THE Mn-Fe SYSTEMATICS OF THE ANGRITE PARENT BODY AS COMPARED TO OTHER MAJOR PLANETARY BODY RESERVOIRS IN THE SOLAR SYSTEM: A CRYSTAL CHEMICAL PERSPECTIVE.

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Introduction: Considerable research and many publications have focused on angrite meteorites which are among the oldest objects (~4.56 Ga, [1]) in the solar system. These meteorites include a diverse suite of silica-undersaturated mafic meteorites. The identity and location of their parent body is still unknown and widely debated. Our new work on angrites SAH 99555, LEW 86010, LEW 87051, NWA 10463, and Angra dos Reis closely examined olivine in these rocks, as well as existing, published data on pyroxene and plagioclase. A revised diagram plotting the Fe/Mn ratio of angrite olivine (Fig. 1) is very similar to the Mn-Fe ratios previously measured in both terrestrial and lunar olivines, suggesting that angrite melts may have been derived from a similar solar system reservoir.

In a previous study [2], we presented a simple technique, using the electron microprobe, to determine planetary basalt parentage. It is based on Mn-Fe systematics in olivine and pyroxene and the anorthite content of plagioclase. This technique was only to be used on basalts and applied only to unequilibrated phases (pyroxene, olivine, and plagioclase, with no exsolution). Angrite melts are truly basalts according to the definition adopted by The Basaltic Volcanism in the Solar System Project [3]. Basalts are melts or near melts with <52% SiO_2, >6% CaO and Al_2O_3, and <12% MgO. Pyroxene, plagioclase, and olivine are the major phases. This technique has been used by many researchers as a quick and easy method to determine planetary parentage. It is most powerful when used with other determiners of planetary parentage like oxygen isotopes. In a summary diagram in that study (Fig. 4 in [2]) based on a plot of Fe/Mn of olivine and pyroxene (y-axis) and anorthite percentage in plagioclase (x-axis), the position of the angrite parent body was plotted in the wrong location. The reason for this was the location was determined by the Fe/Mn ratio of pyroxene and the anorthite content of plagioclase. The first author did not realize at the time that angrite pyroxene was not effective on this diagram because the M2 crystallographic site (6 to 8 coordination, very compliant) was filled with Ca because of the high Ca content of the melt. Both the pyroxene M2 site and M1 site (octahedral) must be in play for the phase to be used for the correct Fe/Mn ratio. This has now been rectified by using angrite olivine instead of pyroxene (Fig. 2). When this is corrected, we see that the Mn verses Fe trajectory for olivine in angrites (Fig. 1) almost coincides with the terrestrial trajectory but is displaced from Earth on the Fe/Mn versus anorthite diagram (Fig. 2) with angrites plotting at higher anorthite content than Earth. This changes our thinking dramatically concerning the possible location of the angrite parent body if it still exists. On a pyroxene Mn versus Fe diagram for 4 Vesta, Mars, Earth, Moon, and angrites (Fig. 1 in [2]), the slopes correspond roughly with heliocentric distance or the distance from the Sun; the sequence being 4 Vesta, Mars, Earth, Moon, and the angrite parent body (furthest from the Sun to closest). An anomaly in this sequence is readily apparent with the Moon plotting at a different slope than Earth even though their oxygen isotope ratio are almost identical. This is likely because of the higher volatility of Mn than Fe which is lost during the giant impact involved with the Moon's formation. When using pyroxene, the angrites plotted on the lowest slope; the implication was that the angrite parent body was closest to the Sun. Now, using olivine (Fig. 1), the sequence is Mars, Earth, APB (the angrite parent body), and then Moon. Asteroid 4 Vesta can not be plotted on this diagram because of the near absence of olivine in basalt from this asteroid. Therefore angrite olivine has given us an important new clue about the possible location of the angrite parent body because it appears to come from the same or similar Mn-Fe reservoir as Earth.

Discussion: Papike et al. [4] demonstrated why exsolution compromises the Mn/ Fe ratio in pyroxenes. Note figure 1.3.2.17b in that

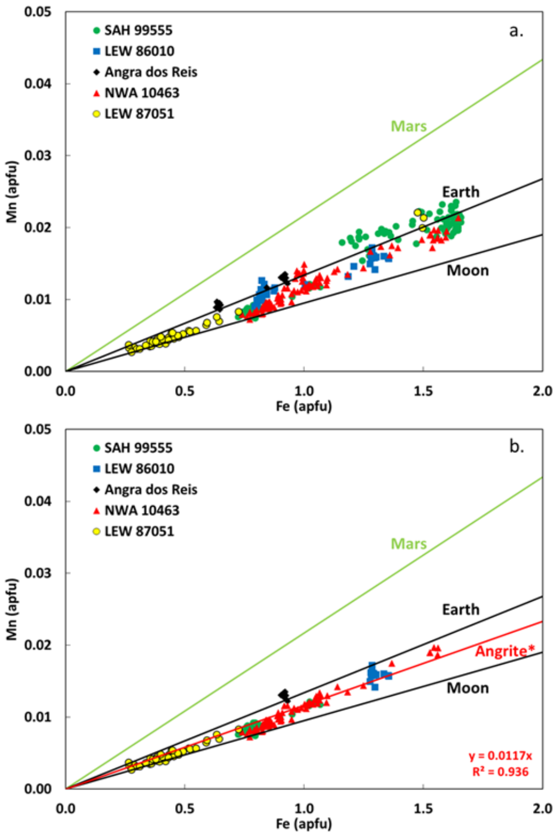

Figure 1. Mn/Fe ratio of planetary olivine grains. Individual analyses shown for angrites only. a. All analyzed olivine in angrites. b. Olivine where the Ca component (Ca-Fe-Mg) is <5 mol.%.

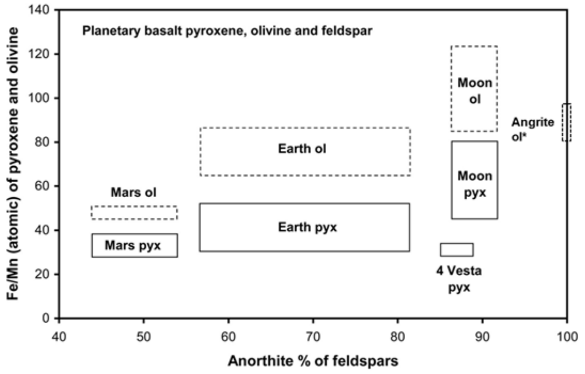

Figure 2. Fe/Mn ratio in olivine and pyroxene from planetary basalts, vs. anorthite content of feldspars. After Fig. 4 in [2]. *Olivine where the Ca component (Ca-Fe-Mg) is <5 mol.%.

publication (Mn-X_{Fe} variations diagrams for six meteorite pyroxene suites). These include equilibrated eucrites Aioun el Atrouss, Juvinas, Stannern, and Nuevo Laredo. These “equilibrated” meteorites display exsolution and their Mn-Fe trajectories shift toward vertical. The symbol X_{Fe} on these diagrams represents the mole fraction of Fe/ (Fe + Mg). Unequilibrated Shergotty pyroxenes show two trends of Mn with increasing X_{Fe}, one for high-Ca pyroxene and one for low-Ca pyroxene. The trends are parallel to each other and show the expected positive correlation of Mn and Fe. However the trend for low-Ca pyroxene is displaced toward higher Mn values. The unequilibrated Pasamonte pyroxenes also show smooth trends in the Mn-Fe trajectory. The crystal chemical interpretation of this feature is that in low-Ca pyroxene, the Mn^{2+} is strongly ordered into the M2 site. The reason for these differing systematics is straightforward: during subsolidus re-equilibration, which causes exsolution in these pyroxenes, Ca is fractionated into the M2 site of augites while Mn^{2+} is fractioned into pigeonite (low- Ca pyroxene). The site preference for the pyroxene M2 site is Ca> Mn^{2+} >Fe^{2+} >Mg.

The nature of the angrite parent body and possible initial location in the Solar System: Keil (2012), in his excellent review of angrites, concludes that the angrite parent body (APB) must have been >100 km in radius. Keil (2012) also points out that some angrite, for example D’Orbigny, contain vesicles indicating vapor loss and suggested the vapor is dominated by CO$_2$. He also observes that angrites do not contain obvious features of a shock or brecciation history. Our earlier paper [2] indicated that the Mn/Fe slope might indicate that the location of the APB was close to the Sun and might even be Mercury. I think many more recent studies can rule out Mercury as the source. We suggest that the APD, with Mn-Fe systematics very much like earth, could have been located near the reservoir that produced the giant impactor that likely impacted Earth and produced the Earth-moon system.

References: [1] Keil, K. (2012) Chemie der Erde 72, 191-218. [2] Papike, J.J. et al. (2003) American Mineralogist 88, 469-472. [3] BVSP (1981) Pergamon, New York, 1286 p. [4] Papike, J.J. et al. BVSP, 340-363.