PETROLOGY AND OXYGEN ISOTOPES OF CHONDRULES IN THE KOTA KOTA EH3 CHONRITE.

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Introduction: The silicate, sulfide, and metal compositions of enstatite chondrites indicate formation under highly reducing conditions [1], which differ sharply from the disk regions in which other chondrite groups formed. Their major silicate phase is near-pure enstatite (FeO <1.0%). They contain high amounts of FeNi metal and the metal is Si-bearing, with more than 2 wt.% Si in the EH chondrites. Elements that are typically lithophile in most chondrites (i.e., Mg, Mn, Cr, Na. K) are both lithophile and chalcophile in the E chondrites. E chondrites contain oxi-nitride and nitride phases sinoite (Si_2N_2O) [2-4] and osbornite (TiN) [4], which are also indicators of highly reducing conditions.

The properties of chondrules in E3 chondrites have been described previously [5-12] and we reported on the petrologic characteristics and oxygen isotopic compositions of olivine and pyroxene in chondrules from the Sahara 97096 and Yamato 691 EH3 and the unusual LEW 87223 E3 chondrite [12, 13, 14]. Here we extend our study to chondrules from the Kota Kota EH3 chondrite. Our goals are to (1) understand the origin of chondrules in E3 chondrites compared to chondrules in other chondrites, (2) provide constraints on their thermal histories in the context of chondrule formation models and, (3) place constraints on conditions within the disk region in which they formed.

Results: Here we report on newly studied chondrules from the Kota Kota EH3 chondrite, 12 of which were selected for oxygen isotope analysis. Kota Kota was selected for study because it is thought to be among the most primitive EH3 chondrites, although its olivine content, a characteristic feature of low metamorphic grade EH chondrites, is relatively low compared to the most primitive EH3's [15]. *Textures and Mineral Assemblages.* Chondrules in the studied Kota Kota section range in size from about 100 to 700 µm with an average of 350 µm and are within the size range previously reported for chondrules in EH3 chondrites (278 ± 229 µm) [11]. Chondrule textures in Kota Kota include prophyritic pyroxene (PP), radial pyroxene (RP) and cryptocrystalline (C). In comparison, porphyritic olivine pyroxene (POP) and porphyritic olivine (PO) are the dominant chondrule types in ordinary (OC) and carbonaceous (CC) chondrites. Rare PO and POP and even BO chondrules were found in Sahara 97096, Y 691 as well other EH3 chondrites [11, 13], but these chondrule types were not found in Kota Kota. The PP chondrules in Kota Kota can be considered type IB (less than 20% of the phenocrysts are olivine). However, there are marked differences between the PP chondrules in EH and type IB chondrules in O and C chondrites, as described below.

The PP chondrules in Kota Kota consist of low-Ca pyroxene (generally enstatite) ± olivine (forsterite) with albitic glass ± silica. Olivine generally occurs as poikilitic inclusions in enstatite. Cr-bearing troilite is commonly present and, in some chondrules, nodules of opaque assemblages of troilite, Si-bearing metal ± oldhamite (CaS) ± niningerite (Mg,Fe,Mn)S are present. Additionally, pyroxene with up to 15 wt. % FeO is present in rare chondrules and fragments. The Sahara 97096 and Y 691 EH3 chondrites are also dominated by enstatite-rich chondrules. However, they also contain minor POP and PO chondrules with large olivine crystals (up to 200 µm size) surrounded by fine enstatite and albitic glass and silica and rare BO chondrules. Most type I chondrules in OC and CC are dominated by olivine, silica is not common and Si-bearing metal, Cr-troilite, niningerite and oldhamite are not present.

Mineral Compositions. Near-endmember enstatite ($Fs_{<1}$) is the most common phase in Kota Kota as in most E3 chondrules. More FeO-rich compositions (up to $Fs_{21.1}$) are also found in some chondrules, with up to 0.6 MnO and 1.7 wt. % Cr_2O_3. Some FeO-bearing pyroxene grains contain tiny (<1 µm) inclusions of FeNi metal. Some show areas of low-Fe enstatite associated with the metal blebs suggesting reduction of Fe from the Fe-rich grains [e.g.,11]. Some chondrules are disequilibrium assemblages containing FeO-bearing pyroxene associated with FeO-poor enstatite. Most olivine in Kota Kota is near-pure forsterite ($Fa_{<1}$). Chondrule mesostases are albitic with (wt. %) up to ~ 68 SiO_2, 18 Al_2O_3, 9 Na_2O and 5 CaO. Precise values are difficult to obtain due to the presence of microcrystals and loss of Na during electron probe analysis.

Oxygen Isotopes. Oxygen isotope analyses were performed using the IMS-1280 at the University of Wisconsin using an ~15µm spot size in Multicollection FC mode with a typical analytical precision of 0.3‰ (2SD) for both $\delta^{17}O$ and $\delta^{18}O$ [16]. The chondrules and fragments that were analyzed were selected to cover a range of textural types and compositions. Most are PP chondrules dominated by near-pure enstatite but some contain olivine or FeO-bearing pyroxene. Enstatite,

FeO-bearing pyroxene and olivine all show a similar range of compositions with most plotting near the values for EC whole rocks, along the terrestrial fractionation line (Fig.1). Some chondrules (e.g., C2 and C15) plot above the TF line close to the region for OC on the three-isotope diagram. Our previous data for other EH3 chondrites also plot near the EC whole rock compositions with some plotting in the OC region, similar to Kota Kota chondrules (Fig. 2). However, some chondrules from other EH3s (Sahara 97096, Y 691 and LEW 87223) plot toward more ^{16}O-rich compositions forming a mixing line that is similar to but displaced from the CCAM line. We refer to this as the ECM (enstatite chondrite mixing) line, but recognize that it may not be unique to the EH chondrules. The chondrules that extend to more ^{16}O-rich compositions are the less common olivine-rich chondrules, which have not been found in Kota Kota. One olivine-rich chondrule from Sahara 97096 expands the range to more ^{17}O-rich values, plotting above the OC field, in the R chondrite region of the 3-isotope diagram (Fig. 2).

Discussion and Conclusions: Chondrules in Kota Kota as well as other EH3 chondrites have petrologic characteristics that differ from those in OC and CC groups. The oxygen isotope compositions of chondrules from Kota Kota and other EH3s were also shown to differ from those of OC and CC [e.g., 17]. Our data show that most chondrules from Kota Kota as well as from other EH3 chondrites plot along the terrestrial fraction line near EC whole rock values. However, some chondrules overlap the OC field on the 3-isotope diagram and some (from Sahara 97096, Y 691 and LEW 87223) extend toward more ^{16}O-rich compositions. Based on this study, Kota Kota does not contain the olivine-rich chondrules with more ^{16}O-rich compositions. The chondrules with ^{16}O-rich compositions appear to form a mixing line similar to but distinct from the CCAM line. We call this the ECM line. The ECM line may extend to the ^{16}O-rich CAIs in EH3 chondrites, $\delta^{17}O < -40$ ‰ [18]. Thus, EH3 chondrules represent a distinct oxygen isotope reservoir from OC and CC, but show oxygen-mixing behavior similar to chondrules in other groups, indicating similar chondrule-forming processes but in a separate nebular region.

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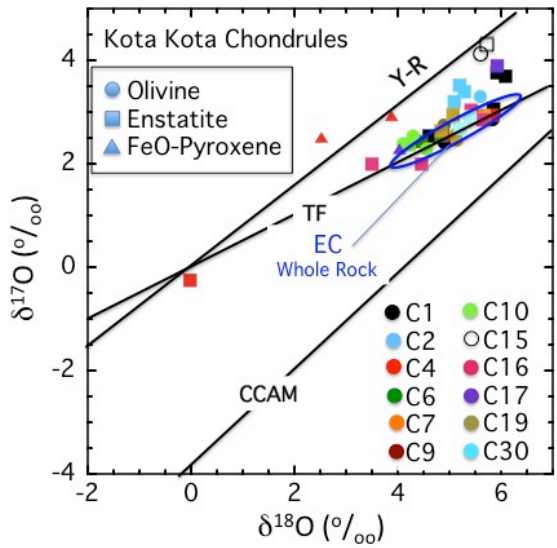

Figure 1. Oxygen isotope compositions of olivine and pyroxene in 12 Kota Kota chondrules. TF- terrestrial fractionation line, Y-R – Young and Russell line, CCAM – carbonaceous chondrite anhydrous mixing line.

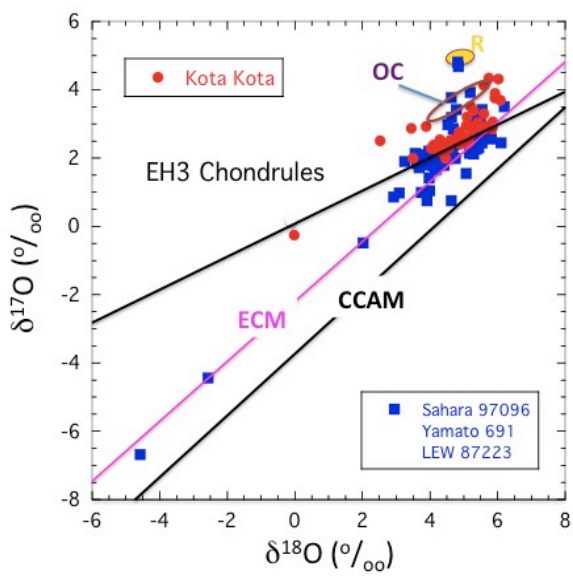

Figure 2. Oxygen isotope compositions of olivine and pyroxene in Kota Kota chondrules compared to chondrules from the Sahara 97096 and Y 691 EH3 and LEW 87223 E3 chondrite. ECM - enstatite chondrite mixing line.