Identification of Anomalous Eucrites and Diogenites by Multivariable Discriminant Analysis.

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Introduction: Howardite, eucrite and diogenite clan (HED) is the largest magmatic achondrite group and has been suggested to be derived from asteroid (4) Vesta (e.g., [1]). Previous geochemical studies have suggested HEDs were generated by asteroid melting followed by crystallization, metamorphism, and impact [1-6]. However, numerous eucrites and diogenites have anomalous compositional, isotopic or petrological characteristics compared to the norm. This diversity might indicate more complex magma processes on the parent asteroid, or they could be linked to different parental asteroids (e.g., [5]). The former case would imply that the parent asteroid is more heterogenous than currently thought, and that our petrologic models are too simple. The latter case would increase the number of asteroids known to have formed mafic crusts, and would allow for petrological comparisons across numerous bodies. We apply multivariable discrimination analysis (MDA) to a large database of HED pyroxene analyses. This technique allows all elemental information to be considered simultaneously to facilitate identification of groupings, trends, and outliers within the dataset.

Method: The MDA is a statistical method for studying differences between two or more groups with multiple variables simultaneously. The main purpose is to classify all cases into groups [7, 8]. The MDA method calculates the best group separations by deriving a set of canonical discriminant functions which are weighted linear relationships with multiple independent variables. More details on our application of the method are in [9]. The basic data set included more that 200 pyroxene analyses from previous studies and includes pyroxene data from several anomalous meteorites. Eight major and minor elements are used in this study: Mg, Al, Si, Ca, Ti, Cr, Mn, and Fe. All data were transformed from weight percent oxides to atomic percent because pyroxenes are inherently molecular species. Some samples known to be anomalous (e.g., NWA 1240, NWA 011 and A-881894, etc.) are treated as unknowns in this analysis. The professional statistics program SPSS is used to analyze these data. Detailed methodology can be found in [10, 11]

Results: Figure 1 is the Canonical Discriminant Function diagram for eucrite and diogenite pyroxene data. Function 1 defines the largest differences between groups with 78.3% of variance and Function 2 encompasses 21.0% of the variance. Only 0.7% of the total variance is unaccounted for by F1 and F2.

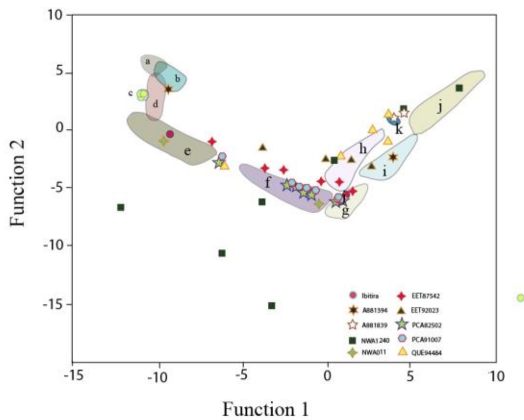

Figure 1. a=diopside in diogenite, b=augite in diogenite, c=diopside in eucrite, d=augite in cumulate eucrite, e=augite in basaltic eucrite, f=pigeonite in basaltic eucrite, g=orthopyroxene in basaltic eucrite, h=pigeonite in cumulate eucrite, i=orthopyroxene in cumulate eucrite, j=orthopyroxene in diogenite, k=pigeonite in diogenite. Anomalous eucrites and one diogenite are identified.

There are two main trends shown in Figure 1, one from basaltic eucrite, cumulate eucrite to orthopyroxenes in diogenites (fields g→j); and the other is from one end of the orthopyroxenes of basaltic eucrites to pigeonites, and then to augites of basaltic eucrite (fields g→e). All cumulate eucrites fall between basaltic eucrite and diogenites fields. The pigeonite of cumulate eucrite falls next to the orthopyroxene side of cumulate euctites. Fields for mineral phases along with the rock types are all well separated with limited overlaps. The results from the MDA for five of the anomalous meteorites are list in Table 1 and discussed in detail below. The groupings obtained by MDA method show the closest field that those samples may belong to (rock type and mineral phase). Oxygen isotope $\Delta^{17}O$‰ values are also listed [4, 5, 12-15]. Most of the mineral phases from the MDA are matched with phases defined by traditional methods such as inspection of pyroxene quadrilaterals. A few mismatched points fall outside the identified mineral phase fields. The $\Delta^{17}O$‰ values of all these samples except for QUE 94484 are different from those of HEDs which average -0.240 +/- 0.001.

Table 1

	Identified by MDA			F-1	F-2	Δ^{17}O‰
EET 87542	opx	basaltic	eucrite	1.81	- 5.27	
EET 87542	pig	cumulate	eucrite	0.82	-4.58	
EET 87542	pig	basaltic	eucrite	-0.25	-4.27	
EET 87542	pig	basaltic	eucrite	-0.56	-3.91	
EET 87542	pig	basaltic	eucrite	-2.73	-3.17	
EET 87542	pig	basaltic	eucrite	-3.95	-3.02	
EET 87542	aug	basaltic	eucrite	-7.22	-0.61	
EET 92023	opx	basaltic	eucrite	2.56	-3.41	-0.122
EET 92023	opx	basaltic	eucrite	1.24	-4.27	
EET 92023	pig	basaltic	eucrite	1.24	-2.75	
EET 92023	pig	basaltic	eucrite	-0.23	-2.34	
EET 92023	pig	basaltic	eucrite	-4.22	-0.97	
PCA 82502	opx	basaltic	eucrite	0.29	-6.91	-0.223
PCA 82502	opx	basaltic	eucrite	0.21	-7.15	
PCA 82502	pig	basaltic	eucrite	-1.33	-6.26	
PCA 82502	pig	basaltic	eucrite	-1.38	-5.99	
PCA 82502	pig	basaltic	eucrite	-2.38	-5.41	
PCA 82502	pig	basaltic	eucrite	-2.99	-5.11	
PCA 82502	aug	basaltic	eucrite	-7.10	-2.86	
PCA 91007	opx	basaltic	eucrite	0.54	-7.00	-0.202
PCA 91007	opx	basaltic	eucrite	0.50	-6.71	
PCA 91007	opx	basaltic	eucrite	0.44	-6.91	
PCA 91007	opx	basaltic	eucrite	0.37	-7.02	
PCA 91007	pig	basaltic	eucrite	-1.86	-5.83	
PCA 91007	pig	basaltic	eucrite	-2.00	-5.67	
PCA 91007	pig	basaltic	eucrite	-2.20	-5.48	
PCA 91007	pig	basaltic	eucrite	-2.72	-4.89	
PCA 91007	aug	basaltic	eucrite	-6.88	-2.04	
QUE 94484	pig	cumulate	eucrite	3.80	1.24	-0.245
QUE 94484	pig	cumulate	eucrite	3.77	-1.25	
QUE 94484	pig	cumulate	eucrite	2.76	-0.02	
QUE 94484	pig	basaltic	eucrite	0.85	-2.26	
QUE 94484	aug	basaltic	eucrite	-6.79	-2.91	

Anomalous meteorites:

EET 87542 is a brecciated eucrite but with more Mg-rich pyroxenes having low Fe/Mn ratios. More than half of its MDA data points fall outside the normal basaltic eucrite fields. Thus, our MDA result does not support EET 87542 as normal eucrite.

EET 92023 is an unbrecciated cumulate eucrite [2] similar to Moore Country but with higher metal contents [12]. The oxygen isotope value (Δ^{17}O‰ = -0.122) is different from those of normal eucrites. Most of MDA data points fall outside of the normal eucrite fields, confirming its anomalous character.

PCA 82502 and PCA 91007 are paired basalts. PCA 82502 is classified as an unbrecciated eucrite but it is a catallactic breccia. PCA 91007 is classified as a brecciated eucrite. Both contain vesicles, which are rare in basaltic eucrites. Fine-grained ophitic intergrowths of pigeonite and plagioclase are observed. Our MDA results show that all of their pyroxenes overlap each other, consistent with pairing. The MDA results fall in the normal eucrite fields, except that augite data fall between the augite and pigeonite fields (e and f) for basaltic eucrites. The oxygen isotopes (Δ^{17}O‰ = -0.223 and -0.202) show small different from normal eucrites. Thus, although there are small differences in oxygen isotopes that identify them as anomalous, they may be grouped as normal eucrites based on pyroxene compositions.

QUE 94484 is unbrecciated, unequilibrated basalt rich in troilite. The pyroxenes have several unusual geochemical and petrological characteristics [16, 17]. The variations may link to formation of QUE 94484 from an anomalously S-rich magma composition that caused reduction of FeO, resulting in low pyroxene Fe/Mn ratios and high modal silica. Its O isotopes (Δ^{17}O‰ = -0.245) match normals HED (Δ^{17}O‰ = -0.240 +/- 0.001) field. Some of the MDA data points for QUE 94484 fall close but not in the cumulate eucrite fields too. Mg-rich cores of the zoned pyroxenes are compositionally close to those of cumulate eucrites.

Discussion: Our results indicate the MDA method can provide reliable evaluation of HED pyroxene compositions for grouping, correlation between elements, and petrological identification. The results from MDA analysis have demonstrated that unknown samples that do not fall in established fields for normal eucrites should be further evaluated for other petrological, chemical or isotopic characteristics that might point to them either arising on a different asteroid, or resulting from an unusual petrogenetic history on the HED parent asteroid.

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