USING IMMERSION OILS TO CLASSIFY EQUILIBRATED ORDINARY CHONDRITES FROM ANTARCTICA. N. G. Lunning[1], C. M. Corrigan[1], L. C. Welzenbach[1] and T. J. McCoy[1] [1]Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119, USA; lunningn@si.edu

Introduction: In the last decade, over 7000 meteorites have been collected in Antarctica by the U.S. Antarctic Search for Meteorites (ANSMET) program. As part of the U.S. Antarctic Meteorite program, one of the Smithsonian Institution's responsibilities is to classify all of these meteorites within two years of being returned from Antarctica, as required by the U.S. Federal Regulations on Antarctic Meteorites. Timely classification of new meteorites requires that limited resources be strategically applied. Our goal is to provide robust classifications that enable researchers to request material relevant to their work. However, robust and timely classification does not mean an exhaustive description of each new meteorite. That is ultimately the role of interested scientists [1].

Background: The oil immersion (OI) method currently used to classify equilibrated ordinary chondrites (EOCs) was developed by Brian Mason and has been used to classify the majority of EOCs in the U.S. Antarctic Meteorite Collection into chemical groups: H, L and LL. While unequivocally less robust than WDS analyses from an electron microprobe, this technique is more accurate than handsample examination alone in distinguishing between chemical groups for EOCs. For these high petrologic type ordinary chondrites, the loss in rigor by using immersion oils is balanced by the substantial decrease in labor and instrument time.

Classifying EOCs serves as a final check that rare meteorite types have not been overlooked during initial processing. While the OI method has potential to flag several groups of rarer meteorites if they have been misclassified as ordinary chondrites, it will not diagnostically catch all rare types (e.g., acapulcoites).

Classification of Equilibrated Ordinary Chondrites: EOCs can be classified into LL, L and H groups by the composition of their olivine grains [2, 3, 4]: LL-group has $Fa_{27.5\text{-}30.2}$, L-group has $Fa_{22.7\text{-}25.6}$, and H-group has $Fa_{16.9\text{-}20.4}$ [2]. The refractive indices of olivine are proportionally related to its composition (mol.% Fa) [6, 7] (Fig. 1).

Review of Relevant Optical Mineralogy: Olivine is an orthorhombic mineral; therefore its three crystal axes (x, y, z) coincide with its axes of least, intermediate and greatest refractive index (α, β, γ). These axes (α, β, γ) are perpendicular to each other in orthorhombic minerals [7, 8]. Even though each axis has a different refractive index (RI), they each linearly change with mol % Fa [4, 5, 6]. Like all biaxial minerals, olivine's birefringence (δ) is defined by the difference in the RI of its slowest (γ, greatest RI) light path and its fastest (α, least RI) light path: $\delta = \gamma - \alpha$. Thus, when looking straight down the β axis of an olivine grain the highest possible interference colors will be observed. From this vantage point, the γ and α axes are perpendicular to the β axis [8, 9]. In cross polarized light, when interference colors are visible, light is passing through a combination of the γ and α axes. When the grain is extinct, light is only passing through one of these two axes, and the immersion oil can be compared to a single axis. In plane polarized light, the Becke line (a halo of light that accumulates at the contact between materials with different RI) will indicate which has higher RI by whether the Becke line moves into the oil or into the grain as the stage is lowered and raised. As the stage is lowered, the Becke line moves towards the material with a higher RI. Alternately, as the stage is raised, the Becke line moves into the material with a lower RI [8,9]. In the OI method, the axis (either γ or α) being viewed can be recognized in plane polarized light by the level of contrast between the grain and the oil, because the γ axis has a closer RI to the immersion oil; therefore viewed through the γ axis the grain will have a lower contrast to the oil.

This procedure uses the relationship between the changes in olivine composition and the RI of the γ axis to distinguish between chemical groups. Two immersion oils are used on EOCs: one oil has a RI (1.720) between the olivine compositions of the LL and the L-groups and the second has a RI (1.710) that lies between the L-group and H-group (Fig. 1).

Classification Procedure: The petrologic type of ordinary chondrites is assessed during a preliminary examination with a binocular microscope. Ordinary chondrites of petrologic type 4 or below are thin sectioned and examined further petrographically, whereas those identified as petrologic types 5 or 6 (EOCs) are assigned their type by this visual evaluation alone.

During this examination meteorites are also given a preliminary classification as LL/L (clearly not an H) or L/H (clearly not an LL) to determine which immersion oil to examine them against. Olivine grains can be compared to both immersion oils if uncertainty exists.

Following visual examination with a binocular microscope, a small piece of an EOC is clipped off the classification chip [1] and disaggregated, but not pulverized, with a mortar and pestle. The disaggregated powder is then sieved through a Number 100 sieve on a Number 170 sieve. This leaves grains sizes ~150-90 microns. This size fraction of grains is then examined against the relevant immersion oil. If the meteorite is an LL/L it is compared to RI=1.720 oil. If it is an L/H, it is compared to RI=1.710 oil.

A drop of the relevant immersion oil is put onto a blank glass microscope slide. With a dissection tool, meteorite grains are added to and dispersed throughout this drop of oil. Then a cover slip is lightly placed on top of the grain-oil mixture.

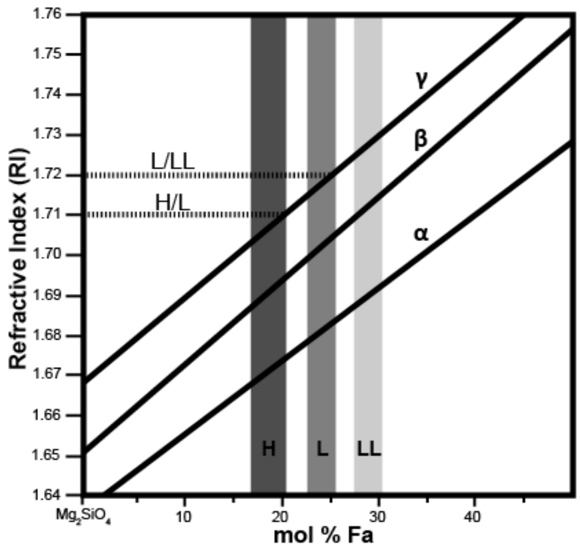

Figure 1: Olivine compositions (gray bars) that define the chemical groups for EOCs [2] with the γ, β, α axes (solid lines) of olivine [6] and the oils (dashed lines).

Next, the grain-oil mixture is viewed through a petrographic microscope with low magnification (usually the 5x objective) using cross polarized light. The grains with the highest interference colors are olivine crystals viewed through their β axis. These grains are compared to the immersion oil. At least fourth-order interference colors should be visible in these highest birefringence grains; if only grains with first order interference colors are present, the chip is treated as a non-EOC because it may be an enstatite chondrite. In plane polarized light, only olivine grains that are transparent, not yellowed or discolored, are used. If there are numerous to choose from, grains with gradually sloping edges are preferable to grains with sharp precipitous edges.

After a grain is selected, magnification is increased (to the 20x objective) and the stage is rotated until the grain is extinct under cross-polarized light. The analyzer is removed and the contrast between the grain and the oil is noted. The analyzer is put back in and the stage rotated 90° to the next extinction position. In the two extinction orientations, the one in which the grain is less distinct (ideally the grain edge disappears into the oil) is the γ axis.

The movement of the Becke line when viewing the γ axis is diagnostic of an EOC's chemical group (Fig. 1). If the Becke line of the γ axis moves into the grain when the stage is lowered, the meteorite is the higher mol % Fa chemical group (an L if using 1.710 oil or an H if using 1.720 oil). If the Becke line of the γ axis moves way from the grain as the stage is lowered, it is the lower mol % Fa chemical group (an H if using 1.710 oil or an L if using 1.720 oil). The Becke line is is examined on several grains.

Caveats: Although this method is very useful, it has some flaws and it may not work well for all meteorite classification programs.

Preliminary Examination: The accuracy of this method relies on the preliminary examination. The OI method will not flag all non-EOCs.

RI of Oils: Immersion oils contain some compounds that will volatize over time; this will change the RI of the oil. Therefore, it is important to check their RI regularly. An oil's RI can be compared to material of known RI or directly measured with an Abbe Refractometer. The Abbe Refractometer we use is accurate within ± 0.002. We use this refractometer to check our oils and to make more immersion oil.

Weathering: Terrestrial weathering can make it difficult to use the OI method on Antarctic meteorites and may make it impossible to use on meteorites found elsewhere in the world, even hot deserts. The iron oxides frequently produced by terrestrial weathering are opaque and will encrust grains, making it difficult to observe Becke lines.

Shocked Olivine: When olivine grains display undulatory extinction or mosaic extinction within a single grain, it is more difficult to compare their α and the γ axes to the immersion oil. In these cases, Becke lines located at areas that are completely extinct are used.

Breccias: Classifications are determined using a classification chip that is only ~0.5-1 cm^3 in size [1]. Therefore, it is not always possible to observe larger scale textures such as brecciation. A classification chip may only sample one clast of a polymict breccia.

Conclusion: The method described here is undeniably not the most rigorous way to examine meteorites, but it allows us to use our resources effectively while still producing accurate and useful classifications for large numbers of equilibrated ordinary chondrites.

References: [1] Corrigan et al. (2010) LPS XXXI #2332 [2] Gomes & Keil (1980) *Brazilian Stone Meteorites*, University of NM Press, Albuquerque [3] Kalleweyn et al. (1989) GCA, 50, 2747 [4] Mason (1963) GCA, 27, 1011 151 [5] Poldervaart (1950) Amer. Min., 35, 1067 [6] Bowen & Schairer (1935) Amer. Journ. Sci., 24, [7] Deer et al. (1962) *Rock Forming Minerals Vol. 1*, Longmans, London [8] Shelley (1985) *Optical Mineralogy 2nd Edition*, Elsevier, New York [9] Phillips (1971) *Mineral Optics: Principles and Techniques*, Freeman, New York