THE MINERAL COMPOSITIONS AND CLASSIFICATION OF HIGH TYPE-3 AND TYPE-4 ORDINARY CHONDRITES.

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Introduction: The "petrologic type" of a chondrite is a parameter that is widely used to indicate the intensity of thermal metamorphism, often as a proxy for peak or closure temperature, in studies of meteorites and their parent asteroids. For ordinary chondrites (OCs), petrologic type was defined in the 1960s [1] to range from 3 (little metamorphism) through 6 (chemical and textural integration, probably heated to near solidus temperatures). Because of intense interest in the identification of highly primitive meteorites, extensive studies of type-3 chondrites have been made over the last 30 years, enabling ever-finer subdivisions to be made to the petrologic type scale [e.g., 2,3]. Primitive OCs (and some carbonaceous chondrites) can now be placed in a well-defined, continuous sequence with the least-metamorphosed samples ranging from type 3.00-3.15 and the more-metamorphosed ones ranging from 3.2-3.9. For the sequence 3.2-3.9, thermoluminescence (TL) sensitivity has proven to be the most useful classification parameter [2].

Despite this progress for type-3 chondrites, the metamorphic sequence ranging from types 4 to 6 remains fairly crude and, we think, poorly defined. The main way that type-3 OCs are distinguished from type 4s is by using a mineralogical parameter devised by [4], the percent mean deviation of FeO measured in randomly selected olivine grains (PMD-ol): OCs with heterogeneous olivine compositions (PMD-ol $\geq$ 5%) are defined to be type 3, whereas OCs with more homogeneous olivine (PMD-ol < 5%) are defined to be type 4. Although a variety of chemical and petrographic parameters are known to correlate with PMD-ol across the type 3/4 boundary, many are difficult to measure (e.g., volatile trace elements like In, Cd, Bi and Tl, and primordial noble gases) or semiquantitative (e.g., the degree to which matrix has recrystallized or the fraction or chondrule glass that has devitrified). None of these parameters, including TL sensitivity, are known to show a large amount of variation across the type 3/4 boundary or a high degree of correlation with other petrographic parameters. The boundary between types 4 and 5 is likewise somewhat uncertain (and rather subjectively applied in practice). The main change used to define the 4/5 boundary is the transformation of low-Ca pyroxene from a predominantly monoclinic structure to the orthorhombic form, a measurement that is rarely done by classifiers in any quantitative way. The >40-year-old statement by Van Schmus and Wood [1] still holds: "Petrologic type 4 is defined by relatively ambiguous characteristics."

We have begun a study that, we hope, will lead to much more quantitative and accurate methods for arranging OCs in a progressive metamorphic sequence. This, in turn, should lead to better tools for understanding metamorphism in the parent asteroids.

Samples and experimental methods: We selected 16 H, 16 L, and 10 LL chondrites for study. Within each group, several high type-3 specimens were chosen, based on literature classifications. The majority of specimens were type 4 or type "4/5", selected based on literature data to span a wide range of heterogeneity of FeO in low-Ca pyroxene (PMD-px). Dodd et al. [4] showed that pyroxene was slower to equilibrate than olivine during metamorphism in OCs; thus, type-4 chondrites with high PMD-px are presumably near the type-3 border and those with low PMD-px should be near the type-5 border. In each specimen, ~100 olivine + pyroxene grains (at least 30 of which were pyroxene) were analyzed by electron microprobe at the USGS, using a very similar grain-selection method as in [4]. Then, 10-15 small (<15 μm) chromite grains were randomly selected for analysis at the USGS and 10-15 grains of kamacite were analyzed at UCLA. All of these meteorites are being characterized at the University of Arkansas for their TL sensitivity and cathodoluminescence (CL) properties [5].

Results and discussion: We were able to duplicate the data of [4] for the parameters PMD-ol and PMD-px for 10 samples in common between the two studies. However, we tended to get lower PMD-ol than is reported in literature data other than [4]; e.g., by our measurements, Dhajala should be classified as H4 (PMD-ol = 3.4%), whereas [6] found it to be H3 (PMD-ol = 12.6%). We attribute such differences to the lack of a standardized method for measuring silicate compositions, and suggest that random methods as in [4] should always be used.

Olivine heterogeneity has long been recognized as a key indicator for metamorphism in type-3 chondrites. Despite the fact that Dodd et al. [4] showed that pyroxene equilibrates more slowly than olivine, PMD-px has rarely been exploited as a metamorphic indicator for the higher petrologic types. In Fig. 1, we show that pyroxenes become more iron rich in each OC group as PMD-px decreases during metamorphic equilibration across high-type-3 and type 4. Analagous to what has

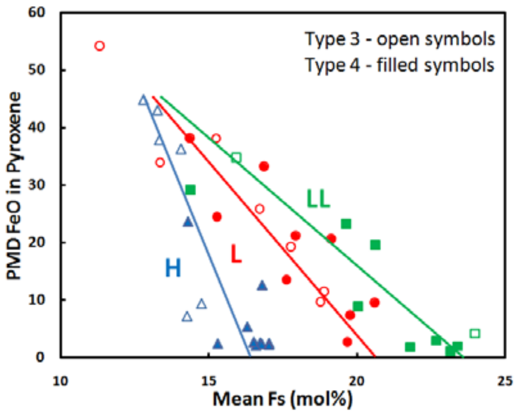

Figure 1. Relationships in OC groups between low-Ca pyroxene heterogeneity (PMD-px) and composition (mean Fs). Lines connect a common heterogeneous starting composition near Fs_{14} with the approximate compositions of equilibrated members of each group.

been shown for olivine in type-3 chondrites [4, in their Fig. 8], pyroxene gradually becomes more FeO-rich as it homogenizes across type 4. Note that there is a large amount of overlap in Fig. 1 between meteorites classified as type 3 (open symbols) and those classified as type 4 (filled symbols), especially in the L group, which we attribute to the failure of existing classification methods to arrange specimens in a meaningful metamorphic sequence. We anticipate being able to use this plot and other data to remedy this situation once our study is complete. For now, we will refer to type-4 chondrites with PMD-px < 5% as "high type 4."

Other mineralogical parameters correlate with PMD-px, and thus change in a quantitative way during thermal metamorphism. Although olivine has homogeneous Fe/Mg ratios in type-4 OCs, it becomes increasingly depleted in CaO and Cr_2O_3 (Fig. 2) and marginally richer in MnO in going from low to high type 4.

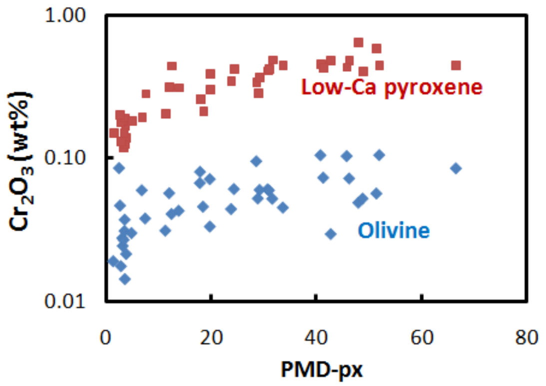

Figure 2. Changes in the Cr content of olivine and pyroxene in high-type-3 and type 4 OCs with metamorphism. Samples with low PMD-px are the most metamorphosed.

Similarly, as the Fe/Mg ratio of pyroxene equilibrates and FeO contents increase during metamorphism, pyroxene also becomes greatly depleted in Cr_2O_3 (Fig. 2) and somewhat richer in MnO. TiO_2 is much higher and Al_2O_3 slightly lower in high-type-4 pyroxene than in pyroxene in rocks of lower petrologic type. The mean CaO content of the low-Ca pyroxene is fairly constant across type 3 and 4. In type 3 and low-type-4, there is a high degree of scatter in CaO (PMD of CaO is near 70-100%), but high type-4 chondrites are much more homogeneous, with PMD of CaO dropping below 20%. This may turn out to be a useful classification parameter for chondrites near the type 4/5 boundary. With the exception of FeO, minor elements are indistinguishable in olivine and pyroxene from H, L, and LL chondrites at all degrees of metamorphism.

Chromite composition also changes in response to metamorphism, with compositional parameters correlated to PMD-px. The most significant change is a >2× increase in Al_2O_3 (from ~ 3 to ~7 wt%) in going from low to high type 4; the Cr_2O_3 content of chromite shows a corresponding drop as Al_2O_3 increases. Concentrations of these components are independent of OC group, in contrast to FeO, MnO, and MgO concentrations (which are different in each chondrite group and independent of metamorphic grade).

The Co content of kamacite does not appear to be related to metamorphic parameters such as PMD-px in high-type-3 to type-4 H and L chondrites. Two of our four high type-4 LL chondrites have elevated Co, above 30 mg/g, which is similar to the difference observed by [7] between LL3-4 and LL5-6 chondrites.

Conclusions: The data presented here should permit the development of classification methods that allow high type-3 to high type-4 OCs to be placed in a meaningful metamorphic sequence. We will support this work with CL and induced TL results when they are complete. At this point in the study, we can already make several conclusions: 1) Many OCs near the type 3/4 boundary are probably misclassified; current methods are probably inadequate to distinguish between high type-3 and low type-4 chondrites. 2) There is a large range of metamorphic effects across type 4 OCs; high type-4 OCs have significantly different mineral compositions than low type 4s.

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