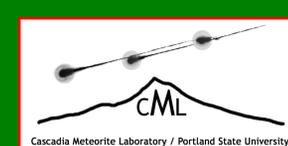


# TRACE-ELEMENT ANALYSES OF PYROXENE AND PLAGIOCLASE IN THREE HED METEORITES

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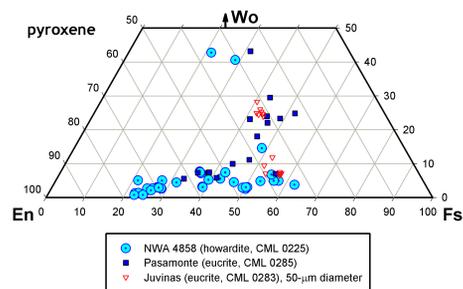


**Introduction:** Although HED meteorites provide a fairly extensive sample of the crust of their differentiated parent asteroid (probably 4-Vesta), fundamental questions remain regarding their origin. For example: (1) How are the mainly basaltic rocks of eucrites genetically related to the plutonic orthopyroxenites of diogenites? (2) Did the eucritic and diogenitic clasts in howardites originate in the same way as eucrites and diogenites? (3) What roles did secondary processes such as thermal metamorphism and impact heating play in changing the original igneous properties of these rocks?

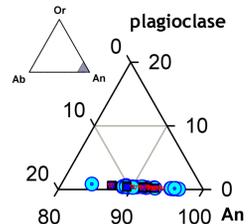
Most geochemical work on HED meteorites has focused on studies of the bulk compositions of the meteorites, but we used a different approach that utilizes LA-ICP-MS to study phase compositions. Here we report preliminary results for pyroxene and plagioclase obtained for three HED meteorites of different classes and metamorphic grades: Pasamonte, an unequilibrated (weakly metamorphosed) Main Group eucrite that contains zoned pigeonite and augite grains; Juvinas, an equilibrated (metamorphosed) Main Group eucrite that contains inverted pigeonite (with exsolved lamellae of augite in an orthopyroxene host); and NWA 4858, a newly-classified howardite. These data permit a preliminary assessment of how igneous and metamorphic processes affected these contrasting sample types.

**Methods:** Prior to trace-element work we characterized the petrography of the samples using optical and SEM techniques and an electron microprobe (EMP) to analyze pyroxene (px) and plagioclase (plag) for major-elements. Most EMP analyses were obtained using 1-micron-diameter spots, but we broadened the beam to 50 microns for Juvinas px to obtain a bulk (host + lamella) composition of the inverted pigeonites. LA-ICP-MS analyses were obtained with 80 micron spots.

## Major-element compositions

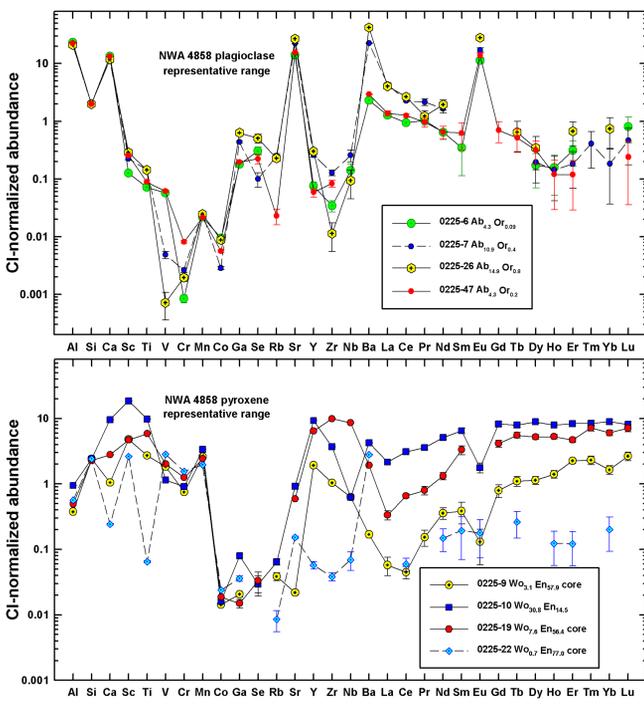


**Figure 1 (left).** Pyroxene quadrilateral compositions. Note the large range in composition for Pasamonte (reflecting the zoned nature of the px grains) and for NWA 4858 (reflecting also the variety of source rocks sampled). Pyroxene types in NWA 4858 range from Mg-diogenite ( $Wo_{0.7}En_{78}$ ), to Fe-diogenite ( $Wo_5En_{58}$ ), to pigeonite ( $Wo_{5-15}En_{56-37}$ ), to inverted pigeonite (including augite  $Wo_{40-43}En_{31-36}$ , and orthopyroxene  $Wo_{2.5-4.9}En_{49-34}$ ).



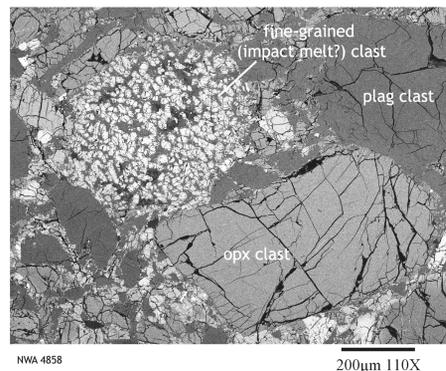
**Figure 2 (right).** Plagioclase ternary compositions. Most compositions vary between  $An_{94-88}$ , with a slightly larger range for NWA 4858 ( $An_{97-84}Ab_{3-15}$ ).

## Representative trace-element abundances

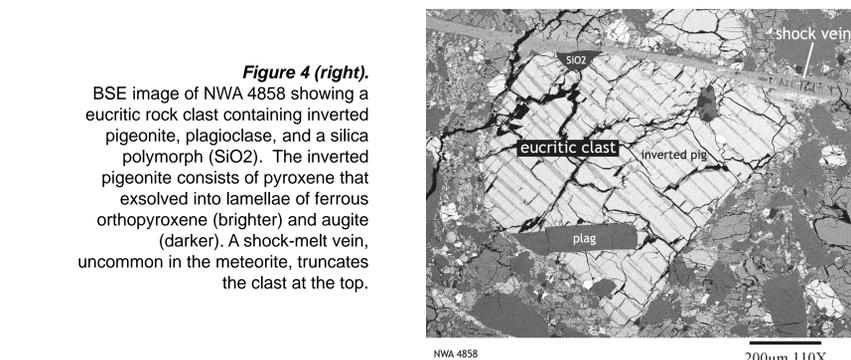


**Figure 6 (left).** CI-normalized abundances for selected coarse-grained px and plag in NWA 4858, illustrating representative ranges of mineral compositions in this howardite. Abundances of the most incompatible elements in px (e.g., Ti, Y) vary by over two orders of magnitude, being lowest in Mg-diogenite and highest in augite, whereas Ba in plagioclase varies by 1 order of magnitude. The larger spread for px compared to plag in NWA 4858 (and in Pasamonte) can be explained in part by a stronger compositional dependence of partition coefficients for px [2], and probably also by a larger crystallization interval for pyroxene. The overall range in mineral compositions for NWA 4858 is greater than for Pasamonte and Juvinas, mainly reflecting a greater diversity of rock types in the howardite.

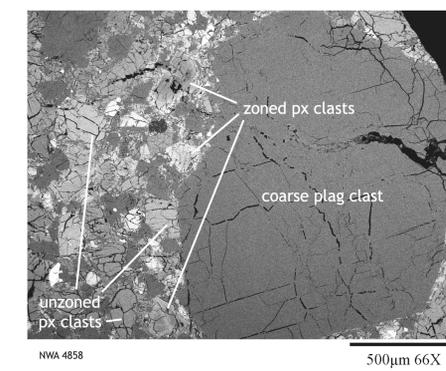
**Petrography of NWA 4858 howardite:** This newly-classified howardite is a fragmental breccia dominated by mineral clasts of px and plag, and also contains rock clasts such as eucritic basalt and fine-grained basaltic clasts, the latter of which are possibly impact-melt rocks (Fig. 3, 4). Uncommon shock veins are present (Fig. 4). A notable feature of this howardite is the wide dispersion of px major-element compositions (Fig. 1) including both magnesian and ferroan diogenite-like compositions. Plagioclase also has somewhat variable composition (Fig. 2). Although most clasts contain minerals with fairly uniform compositions, some px clasts are zoned (Fig. 5). This suggests that the clasts in NWA 4858 were not equilibrated *in situ*; any metamorphism must have pre-dated brecciation and final assembly.



**Figure 3 (left).** Backscattered electron (BSE) image of NWA 4858 showing typical mineral clasts of magnesian orthopyroxene (opx) derived from a diogenitic lithology, and plagioclase (plag) derived from a eucritic lithology, and fine-grained, granular basaltic rock clasts that probably crystallized from an impact melt of an eucritic target.



**Figure 4 (right).** BSE image of NWA 4858 showing a eucritic rock clast containing inverted pigeonite, plagioclase, and a silica polymorph ( $SiO_2$ ). The inverted pigeonite consists of pyroxene that exsolved into lamellae of ferrous orthopyroxene (brighter) and augite (darker). A shock-melt vein, uncommon in the meteorite, truncates the clast at the top.



**Figure 5 (left).** BSE image of NWA 4858 showing a variety of pyroxene clasts, some of which are zoned to more iron-rich margins, and others of which are unzoned. The different zoned pyroxene clasts have different core and rim brightness levels which corresponds to different iron contents. A coarse plagioclase clast dominates the field-of-view. Epoxy (black) is at upper right.

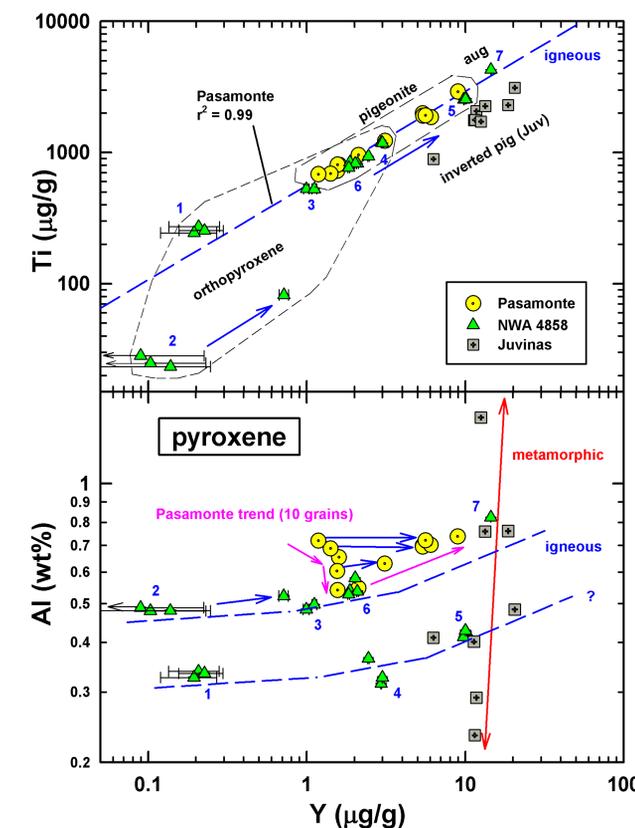
## Trace-element results

**Pasamonte:** We confirm earlier suggestions that mineral trace-element compositions mainly record igneous processes [1,2]. For incompatible elements, we measured a factor of ~10x variation in pyroxene, and a factor of ~1.5-2.5 variation in plagioclase. Yttrium and Ti contents in Pasamonte are highly correlated and consistent with igneous processes (Fig. 6). A noteworthy feature is the different behavior in px of Al compared to other elements, with Al content first dropping as crystallization progressed (i.e. as incompatible elements such as Y became enriched in the magma), then rising (Fig. 6). We interpret this to indicate the rapid onset of plagioclase crystallization part way during pigeonite crystallization. Pasamonte appears to sample a single, evolving magma type (Fig. 6, 7).

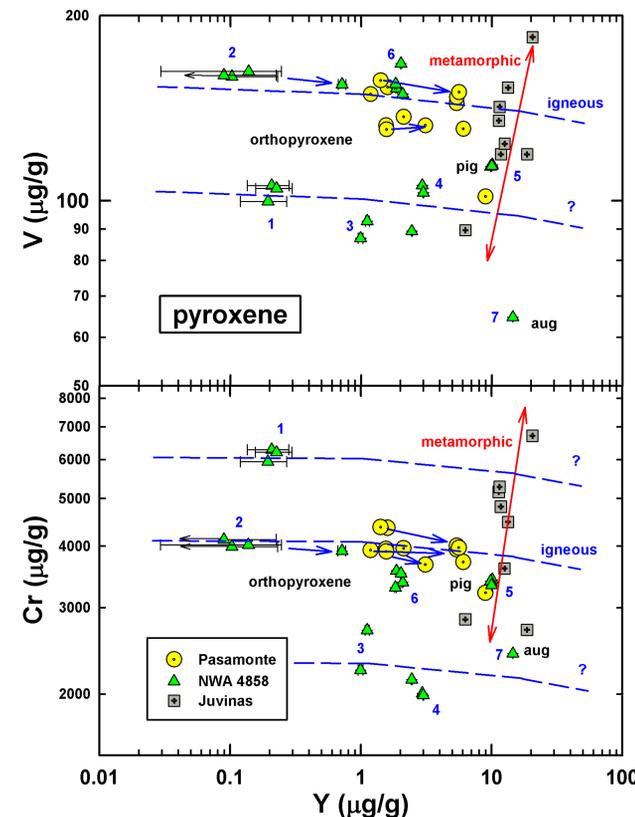
**Juvinas:** Juvinas shows the effects of metamorphic redistribution [1,2], but mainly for px [2] and only for some elements, notably those that concentrate in plag (Al, Sr) and chromite (Cr, V), evidenced by a large spread in the concentrations of these elements that are contrary to presumed igneous trends (Fig. 6, 7). We suggest that these elements were diffusively exchanged between px and other phases during subsolidus metamorphism. Low but relatively constant Ti/Y and Zr/Y values compared to Pasamonte px (Fig. 7) could indicate that Ti and Zr were depleted in a magma by prior ilmenite crystallization, which was otherwise chemically similar to Pasamonte magma. If so, Pasamonte and Juvinas (and other Main Group eucrites?) may have sampled a single evolving magma type.

**NWA 4858:** The trace-element composition of px in the howardite extend over a much larger range than in Pasamonte and Juvinas although compositions overlap the other meteorites (Fig. 6, 7). Pyroxene appears to have crystallized from multiple magmatic systems, mostly different from that in Pasamonte and Juvinas. For example, opx clast 2 appears to have crystallized from a magma with lower Ti/Y than in Pasamonte (Fig. 6). Similarly, clasts 1, 3, 4, 5, and 7 have Al/Y, V/Y, or Cr/Y values significantly different from those in Pasamonte px (Fig. 6, 7). Only pigeonite clast 6 in NWA 4858 chemically resembles pigeonite in Pasamonte for most elements (Fig. 6, 7). Most plag in NWA 4858 also chemically differs from those in Pasamonte and Juvinas. The data imply that differentiation of the HED parent body proceeded in a complex fashion.

**Reference List:** [1] Pun A. and Papike J.J. (1996) *American Mineralogist* **81**, 1438-1451. [2] Hsu W. and Crozaz G. (1996) *Geochimica et Cosmochimica Acta* **60**, 4571-4591.



**Figure 6 (left).** Yttrium-Ti and Y-Al variation diagrams for px. Blue arrows indicate grain core-rim igneous zoning trends pointing to rims (more evolved compositions); blue numbers indicate different px clasts in NWA 4858. Dashed blue lines show inferred igneous trends, whereas the red double arrow indicates an inferred metamorphic redistribution trend for Juvinas. Elements that concentrate in plagioclase (Al, Sr) or chromite (Cr, V) appear to be disturbed in Juvinas px as a result of metamorphism. Pyroxene in Juvinas has low but relatively uniform Ti/Y (and Zr/Y) values compared to Pasamonte px, which can be explained by ilmenite crystallization prior to px in Juvinas. Aluminum-yttrium trends in 10 different px clasts in Pasamonte show a complex pattern (purple), interpreted to reflect the co-crystallization of plagioclase.



**Figure 7 (left).** Yttrium-V and Y-Cr variation diagrams for px. Symbols same as in Fig. 6. Vanadium and Cr behaved as weakly compatible elements during px crystallization. Different px clasts in NWA 4858 have widely different V/Y and Cr/Y values that are difficult to reconcile with a single evolving magma composition. Instead, taking into account both Fig. 6 and 7, it appears that px in NWA 4858 crystallized from at least four different magmatic systems. Moreover, only one px clast in NWA 4858 (#6) could have crystallized from a magma composition similar to that in Pasamonte. Altogether, the data imply that px in some howardites sample a greater variety of magma bodies than do Main Group eucrites.

**Conclusions:** Our data suggest that studies of mineral trace-element compositions in HED meteorites can provide important information. For example, it appears that a magmatic signature in Juvinas pyroxene was incompletely erased by metamorphism, and that the chemical signature in pyroxene of co-crystallizing or prior-crystallizing phases can be identified in Pasamonte and Juvinas. Analysis of clasts in howardites can yield a more comprehensive understanding of the diversity of igneous rock types and their genetic relationships than otherwise possible. Based on our preliminary data, it appears that the igneous petrogenesis of the HED parent body was surprisingly complex, with multiple evolving magma types needed to explain the data for both howardites and eucrites. Metamorphism may have caused elemental redistribution between phases for some elements. Further work is needed to more definitively assess the genetic relationships of different rock types and to model and quantify the magmatic and metamorphic histories of HED meteorites and their parent body.

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