

**EXPERIMENTAL CONSTRAINTS ON A VESTA MAGMA OCEAN.** C. Hoff<sup>1</sup>, J.H. Jones<sup>2</sup>, and L. Le<sup>3</sup> <sup>1</sup>University of Massachusetts, Amherst, Department of Geology, Amherst, MA, <sup>2</sup>KR, NASA Johnson Space Center, Houston, TX, 77058 (john.h.jones@nasa.gov). <sup>3</sup>Jacobs ETS, Houston, TX, 77058

**Introduction:** A magma ocean model [1] was devised to relate eucrites (basalts) and diogenites (orthopyroxenites), which are found mixed together as clasts in a suite of polymict breccias known as howardites. The intimate association of eucritic and diogenitic clasts in howardites argues strongly that these three classes of achondritic meteorites all originated from the same planetoid. Reflectance spectral evidence (including that from the DAWN mission) has long suggested that Vesta is indeed the Eucrite Parent Body [e.g., 2].

Specifically, the magma ocean model was generated as follows: (i) the bulk Vesta composition was taken to be 0.3 CV chondrite + 0.7 L chondrite but using only 10% of the Na<sub>2</sub>O from this mixture; (ii) this composition is allowed to crystallize at 500 bar until ~80% of the system is solid olivine + low-Ca pyroxene; (iii) the remaining 20% liquid crystallizes at one bar from 1250°C to 1110°C, a temperature slightly above the eucrite solidus. All crystallization calculations were performed using MELTS [1].

In this model, diogenites are produced by co-crystallization of olivine and pyroxene in the >1250°C temperature regime, with Main Group eucrite liquids being generated in the 1300-1250°C temperature interval. Low-Ca pyroxene reappears at 1210°C in the one-bar calculations and fractionates the residual liquid to produce evolved eucrite compositions (Stannern Trend).

We have attempted to experimentally reproduce the <1250°C portion of the MELTS Vesta magma ocean. In the MELTS calculation, the change from 500 bar to one bar results in a shift of the olivine:low-Ca pyroxene boundary so that the 1250°C liquid is now in the olivine field [e.g., 3] and, consequently, olivine should be the first-crystallizing phase, followed by low-Ca pyroxene at 1210°C, and plagioclase at 1170°C. Because at one bar the olivine:low-Ca pyroxene boundary is a peritectic, fractional crystallization of the 1210°C liquid proceeds with only pyroxene crystallization until plagioclase appears. Thus, the predictions of the MELTS calculation are clear and straightforward.

**Experimental/Analytical:** A starting composition was produced by quenching a synthetic liquid whose composition closely approximates that of the Righter-Drake 1250°C melt [1]. Experiments were run in 1-bar, gas-mixing Deltech furnaces, initially for short duration (SD) runs (5-7 hrs), and then long duration (LD) runs (24-180 hrs). These experiments were performed at 1250-1170°C, at oxygen fugacities near the iron-wüstite (IW) oxygen buffer, and a pressure of one

**Table 1. Experimental Summary**

Temp (°C)	MgO	CaO	% Melt	Duration (hrs)	Phases Present
<b>1250 LD</b>	<b>9.7</b>	<b>9.4</b>	<b>100.0</b>	<b>23</b>	<b>Melt</b>
1250 SD	8.2	10.0	93.6	5	Melt, Olivine
<b>1225 LD</b>	<b>8.1</b>	<b>9.9</b>	<b>94.9</b>	<b>120</b>	<b>Melt, Olivine</b>
1225 SD	7.5	10.4	90.1	5	Melt, Olivine, pyroxene
<b>1210 LD</b>	<b>7.7</b>	<b>10.0</b>	<b>93.3</b>	<b>173</b>	<b>Melt, Olivine</b>
1200 SD	7.6	10.2	91.8	8	Melt, Olivine
<b>1195 LD</b>	<b>7.5</b>	<b>10.2</b>	<b>92.1</b>	<b>94</b>	<b>Melt, Olivine</b>
<b>1180 LD</b>	<b>6.6</b>	<b>10.5</b>	<b>89.0</b>	<b>49</b>	<b>Melt, Olivine</b>
<b>1170 LD</b>	<b>6.4</b>	<b>10.6</b>	<b>88.4</b>	<b>116</b>	<b>Melt, Olivine</b>

bar. The lowest temperature, 1170°C, is below Stolper's original eucrite liquidus of ~1180°C [4] and is the temperature where MELTS predicts the appearance of plagioclase. The temperature is controlled via a platinum-rhodium (Type B) thermocouple system. The oxygen fugacity is controlled by flowing CO<sub>2</sub>/CO gas and measured using a remote zirconia oxygen-fugacity electrochemical cell.

The charges were suspended on rhenium loops to prevent iron loss, and the rhenium loop was in turn suspended from drop-quench, thin platinum wires. The charges were then sealed in the furnace and later drop-quenched into water.

The experiments were analyzed using a Cameca SX-100 electron microprobe for the 9 elements in the starting composition (Si, Ti, Al, Cr, Fe, Mn, Mg, Ca, Na). For phase identification and visual orientation, a scanning electron microscope (JEOL 5910LV) was used.

The initial experiments were three SD 1250°C, 1225°C, and 1200°C experiments. However, while the SD experiments gave a general sense of phase assemblages, K<sub>D</sub> values [ $K_D = D(\text{Fe})/D(\text{Mg})$ ] and the large amount of zoning (>5%) in the olivines indicated that longer-duration experiments were required in order to reach equilibrium. Experimental temperatures, durations, and abbreviated results are given in Table 1; CaO and MgO concentrations are for the quenched liquid.

**Results:** When only LD experiments are considered, olivines and melt were typically homogeneous and there was good agreement from crystal to crystal within an individual experiment. Our K<sub>D</sub> partitioning results are also broadly consistent with Jones [5] and Filiberto et al. [6] who demonstrated a linear relation-

ship between  $D(\text{Fe})$  and  $D(\text{Mg})$  for olivine-melt. In addition, there is a smooth variation in the CaO and MgO contents of the quenched liquids with temperature. These observations give us confidence in our approach to equilibrium.

Nonetheless, our experimental results do not agree with the predictions of MELTS. In the temperature range of our experiments, both low-Ca pyroxene and plagioclase were predicted to appear, but only olivine is present in our experiments.

**Figure 1. CaO vs. MgO for Experimental Liquids**

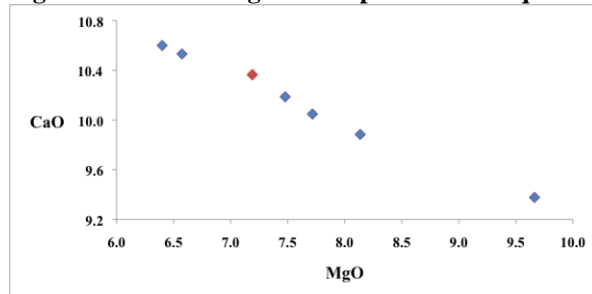


Figure 1. Blue diamonds are experimental glasses showing the liquid line of descent from the 1250°C starting composition (LD only). Red diamond is a composite of the Juvinas and Sioux County eucrites. The experimental trend matches the natural eucrite composition at a significantly higher temperature (~1190°C) than the Stolper experimental liquidus (~1180°C) [4].

This disagreement gives us serious concerns about the applicability of the MELTS calculations described above.

**Discussion:** As predicted by MELTS, the 1250°C composition first has olivine as the liquidus phase. However, even after experimental durations as long as ~5 days, pyroxene fails to appear. Although not as great a concern as the non-appearance of low-Ca pyroxene, plagioclase also did not appear in this same ~5-day experiment — although it was predicted to.

Several experimental observations raise questions about the utility of MELTS to model the differentiation of Vesta and to understand the origins of eucrites and diogenites: (i) The formation of diogenites at >1250°C is modeled as cotectic crystallization of olivine and orthopyroxene, but the presence of olivine in diogenites is limited, to non-existent (typically 0-5%), and the occurrence of olivine and orthopyroxene in igneous contact is rare [7]; (ii) The 1250°C liquid, which is modeled to have post-dated the production of the Main Group eucrites [1], lies within the olivine field of the OL-SI-PL pseudo-ternary, whereas natural eucrites cluster about the OL-PX-PL pseudo-invariant

point, which is a more evolved composition; and (iii) previous 1-bar partial melting experiments on the Murchison chondrite at 1180°C produce eucritic liquids, leaving only small amounts of low-Ca pyroxene in the residuum (~5%), casting doubt as to the relationship between eucrites and diogenites (i.e., no pyroxene remains at 1200°C in the Murchison experiments) [8]. Chemically, the 1180°C pigeonites in the Murchison experiments (Mg# 73) could be consistent with the more ferroan diogenites, but not with those that are more mafic.

Therefore, concerns about how to relate eucrites and diogenites remain [8].

One possibility recently raised by [9] is that Vesta was never homogenized. Possibly eucrites are produced by partial melting of a CM/CO-like mantle, which is poor in pyroxene components, whereas diogenites are cumulates from partial melts of an L/LL-like source. This possibility would render almost any magma ocean scenario either highly improbable or impossible. But such an interpretation would be consistent with the experimental results to date.

**References:** [1] Righter, K. & Drake M. J. (1997) *Meteoritics & Planetary Science* **32**, 929-944. [2] Consolmagno G. and Drake M.J. (1977) *Geochim. Cosmochim. Acta* **41**, 1271-1282. [3] Bartles K.S. and Grove T.L. (1991) *Proc Lunar Planet Sci. Conf. 21<sup>st</sup>*, 351-365. [4] Stolper E. (1977) *Geochim. Cosmochim. Acta* **41**, 587-611. [5] Jones J. H. (1984) *Contrib. Min. and Pet.* **88**, 126-132. [6] Filiberto J. et al. (2009) *Am. Min.* **94**, 256-261. [7] Mittlefehldt D.W. et al. (1998) Non-chondritic Meteorites from Asteroidal Bodies, Chapter 4. In *Planetary Materials*, Reviews in Mineralogy vol. 36 (J.J. Papike, ed.), pp. 104-112; [8] Jurewicz A.J. et al. (1993) *Geochim. Cosmochim. Acta* **57**, 2123-2139; [9] Ammannito E. et al. (2013) *Nature* doi: 10.1038/nature12665.