THE ONSET OF CORE FORMATION IN THE MOST OXIDIZED ASTEROIDS. D. L. Burgin[1,2], S. D. Crossley[1,3], C. A. Goodrich[1]. [1]Lunar and Planetary Institute (USRA), Houston, TX 77058, USA, [2]Department of Geology, University of Otago/Te Whare Wānanga o Ōtākou, Dunedin 9016, Aotearoa/New Zealand, [3]Astromaterials Research and Exploration Sciences, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058, USA.

Introduction: Redox conditions in the solar nebula strongly influenced the types of core-forming phases available during the formation of asteroids and planets. The core forming phases in reduced mineral assemblages are dominated by Fe-Ni metal, which requires extensive silicate melting to segregate from residues and form cores (>1,100°C [1]). Core formation may have also occurred in the most oxidized regions of the protoplanetary disk to form cores composed primarily of Fe-sulfides and Fe-oxides [2], but the geochemical and physical mechanisms of this process are poorly known [3].

To investigate possible melting pathways during core formation in the most oxidized asteroids, we quantified the opaque mineralogy and major element compositions of core forming phases (Fe-sulfides and Fe-oxides) in the most oxidized group of primitive meteorites, the CK chondrites [4-6]. Using previously published Fe-Ni-S and Fe-S-O phase diagrams [7-8], we predict the sulfide assemblage at metamorphic temperatures just prior to the onset of melting and the opaque mineral melting pathways for the most highly oxidized, CK-like asteroids at the onset of melting and core formation.

Methods: Three Antarctic CK chondrite thin sections were obtained from the MWG for this study, EET 87860 (CK5/6), EET 90015 (CK5), and DOM 19035 (CK6). Initial observations were made using a petrographic microscope at the LPI. Backscattered electron images (BSE) and semi-quantitative analyses were collected via SEM at the LPI. Quantitative major element analyses of opaque phases were obtained using EMPA at JSC. Electron dispersive X-ray spectroscopy (EDS) element maps were acquired via EDS/SEM at JSC. Modal mineralogy for opaque core-forming phases was calculated using ImageJ's color threshold tool with RGB Fe, Ni, and S EDS maps.

The bulk composition of core-forming material was estimated using a weighted average composition from EPMA measurements, in which each mineral phase's average composition is multiplied by its modal fraction of the total opaque.

Results: The three CKs contain 7.3 – 9.8 vol% total opaques composed of pyrite (34 at% Fe, 62-65 at% S), pentlandite (23-26 at% Fe, 26-28 at% Ni, 37-48 at% S), and magnetite. Bulk sulfide compositions are 51-57 at% S, 25-31 at% Fe, and 10-23 at% Ni. Bulk opaque

compositions are 40 at% Fe, 3-4 at% Ni, 9-14 at% S, and 43-47 at% O.

Sulfides predominantly occur as pentlandite-pyrite assemblages with magnetite (Fig. 1), and as small inclusions within silicates. Sulfides in EET 90015 are only present as very-fine-grained patches and many were too small to be resolved in EDS maps.
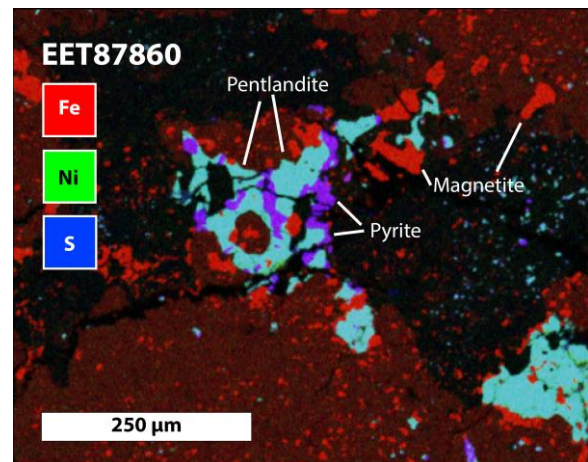

Figure 1: Combined RGB Fe-Ni-S EDS map of pentlandite-pyrite assemblages with magnetite in EET 87860.

Discussion: *Sulfide metamorphic assemblage:* At the average closure temperatures reported for CK5-6 chondrites [6,9], the pentlandite-pyrite assemblages we observed are not stable and will breakdown to form monosulfide solid solution (MSS) [7] (Fig. 2A).

DOM 19035 and EET 90015 have higher modal abundance of pyrite and lower abundance of Ni relative to EET 87860, possibly due to higher fO_2 for the latter [6]. The stable sulfide phases of DOM 19035 and EET 90015 at 750-800°C are MSS and elemental S $\pm$ vaesite (Fig. 2B) [7]. Elemental S, while stable in simple Fe-Ni-S melting experiments, will react with olivine to form orthopyroxene and Fe-sulfide at metamorphic temperatures. Sulfidation of olivine during metamorphism in CK chondrites has been suggested by [10] to explain reaction textures of low-Ca orthopyroxene and sulfides, though the source of sulfur was not found. Elemental sulfur formed by thermal decomposition of pyrite during metamorphism is a likely candidate for the sulfidizing agent. Closure temperatures for these reaction textures were reported using two-pyroxene thermometers and yielded uniform closure temperatures of ~740 ±30°C [10], coincident with the thermal decomposition temperature of pyrite.
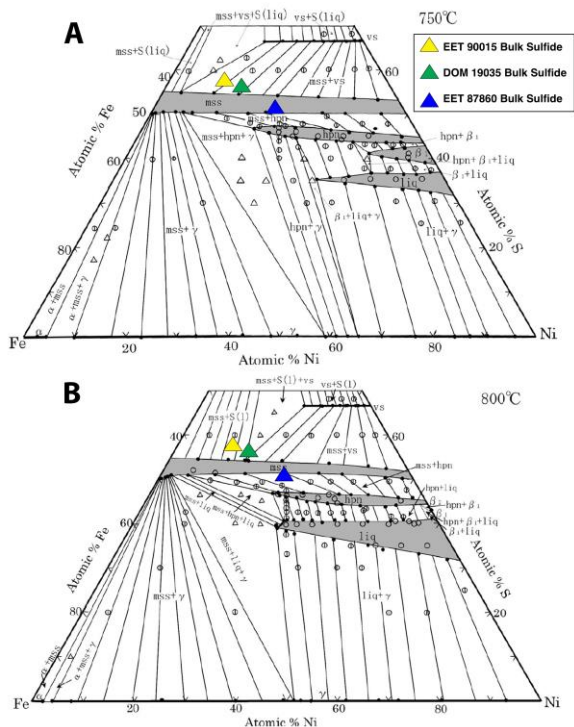
Figure 2: Bulk sulfide compositions in Fe-Ni-S system at 750°C (**A**) and 800°C (**B**), from [7].

Melting Behavior: The Fe-S-O phase diagram [8] is used here to determine the initial melt behavior during core formation in the CK parent body. Melts would first form in EET 87860 at the 934°C eutectic point with compositions of 25 wt% S, 8 wt% O, and 67 wt% Fe (Fig. 3). In EET 90015 and DOM 19035, following the reaction of elemental S with olivine, melts would follow a similar pathway. Continued melting would first consume MSS, which would melt completely by ~1,150°C [11], after which the composition of the melt would evolve towards magnetite, which itself would not completely melt until >1,400°C. Melting in the magnetite-dominated phase space is poorly constrained and the initial reactions that may occur between magnetite and sulfide melts are not well characterized. Melting experiments with synthetic analogues of CK
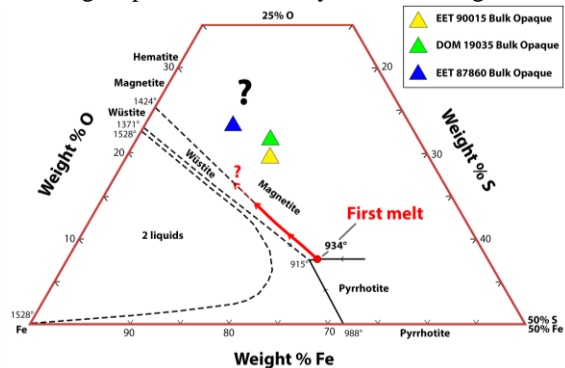

Figure 3: CK melting pathway in the Fe-S-O system [8].

chondrite sulfides and oxides are needed to further investigate the geochemical evolution of highly oxidized core formation.

The initial, sulfide-dominated melts have an anion:cation ratio of 1.07, which is consistent with liquids capable of migrating via grain boundary wetting [12,13]. However, complete melting of the entire sulfide fraction, <2.2 vol%, falls below the ~4 vol% threshold required for the formation of interconnected melt networks [14]. Therefore, core formation in the CK parent body would not be able to occur through percolation prior to the silicate eutectic, in contrast to the most oxidized noncarbonaceous chondrites [15].

This finding indicates there is an upper $f\mathrm{O}_2$ threshold that inhibits core formation by percolation and connected melt networks below the silicate eutectic. However, the local sulfidation of olivine and/or magnetite from decomposing pyrite may alter the proportions and distribution of sulfides prior to partial melting.

Summary: Results for the bulk compositions of sulfides in two CK chondrites suggest that thermal decomposition of pyrite during parent body metamorphism resulted in the sulfidation of olivine to form previously observed reaction textures of MSS and orthopyroxene [10]. Bulk opaque compositions indicate that the first melts to form (~934°C [8]) will be sulfide-dominated, with an anion:cation ratio that would allow for migration via grain boundary wetting. However, connected melt networks would not be able to form due to an underabundance of sulfides, and segregation of core-forming phases would require temperatures above the silicate eutectic.

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