Introduction: Chondritic meteorites consist primarily of chondrules, Ca-, Al-rich inclusions (CAIs), fine grained matrix, and metal-sulfide nodules [1]. Chondrules are near-spherical objects that were once partially molten, retaining significant chemical and isotopic information about their formation. Chondrules are either nonporphyritic [2] or porphyritic with phenocrysts primarily of olivine and Ca-poor pyroxene. Ordinary chondrules account for ~85% of all meteorites, and in contrast to most carbonaceous chondrites, contain practically no CAIs. Since CAIs are enriched in rare earth elements (REE), but the ordinary chondrules are not especially depleted in REE, one question is: where do the REE reside in the ordinary chondrites?

The iron-poor LL chondrites represent increasing degrees of parent body metamorphism. The porphyritic ordinary chondrite Semarkona (LL 3.0) is the least equilibrated with practically no CAIs. A study performed by [3] indicated the metamorphic temperatures at which LL unequilibrated ordinary chondrites experienced was too low for REE chemical exchange to occur. Here, we report the distribution of REE among its components. Previous studies reported negative Eu anomalies, consistent with igneous crystallization [4, 5]. Partitioning of REE may allow distinguishing between open or closed system fractional crystallization of chondrule melts, such as their response to compositional changes, such as the addition or loss of water. Partitioning may also reveal environmental changes, such as changes in temperature or oxidation state of surrounding gas, that chondrules underwent during crystallization. Glass, olivine, and Ca-poor pyroxene are the most common phases within Semarkona chondrules. The relative abundance of olivine, pyroxene and glass may affect the distributions or absolute amounts of REE among phases.

Analytical Techniques: Compositions of fourteen REE were analyzed in olivine and quenched glassy mesostasis in Semarkona chondrules. A total of 81 chondrules were mapped from five different Semarkona sections. Complete data from only 36 of the 81 chondrules was obtained due to navigation issues. A variety of chondrule types were analyzed including FeO-poor and FeO-rich barred olivine chondrules, pyroxene-rich and olivine-rich porphyritic olivine chondrules, and Ca-rich chondrules. Analyses were carried out using an electron microprobe (CAMECA SX100 at AMNH) to make x-ray element maps to navigate around the chondrite, an optical microscope to obtain reflected light images of chondrules of interest, a Laser Ablation-Inductively Coupled Plasma-Mass Spectrometer (LA-ICP-MS, at Rutgers U.) to analyze REE abundances, and a Zeiss EVO-60 scanning electron microscope (SEM) to precisely locate spots after analysis. Large area maps at 5-10µm/pixel resolution were used on the polished sections of Semarkona combined into red-green-blue (RGB) composites (e.g., Mg=red, Ca=green, Al=blue) to locate chondrules and estimate their abundances of different mineral phases. Large euhedral grains indicate slow cooling of the minerals, while the chondrules with barred textures (e.g., ch52 in Sem1-ps2A, Fig. 1) were rapidly quenched. Next, secondary submaps at 1 µm/pixl were constructed for each region that was found to be of interest in each chondrule, at high beam current (40 nanoAmps, nA) and long dwell time (30 milliseconds, ms) with wavelength dispersive spectrometers only, in only 5 elements (e.g., Figs. 2, 3). The smaller, high resolution maps were used to determine exact spots for laser ablation.

After analyzing the samples with the LA-ICP-MS, the location of each LA-ICP-MS spot in the samples was obtained using the SEM to make BSE images. From these, masks were created to isolate each spot in high-resolution maps (Fig. 2) so that the x-ray intensities in the pixels in each LA-ICP-MS spot could be counted in the x-ray maps. To allow calibration based on MgO, SiO₂, and CaO, the high resolution, long dwell-time maps were used with 128x128 pixel maps of known standards such as Mg₂SiO₄ (forsterite), MgCaSi₂O₆ (diopside), and MgAl₂O₄ (spinel), to determine within the sample the average MgO in the analyzed spot. Counting the total MgO, SiO₂, and CaO counts/pixel in the spot in the x-ray maps allowed conversion to wt% MgO, etc. We then transferred the
collected MgO, SiO$_2$, and CaO data to the LazyBoy 3.11 reduction software to convert the trace element data into raw elemental abundances and calibrate them against the element intensity data from the high-resolution microprobe maps. The standards NIST610, NIST612, NIST614, BIR, and BCR were used internally on the LA-ICP-MS instrument. Measured REE abundances are normalized to the CI chondritic abundances of [6].

Results and Discussion: Fig. 4 displays data from [5] for LL chondrites Semarkona, Bishunpur, and Chainpur, recalculated and plotted in the same way as our results (Figs. 2, 3). Four main phases are represented by [5]: olivine, orthopyroxene, clinopyroxene, and glass. The REE partition most strongly into glass, followed by Ca-rich pyroxene, interpreted to form during quench of the liquid to glass. Our results are very similar to those of [5]. What is remarkable is the consistency of ~10xCI in mesostasis, and 0.1 to 1.0xCI in olivine, across a wide range of chondrule types in LL chondrites.

Future Work: Matrix, and more chondrules from Semarkona will be analyzed for a more complete survey of chondrule textural and chemical types.

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