].

Old Ar-Ar ages were recently obtained by laser ablation in basaltic and olivine-phyric shergottites [11]. Twenty-four melt pockets included in these rocks gave ages ranging from 735 to 4540 Ma and half of these ages were older than 3.3 Ga. Walton et al. [11] interpreted these ages as the result of foreign Ar trapped during shock. We contend that if this was the case, there would be no simple explanation for why ages older than 4.56 Ga are completely missing. Shock melting is an instantaneous, very localized, essentially 'cold' process and the very fast cooling required by the presence of maskelynite is expected to leave Ar very little time to diffuse out of the system before the closure temperature is reached. We therefore suggest that the old Ar-Ar ages represent minimum crystallization ages and are not due to an artifact of trapped Ar.

Conclusion: We contend that a Pb-Pb age of ~4 Ga is the only tenable interpretation of Pb-Pb isotope systematics in shergottites and that this age is supported by laser ablation Ar-Ar data. It provides a straightforward explanation for the existence of variable extinct radioactive nuclide anomalies (^{182}Hf and ^{146}Sm) [2] with implications for mantle convection. It further removes the need for complex scenarios of meteorite extraction, thereby potentially improving the understanding of Martian cratering chronology.

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