INTRODUCTION: We have studied the petrography and Fe-isotope composition of seven chondrules, four from the Allende (CV3) carbonaceous chondrite and three from the Chainpur (LL3.4) ordinary chondrite. Three textural-chemical chondrule types are represented within this sample set: (1) BO, (2) RP and (3) PO/POP. These textural differences allow us to examine the Fe-isotope composition in material with different thermal histories.

Fe-isotope measurements may help to constrain the chondrule forming process and determine the nature of chondrule precursor material. Fe is the most volatile major element found within chondrules [1], and thus the Fe-isotope composition may reflect evaporative loss of iron, if evaporation occurred by a Rayleigh fractional process.

Experimental Techniques: A Phillips XL-30 SEM was used for textural characterization of a polished subsample of each chondrule. Quantitative silicate and metal phase analysis was undertaken using a Cameca SX-50 electron microprobe. Chondrule dissolution follows a two step HF-HClO₂-HCl method [2]. Digests are purified using anion exchange chromatography, which separates out Fe, Cu and Zn. This procedure has been detailed elsewhere [3]. Fe-isotope compositions (δ⁵⁶Fe and δ³⁶Fe) were measured on a fixed resolution (m/Δm = 500) MC-ICP-MS (IsoProbe, Micromass, U.K.) with respect to the Fe-isotope standard IRMM-014, using the sample-standard bracketing method [3].

Correction for ⁵⁵Cr on ⁵⁶Fe is made by monitoring the ⁵⁵Cr signal and applying an on-line mathematical correction at mass 54. Blank subtraction is undertaken off-line. The effect of Ar⁴⁰O⁴⁰H background at mass 57 is reduced by analysing at relatively high concentrations [4]. Standard and sample solutions are analysed at approximately 10ppm concentration and are concentration matched to within 2%.

Chondrule Petrography:

Allende EM-1 (Figure 1A). Allende EM-1 is a barred olivine chondrule. Olivine bars range in composition from Fo₈₈ to Fo₉₇. The groundmass consists of plagioclase laths (An₉₁ to An₉₇) set in diopside (Wo₂₉En₃₀Fs₁₃ to Wo₃₁En₃₀Fs₅). Allende EM-2 (Figure 1B). Allende EM-2 is a radial pyroxene chondrule which is rimmed with forsteritic olivine of variable composition (Fo₀₉ to Fo₁₇). Pyroxene (enstatite) is homogeneous in composition (Wo₂₉En₃₀Fs₁₃ to Wo₃₁En₃₀Fs₅).

Allende EM-3 (Figure 1C). Allende EM-3 is a porphyritic olivine chondrule with rare pyroxene phenocrysts set in an anorthitic groundmass (An₉₉ to An₉₅). All but the smallest olivine phenocrysts are zoned. Phenocrysts comprise Fo₁₂ to Fo₉₆ whereas rims comprise Fo₆₈ to Fo₉₂. Smaller unzoned olivine phenocrysts approximate to rim Fo content, with compositions falling between Fo₆₈ and Fo₉₆. Diopside phenocrysts range from Wo₂₉En₃₀Fs₁₃ to Wo₃₁En₃₀Fs₅.

Allende EM-4 (Figure 1D). Allende EM-4 is a porphyritic olivine chondrule. Olivines exhibit clear compositional delineation between cores and rims. In contrast to EM-3, the olivines in this chondrule have more magnesian cores (Fo₈₄ to Fo₉₉) and more iron rich rims (Fo₉₀ to Fo₉₃). Pyroxene (augite - subcalcic augite) only occurs in the mesostasis and ranges in composition from Wo₂₉En₃₀Fs₁₃ to Wo₃₁En₃₀Fs₅. Individual pyroxene crystal compositions do not vary systematically in composition.

Chainpur EC-1 (Figure 1E) is a porphyritic olivine pyroxene chondrule. The larger olivine phenocrysts are zoned with MgO rich cores (up to Fo₉₃) and less...
magnesian rims (Fo<sub>24</sub> minimum). Smaller unzoned phenocrysts have have compositions in the range Fo<sub>75</sub> to Fo<sub>94</sub>. Pyroxene phenocryst cores are enstatite (average Wo<sub>80</sub>En<sub>20</sub>Fs<sub>12</sub>), and rims are augite (average Wo<sub>80</sub>En<sub>20</sub>Fs<sub>13</sub>). Enstatite and augite are clearly delineated, with no intermediate compositions found. The Fs content of both rims and cores is almost identical. Tiny unzoned skeletal pyroxene laths scattered within the mesostasis also comprise augite (average Wo<sub>92</sub>En<sub>8</sub>Fs<sub>10</sub>). These laths have slightly more Fs component than pyroxene rims, but are otherwise similar in composition.

Chainpur EC-2 (Figure 1F) is a porphyritic olivine pyroxene chondrule set in a glassy mesostasis. Olivine compositions average Fo<sub>94</sub>, but range from Fo<sub>76</sub> to Fo<sub>94</sub>. There is very little evidence of zoning within individual phenocrysts. Pyroxene phenocrysts are composed of enstatite and range from Wo<sub>80</sub>En<sub>20</sub>Fs<sub>15</sub> to Wo<sub>92</sub>En<sub>8</sub>Fs<sub>10</sub> in composition.

Chainpur EC-3 (Figure 1G) is a radial pyroxene chondrule formed mainly of skeletal pyroxene of very restricted enstatite composition from Wo<sub>80</sub>En<sub>20</sub>Fs<sub>15</sub> to En<sub>90</sub>Fs<sub>10</sub>. Mesostasis constitutes less than 3% and defines an igneous crystallization trend between the following end-members: (1) 60% SiO<sub>2</sub> + 20% MgO + 8% FeO + 5% Al<sub>2</sub>O<sub>3</sub> and (2) 74% SiO<sub>2</sub> + 18% Al<sub>2</sub>O<sub>3</sub> + 24% MgO + 1.5% FeO.

Fe-isotope Fractionation: The range of δ-values are illustrated in Figure 2. The overall variation in δ<sup>57</sup>Fe is 1.98‰ and in δ<sup>56</sup>Fe is 2.87‰. EM-1 (BO) is most isotopically heavy and EM-3 (PO) is most isotopically light, with all other chondrules falling in a mass fractionation line between these two end-members. This line is defined by the equation δ<sup>56</sup>Fe = (1.450±0.050)δ<sup>56</sup>Fe - (0.009±0.016) (R<sup>2</sup> = 0.9995).

![Figure 2: δ<sup>56</sup>Fe vs. δ<sup>57</sup>Fe for Allende and Chainpur chondrule samples. Error bars are ± 0.05‰ (2σ).](image)

Discussion: Fe-isotopic fractionation in excess of 6‰ is expected if fractionation occurred under Rayleigh conditions [5]. The reduced fractionation exhibited by Fe-isotopes suggests that Rayleigh conditions were not fulfilled during chondrule melting.

The Chainpur chondrules we have measured exhibit less Fe-isotope fractionation than the Allende chondrules, a total of 0.46‰ (δ<sup>56</sup>Fe) and 0.61‰ (δ<sup>57</sup>Fe), in contrast to 1.98‰ (δ<sup>56</sup>Fe) and 2.87‰ (δ<sup>57</sup>Fe), respectively. This may reflect different degrees of equilibration of each chondrite, thus Chainpur may be more equilibrated than Allende. Chainpur Fe-isotopic systematics may have been shifted towards more homogeneous values by later addition of Fe, either from (1) nebular reservoir or (2) parent body alteration.

Variation in FeO content in phenocryst core-rim relationships is complicated. EM-3 olivines show Fo-rich rims and slightly more Fe-rich cores. In contrast, two chondrules (EM-4 and EC-1) have Fo-rich cores, with more fayalitic rims, indicating later addition of Fe. These latter two chondrules have similar isotopic compositions, and are different in composition to EM-3. This supports later equilibration of the Fe-isotopes.

Nonporphyritic chondrules are produced by almost total or complete melting of the precursor material. In contrast, porphyritic chondrules experienced lower peak temperatures with the preservation of some crystallization nuclei. However, Fe-isotope fractionation does not appear to vary systematically with texture and assumed temperature of chondrule formation. Those chondrules which experienced almost complete melting and obliteration of crystallization nuclei are both isotopically light (EM-2) and isotopically heavy (EM-1 and EC-3), respectively, with respect to the standard (Figure 2). Similarly, porphyritic chondrules do not exhibit systematic variation with respect to texture. We conclude that Fe-isotopic signatures of the chondrules represent that of the precursor material and in the case of the Chainpur chondrules, this signature was later equilibrated.

Another consideration is the number of melting events these chondrules have undergone. The melt that the isotopically heaviest chondrules (e.g. EM-1 and EC-3) derive from may have attained liquidus temperatures more than once. The precursor to EM-2, the isotopically lightest chondrule, may not have been subject to as many aggressive heating events.