# GEOCHEMICAL RELATIONSHIPS AMONG SELECTED DIOGENITES, CUMULATE EUCRITES, HARZBURGITES, AND EUCRITES.

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**Introduction:** Although not typically emphasized, significant differences of opinion still exist as to the origins of the HED suite of basalts and related lithologies (e.g., [1-6]). For example: Are Main Group eucrites primary or evolved liquids? Did orthopyroxene fractionation and accumulation (diogenites) lead to Main Group eucritic liquids? Are the Nuevo Laredo Group eucrites derived by fractionation of Main Group liquids? What is the origin of the Stannern Group?

Understanding the diogenites is especially difficult because: (i) They often approximate monomineralic lithologies; and (ii) They have often been highly metamorphosed, with concomitant erasure of major element igneous zoning. Consequently, many, if not most, models of diogenite petrogenesis rely heavily on trace element patterns and abundances, as will we.

We find plotting diogenite Sc/La vs. Lu/Sm to be useful. Using these element ratios has several advantages: (i) Ions with a 3+ charge are less susceptible to sub-solidus erasure of igneous zoning; (ii) Ratios of elements may be more indicative than absolute abundances; (iii) Because it is highly incompatible, La is a good tracer of magmatic evolution; (iv) Sc and Lu have some affinity for mafic silicates; (v) Incorporation of elemental into pyroxenes as a ratio is less susceptible to changes in intensive variables, such as temperature; and (vi) Combined La, Sm, and Lu abundances give a sense of variation in REE patterns. Most importantly, plotting Sc/La vs. Lu/Sm has allowed us to systematize many of the diogenites into several distinct quasi-linear arrays.

**Data Presentation:** Here we discuss just one of these linear arrays that we term the Type-B Group. This particular trend is interesting in that it seems to contain several Eucrite Parent Body lithologies (Fig. 1).

Figure 1 shows the entire Group dataset. With modifications, we model the trend as a mixing line following the mixing formalism of [7]. Error bars of ±5%, relative, are shown for scale and may not be reflective of the true errors. Given the uncertainties associated with even



Figure 1. (Sc/La)$_{CI}$ vs. (Lu/Sm)$_{CI}$ for the Type-B Group. Figures 1a, 1b, and 1c illustrate the dataset at differing limits of Lu/Sm. Lithologies are color-coded: Green, Diogenites; Red, Johnstown; Light Blue, Cum. Eucrites; Magenta, Harzburgites; Tan, Manegaon; Sky Blue, Bouvante. EC denotes enriched endmember. Error bars are for scale only. Trendline: parameterization of the trial-by-error fit, not the fit itself. Samples which are not well fitted are denoted. We do not consider Manegaon a Group member, as its position changes radically from diagram to diagram.
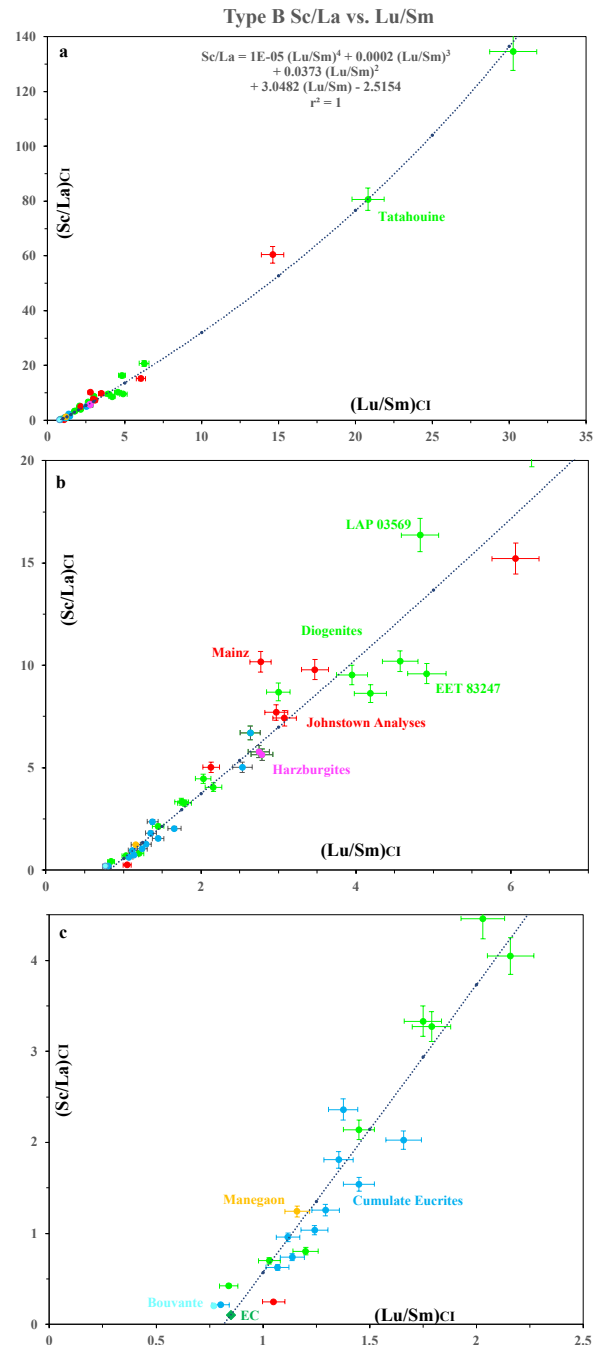
a single analysis, we would not anticipate that the true errors would be significantly smaller, but they could be significantly larger.

Our fit to the data is non-unique, but a theme emerges. We have produced two, nearly identical, trial-

by-error fits. Both models use (i) a fictitious, enriched component (EC) and (ii) an analysis of Tatahouine as endmembers. One fictitious endmember is based on Bouvante and the other on diogenite QUE 93009. The commonality of these two fits is that both EC endmembers are enriched in the LREE and have a (La/Lu)$_{CI}$ of ~2. Therefore, we believe that a LREE-enriched reservoir is essential in the formation of this Group.

Y-75032 is perhaps the best example of the Type-B, ferroan, diogenites [8]. Other diogenites such as Johnstown and NWA 4215 are not commonly known to have a Type-B affinity, but do fall on our Group B array. Others have suggested that the cumulate eucrites (CE) were produced in a LREE-enriched environment and might be related to the Type-B diogenites [9,10], whereas [11], using different criteria, concluded just the opposite. Further, diogenites are known to have a component that is rich in the LREE, perhaps in the matrix [1,4,12,13].
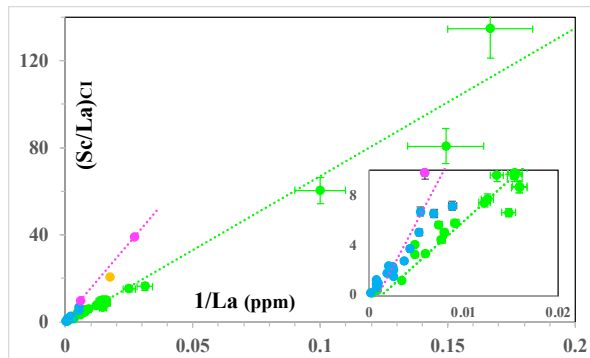


**Figure 2. Sc/La vs. 1/La for Diogenites and Cumulate Eucrites**. Inset expands the region near the origin; error bars ±10%. Diogenites and harzburgites (green) appear to define a mixing line, excluding Dhofar 700B (tan; [4]). The CE (blue) appear to also define a mixing line, which differs from that of the diogenites. Ion probe analyses of CE pyroxenes (magenta) appear to extend the CE trend [14], but do not fall on the trend of Figure 1.

**Discussion: Diogenites and the CE.** *Diogenites.* Figure 1 is partially illusory. We require two criteria to interpret a trend as a mixing line. The first is illustrated in Fig. 1, which is arrived at by trial-and-error, and can, therefore, be subjective.

Our second criterion is shown in Fig. 2 — the well-known mixing plot of y/x vs. 1/x. In this case we use Sc/La vs. 1/La. The only diogenite to seriously fall off the trend of Fig. 1a is Dhofar 700B, which we hereby exclude from the Type-B Group. Therefore, we judge that the Type-B Group has met an important mathematical criterion and can be interpreted as a mixing line.

This conclusion has important petrologic consequences. For example, we do not consider the trend in

Fig. 1 to represent a conventional liquid line of descent; but also, we do not necessarily consider our trend to simply represent binary mechanical mixing. In either case, large degrees of crystallization are not needed to explain the variation of highly incompatible elements (HIE) within the diogenite suite. Therefore, a magma ocean is unnecessary in this regard.

Ion-probe analyses of diogenitic pyroxenes have not generally analyzed for the same elements that we used in Fig. 1. But using spot analyses of V/Ce vs. Yb/Y (as a proxy for Sc/La vs. Lu/Sm), we again find a quasi-linear trend and a spread in V/Ce of a factor of ~18. This suggests that a significant part of the chemical variation in Fig. 1 could be due to changes intrinsic to the pyroxenes and not to a foreign, mechanical component.

If the pyroxenes and whole-rocks are both recording chemical variation and also both consistent with two-component mixing, then we must consider the possibility of open system behavior during diogenite crystallization. We believe it is physically possible that hot liquids, crystallizing low-Ca pyroxene, invaded and partially melted a basaltic host (e.g., [6]). These small-degree partial melts (<~5%) should be enriched in HIE — especially the LREE. In this model, diogenite parent liquids might be progressively contaminated with HIE as diogenites crystallized. Therefore, a large question for this model is whether diogenite pyroxenes could have acquired their HIE subsolidus.

*Cumulate Eucrites.* Whole-rock analyses of the CE Group share a Sc/La vs. Lu/Sm trend with the diogenites, but have their own mixing line, whose enriched component is currently indistinguishable from that of the diogenites.

**Conclusions:** We find ourselves with an intriguing possibility: Mafic liquids invaded a basaltic HED crust, with subsequent partial melting of crustal wallrock. HIE-enriched melts then mingled with the diogenite parent liquids. Also, the CE Group appears to have lost an HIE-rich component. Thus, we wonder if the CE suite could originate from the HIE-depleted wallrock.

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