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The parent magmas of the cumulate eucrites: A mass balance approach

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Abstract–The cumulate eucrite meteorites are gabbros that are related to the eucrite basalt meteorites. The eucrite basalts are relatively primitive (nearly flat REE patterns with La ~ 8–30 × CI), but the parent magmas of the cumulate eucrites have been inferred as extremely evolved (La to > 100 × CI). This inference has been based on mineral/magma partitioning, and on mass balance considering the cumulate eucrites as adcumulates of plagioclase + pigeonite only; both approaches have been criticized as inappropriate. Here, mass balance including magma + equilibrium pigeonite + equilibrium plagioclase is used to test a simple model for the cumulate eucrites: that they formed from known eucritic magma types, that they consisted only of magma + crystals in chemical equilibrium with the magma, and that they were closed to chemical exchange after the accumulation of crystals. This model is tested for major and rare earth elements (REE). The cumulate eucrites Serra de Magé and Moore County are consistent, in both REE and major elements, with formation by this simple model from a eucrite magma with a composition similar to the Nuevo Laredo meteorite: Serra de Magé as 14% magma, 47.5% pigeonite, and 38.5% plagioclase; Moore County as 35% magma, 37.5% pigeonite, and 27.5% plagioclase. These results are insensitive to the choice of mineral/magma partition coefficients. Results for the Moama cumulate eucrite are strongly dependent on choice of partition coefficients; for one reasonable choice, Moama's composition can be modeled as 4% Nuevo Laredo magma, 60% pigeonite, and 36% plagioclase. Selection of parent magma composition relies heavily on major elements; the REE cannot uniquely indicate a parent magma among the eucrite basalts. The major element composition of Y-791195 can be fit adequately as a simple cumulate from any basaltic eucrite composition. However, Y-791195 has LREE abundances and La/Lu too low to be accommodated within the model using any basaltic eucrite composition and any reasonable partition coefficients. Postcumulus loss of incompatible elements seems possible. It is intriguing that Serra de Magé, Moore County, and Moama are consistent with the same parental magma; could they be from the same igneous body on the eucrite parent asteroid (4 Vesta)?

THE CUMULATE EUCRITE PROBLEM

Eucrites, the most abundant variety of igneous meteorite, are pigeonite–plagioclase basalts and are petrographically similar to many terrestrial basalts. Cumulate igneous rocks that are related to eucrites, the cumulate eucrites, and diogenites, are similarly comparable to many found in terrestrial basaltic intrusions. The eucrite basalts and cumulates are extremely old, ~4.56 Ga (Lugmair *et al.*, 1994; Wadhwa and Lugmair, 1995a,b), and so represent a very brief episode of melting and basaltic volcanism on a planetary body in the early solar system. It is widely inferred that the eucrites represent basaltic volcanism on an asteroid; 4 Vesta is the only large asteroid with a basaltic surface and may be the eucrites' source (Drake, 1979; Binzel and Xu, 1993).

The eucrites are significant far beyond their modest abundance. If the eucrites are from Vesta, they can be treated like returned samples, as guides to Vesta's geology, and as ground truth for remote sensing observations (*e.g.*, Binzel and Xu, 1993; Hiroi *et al.*, 1994). The eucrites also stand as potential calibration points for understanding basalt genesis on larger, more complex, and more recently active planetary bodies. However, there is yet no consensus on whether the eucrite basalts are primary partial melts from a chondritic source region (*e.g.*, Stolper 1977; Jurewicz *et al.*, 1993) or products of extended fractional crystallization (*e.g.*, Mason, 1962; Warren and Jerde, 1987). Much of this controversy centers on the diogenite meteorites, orthopyroxene-rich cumulate igneous rocks (Fowler *et al.*, 1994a,b; Mittlefehldt, 1994), and whether they formed in the same magmatic systems as the eucrite basalts.

To some extent, it is also not clear whether the cumulate eucrites formed from the same magmatic systems as the eucrite basalts. The

cumulate eucrites appear to be related to the eucrite basalts in having similar mineralogies, chemical compositions, and O-isotope compositions (*e.g.*, Mason, 1962; Dodd, 1981; Clayton and Mayeda, 1983; McSween, 1989). However, it has seemed impossible to derive the cumulate eucrites from known eucrite magma compositions. Quoting some original works: "[m]ost of the cumulate eucrites (*e.g.*, Moama, Moore County, Serra de Magé) could not have equilibrated with liquids similar in composition to known eucrites" (Stolper, 1977); and "Collectively, [Y-791195 and RKPA80224] suggest that cumulate eucrites formed from parent melts more diverse than the known non-cumulate eucrites" (Warren and Kallemeyn, 1992).

Parent magma compositions for the cumulate eucrites must be derived indirectly, as the rocks themselves are not of magma compositions. Most studies of the cumulate eucrites have derived parent magma compositions using mineral/melt partition coefficients:

$$C_E^{magma} = \frac{C_E^{xtal}}{D_E^{xtal/magma}} \qquad \text{Eq. (1)}$$

where C_E^{magma} is the concentration of element E in magma, and $D_E^{xtal/magma}$ is the partition coefficient for that element between the solid phase *xtal* and basaltic *magma* (Beattie *et al.*, 1993). Measuring pyroxene or plagioclase compositions by electron microprobe, instrument neutron activation analysis (INAA), or SIMS, these methods suggest that cumulate eucrites formed from highly ferroan, strongly fractionated and incompatible-element enriched magmas that are not among the known eucrite basalts (Stolper, 1977; Ma and Schmitt, 1979; Pun and Papike, 1995; Hsu and Crozaz, 1995; Pun *et al.*, 1996).

Another approach has been to estimate the bulk composition of a cumulate eucrite as cumulus pigeonite and cumulus plagioclase, originally in equilibrium with a eucrite magma or a fractionated derivative, but without intercumulus magma or other chemical components. This approach has also suggested that cumulate eucrites formed from extremely fractionated magmas unknown among the eucrite basalts (Consolmagno and Drake, 1977; Hamet et al., 1978).

Both of these approaches have been criticized as inappropriate for the cumulate eucrites. The first method, calculation from $D^{xtal/magma}$, is applicable only if minerals in the cumulate eucrites retain equilibrium magmatic compositions. Minerals in the cumulate eucrites do not appear to retain their magmatic compositions (Schnetzler and Philpotts, 1969; Phinney et al., 1993; Treiman, 1996) as a result of their protracted subsolidus cooling histories (e.g., Hostetler and Drake, 1978; Harlow et al., 1979; Takeda et al., 1983; Pun and Papike, 1995). Thus, the first approach may not yield parent magma compositions (Consolmagno and Drake, 1977; Treiman, 1996). The second approach, modeling the cumulate eucrites as pyroxene plus plagioclase only, is limited in not considering the compositional effects of trapped intercumulus magma. Trapped magma is a major carrier of incompatible elements and can dominate the incompatible element budget of a cumulate rock (Barnes, 1986; Chalokwu and Grant, 1987; Cawthorn, 1996; Treiman, 1996). If intercumulus magma was present and is not accounted for in modeling, the incompatible elements load of intercumulus magma is ascribed to the crystalline cumulus plagioclase and pyroxene; such incompatible-rich minerals could then only come from a highly fractionated, incompatible-enriched parent magma (Cawthorn, 1996; Treiman, 1996)!

Thus, an appropriate approach to retrieving parent magma compositions for the cumulate eucrites must avoid both pitfalls; it must not rely on chemical analyses of minerals in the cumulate eucrites, and it must consider explicitly the effects of magma trapped among cumulus crystals. One such approach is to model the bulk composition of the cumulate eucrites as magma plus equilibrium crystals. The compositions of the equilibrium crystals can be taken from experiments or calculated from the magma composition and equilibrium D values (Eq. 1). This general approach (with variations) has been used to unravel the petrogeneses of terrestrial cumulates (e.g., Chalokwu and Grant, 1987; Bédard, 1994; Cawthorn, 1996).

A few investigators have used similar mass-balance approaches with the cumulate eucrites but only in limited detail. Reid et al. (1979) modeled the bulk compositions of some cumulate eucrites as mixtures of cumulus pyroxene and plagioclase with trapped eucrite magma but provided few details. Warren (1983) briefly considered the cumulate eucrites as forming from cumulus crystals and magmas like the known basaltic eucrites but looked at a limited suite of elements and did not calculate phase proportions in the cumulates. Finally, Treiman (1996) showed that rare-earth-element (REE) abundances in the Moore County cumulate eucrite bore a strong resemblance to REE abundances calculated for cumulates containing significant intercumulus magma. This paper extends Treiman (1996) to a detailed evaluation of additional cumulate eucrites: Serra de Magé, Moore County, Moama, and Y-791195.

THE MODEL

This paper tests a very simple model for the origin of a cumulate eucrite: (1) its parent magma is among the known eucritic basalts; (2) it formed as a cumulate of pigeonite and plagioclase crystals with some parent magma trapped among them; (3) its pigeonite and

plagioclase crystals were in chemical equilibrium with its parent magma when they accumulated; and (4) it experienced no chemical interactions with its surroundings after accumulation (i.e., it was a chemically closed system). More precisely, the null hypothesis to test is whether a specific cumulate eucrite could not form via this model. If any set of inputs to the model can yield an acceptable fit to the bulk composition of the cumulate eucrite (the null hypothesis is falsified), then Occam's razor might suggest that this simple model is plausible and that unusual magma types or complex petrogenetic processes need not be invoked.

It is worth expanding on the assumptions inherent to this model of cumulate eucrite genesis. First, eucrite basalt magma is taken to mean the compositional range of monomict eucrites thought to represent unadulterated magmas. These magmas include "main group" eucrites like Juvinas and Sioux County with flat REE abundances at 8–10 × CI and Mg* ≅ 0.4; "Stannern trend" eucrites like Stannern and Bouvante with fractionated REE patterns, La abundances to ~30 × CI, and Mg* ≅ 0.4; and "Nuevo Laredo trend" eucrites with fractionated REE patterns, La abundances to ~20 × CI, and Mg* ranging down to ~0.3 (Figs. 1, 2; BVSP, 1981; Warren and Jerde, 1987). Compositions of Nuevo Laredo trend eucrites are consistent with fractional crystallization of main group eucrite magmas (Warren and Jerde, 1987), and compositions of the Stannern trend and main group eucrites are consistent with varying degrees of partial melting of a chondritic source region (Jurewicz et al., 1993). Excluded, perhaps arbitrarily, are magnesian and REE-rich compositions represented only by clasts in breccias, like Kapoeta ρ, Kapoeta CF-3, Petersburg RC-03, and Petersburg A (Dymek et al., 1976; Mittlefehldt, 1979; Smith, 1982; Buchanan and Reid, 1996). The Pomozdino meteorite is comparable but may not represent a magma composition (Warren et al., 1990). Also excluded here are magma compositions that might be derived from known basaltic eucrites by processes like magma mixing or assimilation-fractionation-crystallization (O'Hara and Mathews, 1981).

Second, the model requires explicit consideration of parent magma trapped among the cumulus crystals. Trapped magma can be an
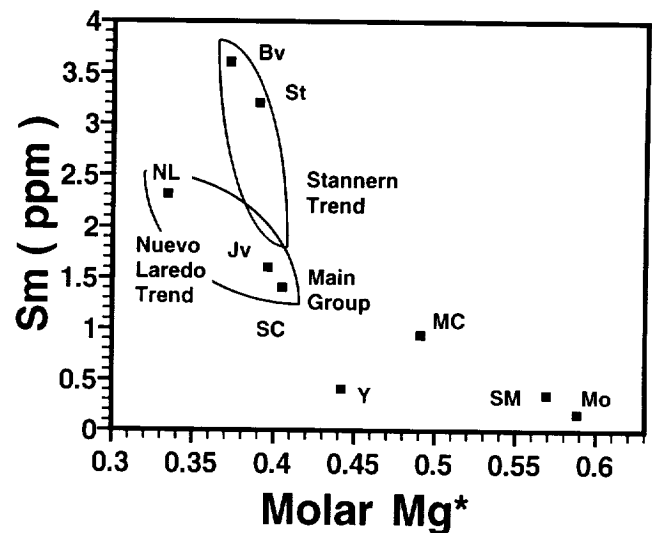

FIG. 1. Samarium vs. Mg* = Mg/(Mg + Fe) for all eucrites and cumulate eucrites discussed here (Hamet et al., 1978; Palme et al., 1978; BVSP, 1981; Warren and Jerde, 1987; Warren et al., 1990; Mittlefehldt and Lindstrom, 1993). Also shown are fields of Main Group, Stannern Trend, and Nuevo Laredo trend eucrites. Bv = Bouvante; St = Stannern; Jv = Juvinas; SC = Sioux County; NL = Nuevo Laredo; Y = Y-791195; MC = Moore County; SM = Serra de Magé; Mo = Moama.

FIG. 2. Rare-earth-element patterns of all compositions studied or used here (Hamet et al., 1978; Palme et al., 1978; BVSP, 1981; Warren and Jerde, 1987; Warren et al., 1990; Mittlefehldt and Lindstrom, 1993). Bv = Bouvante; St = Stannern; Jv = Juvinas; SC = Sioux County; NL = Nuevo Laredo; Y = Y-791195; MC = Moore County; SM = Serra de Magé; Mo = Moama.
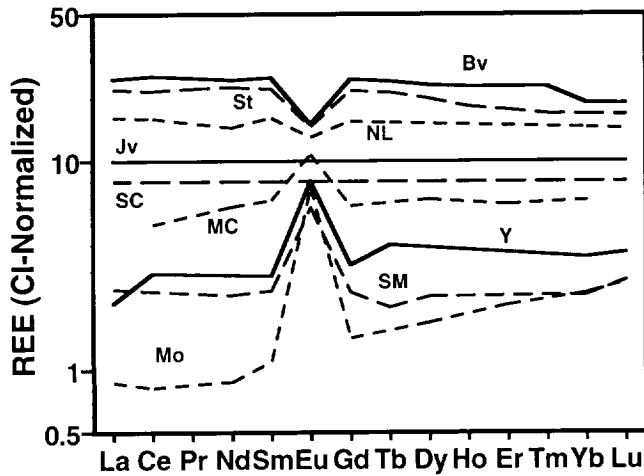
important repository of incompatible elements and can significantly affect the composition of the cumulate (Barnes, 1986; Chalokwu and Grant, 1987; Treiman, 1996). Of course, a cumulate could contain no intercumulus magma, and that possibility must also be considered.

Third, the model requires that the cumulus crystals and parent magma were in chemical equilibrium when the cumulate was formed. At equilibrium, mineral compositions can be calculated from parent magma composition via Eq. (1) and via parametric models of mineral-melt equilibria. Chemical equilibrium rules out disequilibrium crystallization (e.g., Treiman and Sutton, 1992), magma mixing (e.g., Grant and Chalokwu, 1992), entrainment of xenoliths, and similar pre-emplacement complications. The requirement of equilibrium implies that the cumulus crystals were not chemically zoned, implicitly suggesting that the cumulate formed in a large magma body or at crystallization rates that were slow compared to chemical diffusion within the crystals.

And fourth, the cumulate must remain a chemically closed system from the time of crystal accumulation to the present. This requirement rules out the many possible postaccumulation processes that might alter the compositions of cumulate rocks: "sweating out" of the last dregs of silicate magma, magma infiltration metasomatism, hydrothermal alteration, etc. (Sparks et al., 1985). Loss of intercumulus magma, as through compaction, is permitted so long as both the magma and crystals retain the compositions they had on accumulation. This constraint also requires that secondary processes, like brecciation on the eucrite parent body and weathering on Earth, have had no effect on the bulk composition of the cumulate eucrite.

So, this simple model for the origins of cumulate eucrites is actually extremely restrictive. Only a small range of potential parent magmas is considered, and a great many reasonable processes and circumstances are excluded. If the model were to succeed, it would suggest but not prove that unusual parent magmas and complex processes were not involved. On the other hand, if the model failed, one could infer that it excluded the proper parent magma or some geochemically significant process.

TESTING THE MODEL

Tests of this model for the cumulate eucrites must rely on their bulk compositions, reflected in chemical analyses and modal min-

eralogy, because mineral compositions have been compromised by subsolidus chemical diffusion (Consolmagno and Drake, 1977; Phinney et al., 1993; Pun and Papike, 1995; Treiman, 1996). In this case, the cumulate eucrites can be investigated by mass balance, recognizing that trapped intercumulus magma can contribute significantly to the cumulate rock's final composition (Barnes, 1986; Treiman, 1996). From mass balance, the concentration C of an element E in a cumulate eucrite is given by

$$C_E^{cumulate} = X^{plag} \cdot C_E^{plag} + X^{pig} \cdot C_E^{pig} + X^{magma} \cdot C_E^{magma}$$
Eq. (2)

where plag and pig refer to cumulus plagioclase and pigeonite, respectively, and X is the mass fraction of a phase in the cumulate system:

$$X^{plag} + X^{pig} + X^{magma} = 1$$
Eq. (3)

Since the cumulus crystals are assumed to be in chemical equilibrium with the magma, all abundances of E can be written in terms of C_E^{magma} and $D_E^{xtal/magma}$ following Eq. (1):

$$C_E^{cumulate} = C_E^{magma} \left(\frac{X^{magma} + X^{plag} \cdot D_E^{plag/magma}}{+ X^{pig} \cdot D_E^{pig/magma}} \right)$$
Eq. (4)

This problem is underdetermined and cannot be solved explicitly to yield C_E^{magma}. Rather, one must explore the full range of permissible C_E^{magma}, X^{magma} and $X^{pigeonite}$, searching for combinations that yield acceptable approximations to $C_E^{cumulate}$. For convenience, this test is divided into three parts: rare-earth-element (REE) abundances, MgO, and all major elements.

The REEs are useful because they exhibit a range of geochemical behaviors and because their partition coefficients are fairly well known (Table 1). The goodness of fit between each hypothetical cumulate and the real rock can be quantified as a normalized sum of squares:

$$\Delta_{REE}^2 = \sum_{REE} \frac{(C_{REE}^{rock,calc} - C_{REE}^{rock,meas})^2}{(C_{REE}^{rock,meas})^2}$$
Eq. (5)

where $C^{rock,calc}$ comes from calculations, and $C^{rock,meas}$ is the actual element abundance measured in the rock. For consistency, all Δ_{REE}^2 were calculated using six REE: La or Ce, Nd, Sm, Eu, Gd or

TABLE 1. Rare earth element mineral/magma partition coefficients D (Eq. 1).

	Primary Values		Alternate Values	
	pig/magma*	plag/magma[†]	pig/magma[‡]	plag/magma[§]
La	0.0035	0.051	0.001	0.0418
Ce	0.0041	0.044	0.004	0.0302
Nd	0.015	0.038	0.01	(0.025)
Sm	0.024	0.031	0.042	0.17
Eu	0.011	1.15	0.011	(1.2)
Gd	0.055	0.021	(0.06)	0.012
Tb	(0.067)	(0.0095)	(0.065)	0.0095
Yb	0.096	0.0038	0.129	0.0065
Lu	(0.096)	0.0027	(0.129)	0.0068

Primary D values used for all computations herein, except when alternate D values are specifically mentioned. Extrapolated and interpolated values in parentheses.
*Jones (1995) for logD(Ca) = –0.47, pigeonite with 3.5% CaO, magma with 10.3% CaO. Europium value from McKay et al. (1990).
[†]Jones (1995). Europium value from McKay et al. (1990).
[‡]Pun and Papike (1994). Europium value from McKay et al. (1990).
[§]Phinney and Morrison (1990). Europium value estimated.

Tb, and Yb or Lu (except where noted otherwise). The minimum value of Δ^2_{REE} for the range of C_E^{magma} and Xs is the model's "best fit" to the REE pattern of the real cumulate, and some value of Δ^2_{REE} can be estimated as the upper bound for acceptable fits to the real REE abundance pattern. Figure 3 shows that adequate fits to a measured REE pattern have $\Delta^2_{REE} < 0.1$. An Δ^2_{REE} of 0.1 could arise if one of the predicted REE abundances were 30% off the measured value and the rest were perfect, or if all of the six predicted REE values were 13% off the measured values. Considering the small sample sizes involved here and analytical uncertainties, these are considered reasonable limits.

Values for partition coefficients $D_{REE}^{xtal/magma}$ used here are given in Table 1. The 'Primary Values' of Table 1 were used except where otherwise noted. Values of $D_{REE}^{pigeonite/magma}$ were calculated from the regressions of Jones (1995), except for Lu which was taken to be equal to that for Yb. These D values are based closely on the experimental determinations of McKay *et al.* (1986), which include the temperature and composition range of eucrite pigeonites. Values of $D_{REE}^{plagioclase/magma}$ are based on experiments reported in Jones (1995). To explore the sensitivity of the model to the exact choice of D values, selected calculations were redone using the 'Alternate Values' of Table 1. The $D_{REE}^{pigeonite/magma}$ of Pun and Papike (1994) are based on SIMS chemical analyses of REE zoning patterns in the Pasamonte unequilibrated basaltic eucrite. The $D_{REE}^{plagioclase/magma}$ of Phinney and Morrison (1990) are based on INAA analyses of terrestrial basalts and their phenocrysts of calcic plagioclase.

The second test, MgO, screens possible solutions for acceptable matches with a compatible element (all REE except Eu^{2+} are incompatible in plagioclase and pigeonite). Magnesium oxide abundance is most sensitive to the proportion of cumulus pigeonite, and less so to the proportion of trapped magma.

Finally, a full chemical composition can be calculated and compared to the analyzed composition. Although the goodness-of-fit to major elements can be judged qualitatively by an 'educated' comparison of analyzed and predicted compositions, it is perhaps instructive to compute a quantitative measure of the major element fit. Following Eq. (5) above, a major element goodness of fit is calculated as

FIG. 3. Rare-earth-element abundances in Serra de Magé (Palme *et al.*, 1978), circled dots. Lines are calculated REE fits to the measured abundances from Table 4. NL is for Nuevo Laredo parent magma, Δ^2_{REE} = 0.052; SC is for Sioux County parent magma, Δ^2_{REE} = 0.030; St is for Stannern parent magma, Δ^2_{REE} = 0.41. Calculated REE patterns with Δ^2_{REE} < 0.10 are considered acceptable fits.

$$\Delta^2_{Maj} = \sum_{Maj} \frac{(C_{Maj}^{rock,calc} - C_{Maj}^{rock,meas})^2}{(C_{Maj}^{rock,meas})^2} \qquad \text{Eq. (6)}$$

where *Maj* spans the five element oxides SiO_2, Al_2O_3, MgO, FeO, and CaO. Specifically excluded here are TiO_2 and Cr_2O_3, the former because it behaves like a heavy REE, and the latter because of the possibility of cumulus chromite. Values of $\Delta^2_{Maj} < \sim 0.005$ imply superb matches—no individual oxide is off by >7% of the amount present, and the average deviation is <3% of the amount present. Values of Δ^2_{Maj} above ~ 0.01 are unacceptable matches to the analyzed rock compositions.

Input Magma Compositions

These quantitative tests of REE and major element abundances require fairly detailed knowledge of magma and mineral compositions. Magma compositions used were from eucritic basalts themselves, experimental results, and calculations (Appendix); their REE abundances are compared with the cumulate eucrites themselves in Fig. 2. Compositions for Sioux County, Juvinas, Stannern, Bouvante, and Nuevo Laredo were taken from the literature (Appendix). Equilibrium mineral compositions are taken as core compositions from unequilibrated eucrites, and extrapolated or interpolated from relevant experimental studies (Stolper, 1977; Jurewicz *et al.*, 1993), see the Appendix.

Along the Stannern trend (partial melting), REE abundances for intermediate compositions with La = 13, 16, and 19 × CI were interpolated between the compositions of Juvinas and Stannern, with Mg* held essentially constant, and most other elements buffered by olivine, pyroxene and plagioclase. A composition more fractionated than Bouvante, with La = 28 × CI, was calculated from a partial melting model; it is comparable to some eucritic clasts from breccias (Dymek *et al.*, 1976; Mittlefehldt, 1979; Smith, 1982; Buchanan and Reid, 1996).

Magma compositions along the Nuevo Laredo trend (fractional crystallization) were taken from the experiments of Stolper (1977), corresponding to La = 14 × CI, and La = 16 × CI (like Nuevo Laredo itself); REE contents were modeled by fractional crystallization from a Juvinas magma composition. Compositions beyond Nuevo Laredo were calculated for comparison, although they do not fit the model proposed here; bulk compositions were taken from experiments for magmas corresponding to La = 19 × CI and 26.5 × CI (run products SC-64 and Jv-15 of Stolper, 1977).

For all these magmas, pigeonite bulk compositions were modeled on compositions from experiments of Stolper (1977) and Jurewicz *et al.* (1993), with adjustments (if needed) for incompatible element (*e.g.*, Ti) content. Plagioclase bulk compositions were taken as An95 for main group magmas and An92 for Stannern and Nuevo Laredo trend magmas. Details are given in the Appendix. For each meteorite and each parent magma composition, Δ^2_{REE} values were calculated at 0.05 increments each of X^{magma} and $X^{pigeonite}$. Focusing on the area of best fit, Δ^2_{REE} values and MgO contents were calculated at X increments of 0.025 to 0.001.

SERRA DE MAGÉ

Serra de Magé was chosen as a first test because it is a "typical" cumulate eucrite, not nearly so ferroan and REE-rich as Moore County, and not nearly so magnesian and REE-poor as Moama or Binda (*e.g.*, Warren and Jerde, 1987). In addition, preliminary calculations showed that REE abundances in Serra de Magé could be fit closely with the simple model above. In retrospect, uncertainty
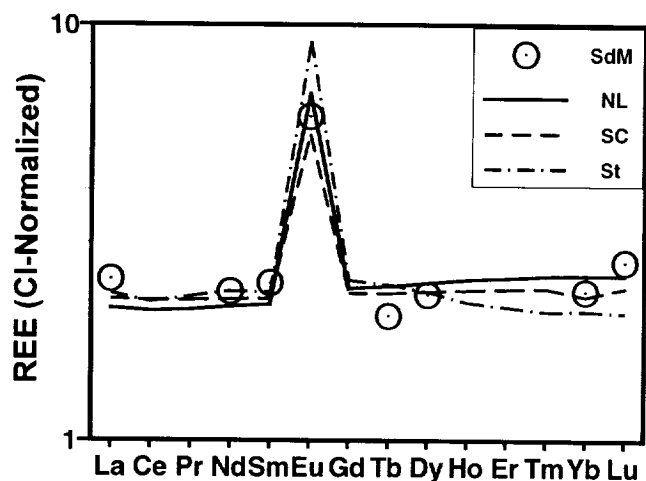
about the actual bulk composition of Serra de Magé makes it less than ideal; its chemical heterogeneity dictates that the analyses used here must be evaluated carefully.

Bulk Composition

As is typical of cumulate eucrites, Serra de Magé consists of plagioclase, orthopyroxene, and augite with lesser quantities of chromite, tridymite, Fe-Ni metal, and troilite, and trace amounts of ilmenite, zircon and Ca-phosphate (Prinz et al., 1977; Delaney et al., 1984). Mineral compositions are quite homogeneous (Prinz et al., 1977; Harlow et al., 1979).

Serra de Magé is grossly heterogeneous in chemical composition at the mass scale used in typical analyses (Tables 2, 3). Major and minor element analyses yield normative plagioclase contents of 35 to 75% (Table 2) and likely represent an inhomogeneous distribution of minerals. The analysis of Moraes and Guimarães (1926) is quite anomalous and possibly inaccurate (Table 2). The few available modal mineral analyses echo the gross heterogeneity of the bulk chemical analyses (Duke and Silver, 1967; Prinz et al., 1977; Delaney et al., 1984). The trace element content of Serra de

Magé is equally variable, with abundances of a REE differing by a factor of two or more (Table 3). The sample with the lowest REE content (Schnetzler and Philpotts, 1969) is reported to contain >90% feldspar and is certainly unrepresentative. Other trace elements show similar ranges of variability.

Given this chemical variability, it is important that mass balance calculations be based on a single sample for which major, minor, and trace elements abundances are all known. The only such analysis is from Palme et al. (1978), columns 1 of Tables 2 and 3, and Fig. 3. In major and minor elements, their analysis is near the average of all available analyses (Table 2; e.g., it implies 41.3% normative feldspar vs. the average of 44.9%); in REE abundances, it is nearly identical to one of the two other available analyses. However, the Palme et al. analysis could still be unrepresentative in that it implies considerably less feldspar than the analysis of Jarosewich (1990), reported to represent a 5.6 g sample (Gomes and Keil, 1980). Trace element analyses of the Jarosewich (1990) sample are in progress and will be reported later.

Background

Most petrogenetic studies of Serra de Magé have suggested a highly fractionated parent magma, unlike any known eucrite basalt; estimates include La contents from hundreds to thousands times CI, and La/Lu ratios to tens or hundreds times the CI ratio (e.g., Stolper, 1977; Consolmagno and Drake, 1977; Hamet et al., 1978; Ma and Schmitt, 1979; Pun and Papike, 1995; Pun et al., 1996). Only a few studies have suggested that Serra de Magé formed from a known eucritic magma type (Schnetzler and Philpotts, 1969; Reid et al., 1979; Warren and Jerde, 1987). Schnetzler and Philpotts (1969) inferred that its parent magma was a known basaltic eucrite type using $D^{plagioclase/basalt}_{REE}$ and their mass spectrometric analyses of a plagioclase-rich bulk sample, not a pure plagioclase separate. Their result must be seen as coincidental because $D^{mineral/magma}$ are inapplicable to rocks that equilibrated in the absence of magma (see above; Treiman, 1996), and because $D^{plagioclase/basalt}$ values are inappropriate for a sample with significant proportions of other minerals.

Calculation

Serra de Magé, as it turns out, can be modeled almost exactly as a simple cumulate with trapped magma (Table 4, Fig. 3). The REE alone do not compel a unique choice of parent magma and cumulus proportions; in fact, an adequate match to Serra de Magé's REE can be calculated from any normal eucrite parent magma. Consideration

TABLE 2. Serra de Magé: Bulk compositions and CIPW norms.

	(1)	(2)	(3)	(4)	(5)	(6)
SiO₂	48.45	48.42	46.69	43.42	47.50	
TiO₂	0.13	0.166	0.11		0.19	0.13
Al₂O₃	14.77	12.69	20.89	27.2	16.93	15.96
Cr₂O₃	0.63	0.54	0.33	0.33	0.35	0.58
FeO	14.40	16.18	9.97	6.56	14.10	13.17
MnO	0.48	0.55	0.36	0.58	0.41	
MgO	10.66	11.34	7.52	3.18	10.10	11.41
CaO	9.75	9.08	13.09	14.53	10.85	10.11
Na₂O	0.25		0.3	1.59	0.19	0.27
K₂O	0.012	0.007	0.0	0.2	0.02	
P₂O₅	0.028	0.057	0.05		0.19	
S	0.15			0.04	0.20	
SUM	99.70	99.03	99.31	97.63	101.03	

CIPW Norm*

Q	0.14	0	0	0	0	0‡
Or	0.07	0.04	0	1.2	0.1	0
Ab	2.1	1.8†	2.5	8.2	1.6	2.3
An	39.1	33.6	55.6	66.4	45.3	42.3
Neph	0	0	0	2.9	0	0
Di	7.4	9.5	7.4	4.7	6.0	6.4
Hy	49.4	51.7	31.0	0	41.7	48.6
Ol	0	1.3	1.9	13.7	4.8	0†
Il	0.2	0.3	0.2	0	0.4	0.2
Chr	0.9	0.8	0.5	0.5	0.5	0.9
Ap	0.07	0.13	0.1	0	0.4	0
SUM	99.4	99.2	99.2	97.6	100.8	100.7
Mg*	0.568	0.553	0.571	0.448	0.561	0.614

References: (1) Palme et al. (1978), recalculated as oxides, ignoring their O analysis; (2) McCarthy et al. (1973); (3) Jarosewich (1990); (4) Moraes and Guimarães (1926) with Fe₂O₃ recalculated as FeO; (5) Yanai et al. (1995); (6) Jeromé (1970).
*CIPW norm calculation follows Morse (1980), with Fe₂O₃ recalculated as FeO, and chromite (Chr) was calculated as FeO·Cr₂O₃ from all Cr₂O₃ before allocation of FeO to silicate minerals. Calculations verified with computer program IGNEOUS (Dunn, 1995).
†Albite calculated assuming An₀₅ plagioclase, which implies 0.22 wt% Na₂O in bulk analysis.
‡Lacking an analysis for SiO₂, CIPW norm calculated assuming Q and Ol are zero.
Mg* is molar MgO/(MgO + FeO + MnO).

TABLE 3. Serra de Magé: Rare-earth-element abundances (parts per million).

	(1)	(2)	(3)	(4)	(5)
La	0.58		0.257		
Ce		1.22			
Nd		1.06			
Sm	0.35	0.327	0.123	0.3	
Eu	0.33	0.298	0.35	0.5	
Gd		0.47			
Tb	0.07				
Dy	0.6	0.554			
Er		0.33			
Yb	0.39	0.367	0.148		
Lu	0.066		0.03	0.06	0.043

References: (1) Palme et al. (1978); (2) Schnetzler and Philpotts (1969); (3) Ma and Schmitt (1979); (4) Morgan et al. (1976); (5) Patchett and Tatsumoto (1980).

TABLE 4. Best fits to Serra de Magé cumulate:
Lowest Δ^2_{REE} for MgO = 10.66 ± 0.3%.

	Serra de Magé	Best cumulate calculated from given parent magma		
		Nuevo Laredo	Sioux County	Stannern
SiO_2	48.45	49.07	48.97	48.90
TiO_2	0.13	0.21	0.20	0.14
Al_2O_3	14.77	14.29	16.83	17.74
Cr_2O_3	0.63	0.24	0.31	0.35
FeO	14.4	14.75	11.64	10.50
MnO	0.48	0.52	0.42	0.36
MgO	10.66	10.55	10.65	10.66
CaO	9.75	9.81	10.64	10.51
Na_2O	0.25	0.37	0.32	0.45
K_2O	0.012	0.013	0.01	0.016
P_2O_5	0.028	0.012	0.02	0.009
SUM	99.56	99.84	100.01	99.63
Δ^2_{REE}		**0.052**	**0.030**	0.41
Δ^2_{Maj}		**0.002**	0.064	0.12
X^{magma}		0.11	0.255	0.0775
$X^{pig.}$		0.525	0.375	0.450
$X^{plag.}$		0.365	0.370	0.4725

Serra de Magé analysis from Palme et al. (1978).
Values of Δ^2_{REE} < 0.1 and Δ^2_{Maj} < 0.005, shown in **bold**, represent good fits between model cumulate and analyzed rock.

of MgO abundances permits only a few possible combinations of parent magmas and cumulus proportions. Choosing the best among these few requires the full chemical analysis.

First, REE abundances of hypothetical cumulates were calculated following the model (Eq. 4) for known eucritic parent magmas and for ranges of X^{magma} and $X^{pigeonite}$. Values of Δ^2_{REE} were calculated for each permutation of the Xs using Ce, Nd, Sm, Eu, Gd, and Yb. The Δ^2_{REE} were essentially unaffected by substitution of La for Ce, or of Lu for Yb, and were essentially unaffected by use of 'primary' or 'alternate' distribution coefficients (Table 1). The Δ^2_{REE} is most sensitive to X^{magma}, which is the main control on the overall level of the REEs except Eu (Fig. 4). The Δ^2_{REE} is less sensitive to $X^{pigeonite}$, and therefore $X^{plagioclase}$ (Fig. 4). It is a major contributor to Eu but contributes little of the other REE, while $X^{pigeonite}$ contributes little to the LREE and only modestly to the HREE.

Figure 4 shows that Δ^2_{REE} calculated for all normal eucrite magmas have minima lower than 0.1, indicating that the REE pattern of Serra de Magé can be modeled (to reasonable accuracy) as a pigeonite-plagioclase-magma cumulate from any normal eucritic magma. However, few of these hypothetical cumulates match the analyzed MgO of 10.7 ± 0.3%; model cumulates with acceptable MgO fall within the parallel lines crossing Figs. 4a–d. Cumulates from Main Group and Nuevo Laredo Trend magmas can satisfy the constraints from both REE and MgO, but Stannern Trend magmas can not. For a cumulate from a Stannern trend magma to have low enough REEs, it will have too much MgO. Even so, model cumulates that satisfy constraints of MgO and the REE may still be unacceptable, as other element abundances may be discrepant.

Looking at the full chemical analyses and Δ^2_{Maj}, it is clear that Serra de Magé's composition can be modeled nearly exactly as a cumulate from a Nuevo Laredo type eucrite magma (Table 4). The major and minor element composition of Serra de Magé is nearly exactly the same as a cumulate consisting of 11% Nuevo Laredo

magma, 52.5% cumulus pigeonite, and 36.5% cumulus plagioclase. The match between analysis and model is nearly perfect for Si, Ti, Al, Fe, Mn, Mg, Ca, and K, and yields a Δ^2_{Maj} of 0.002! The few differences between the analysis and the model are minor. The model predicts only half the Cr that was present in the analysis, which could reflect a small proportion of cumulus chromite. And the model predicts slightly too much Na, which could reflect a model plagioclase composition that is slightly too sodic. The REE abundances predicted by this model cumulate are within analytical error of those in the Palme et al. (1978) sample of Serra de Magé, as shown in Fig. 3, yielding Δ^2_{REE} = 0.065.

Equally clearly, main-group eucrite parent magmas do not yield good matches for the composition of Serra de Magé. For instance, a Sioux County parent magma can match the REE and MgO (Table 4), but only with excess Al and insufficient Fe. Given the latitude in matching REEs (Fig. 5) and MgO, it is not possible to distinguish among similar possible parent magmas; results for Juvinas type parent magma are little different from those of Sioux County, and results for Lakangaon type parent magma (Warren and Jerde, 1987) are little different from those for Nuevo Laredo.

Thus, the bulk composition of the Palme et al. (1978) sample of Serra de Magé can be modeled very closely as a cumulate from a Nuevo Laredo type eucrite magma, despite the significant limitations of the model used here. For Serra de Magé, it is not necessary to invoke highly fractionated magmas or unusual petrogenetic processes. In this light, Serra de Magé can be viewed as a natural product of simple igneous processes acting on a known eucrite basalt magma.

MOORE COUNTY

The Moore County meteorite is, like Serra de Magé, an archetypal cumulate eucrite lithology: feldspar, pyroxenes, silica, and opaque minerals (Duke and Silver, 1967; Delaney et al., 1984). Its chemical composition has been analyzed repeatedly (Henderson and Davis, 1936; Schnetzler and Philpotts, 1969; Schmitt et al., 1972; Jerome, 1970; McCarthy et al., 1973). Moore County is considered a cumulate because it is significantly more magnesian than known eucrite basalts (Mg* = 0.52), has REEs at ~5–7 × CI (lower than eucrite magmas), and has a strong positive Eu anomaly. Unfortunately, no single sample of Moore County has been analyzed for both major elements and the REE. This work uses the REE data of Schnetzler and Philpotts (1969) and the average of major element analyses from Jerome (1970) and McCarthy et al. (1973), as given in Fig. 6 and Table 5.

Previous studies of Moore County have generally concluded that its parent magma was not among the known eucrite basalts (Stolper, 1977; Consolmagno and Drake, 1977; Ma et al., 1977; Ma and Schmitt, 1979), with some studies suggesting that it contains a significant proportion of intercumulus magma (Reid et al., 1979; Pun and Papike, 1995). Within the model here, Moore County can be modeled successfully as a cumulate from a eucrite basalt like Nuevo Laredo. The calculation of Δ^2_{REE} used Ce, Sm, Nd, Eu, Gd, and Yb (Schnetzler and Philpotts, 1969). Substitution of Lu for Yb gave much larger Δ^2_{REE} values, as its abundance is anomalously high compared to the other trivalent REE; Lu is commonly enriched or depleted relative to Yb without obvious cause (Haskin, 1990). Figure 7 shows the minimum values of Δ^2_{REE} for model cumulates from normal eucritic magmas, and minimum Δ^2_{REE} for model cumulates that match the MgO content of Moore County. As with Moama, use of 'primary' or 'alternate' distribution coefficients (Table 1) had
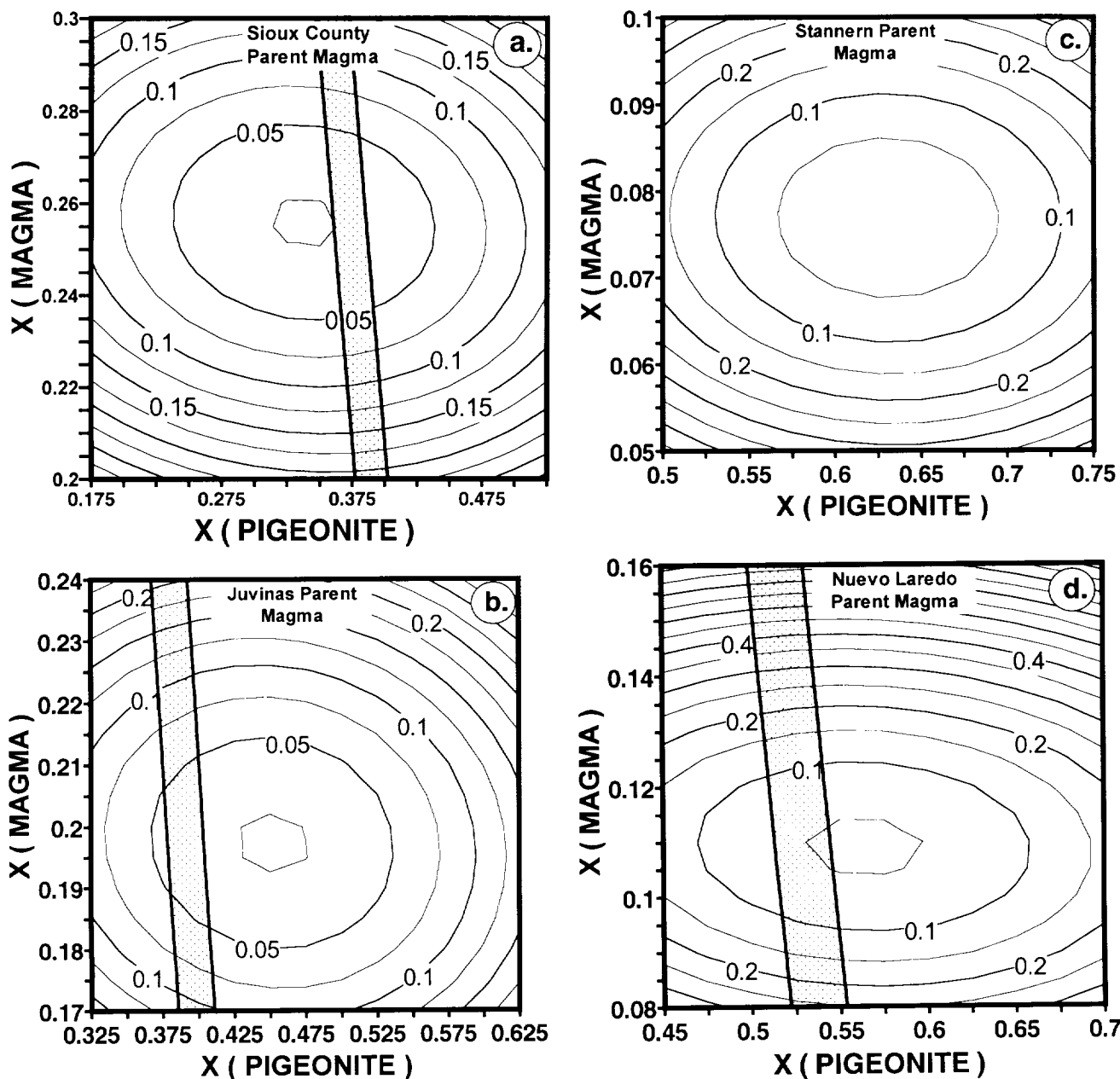
Fig. 4. Goodnesses of fit for Serra de Magé (Palme *et al.* 1978) modeled as simple cumulates from various eucritic magmas. Contours are Δ^2_{REE} values for REE fit (Table 4, Eq. 5). Stippled fields have predicted MgO <0.3 wt% away from the analyzed value of 10.7% (Table 2). Acceptable models for Serra de Magé must have Δ^2_{REE} < 0.1 and MgO in the stippled field (*e.g.*, $|MgO_{meas}-MgO_{calc}|$ < 0.3%). (a) Sioux County as parent magma. (b) Juvinas as parent magma. (c) Stannern as parent magma. (d) Nuevo Laredo as parent magma.

essentially no effect on the results. Adequate REE fits are possible from all magma compositions along the main group and Nuevo Laredo trends (Fig. 7); only Stannern trend magmas are incapable of yielding adequate fits to the REE in Moore County. However, the best fits to the REE do not yield adequate fits to MgO, for example cumulates from a Sioux County parent magma (Fig. 7). The best fit from a Sioux County parent magma, constrained to match MgO, matches major elements quite well (Δ^2_{Maj} = 0.002) but is a poor match to the REE (Δ^2_{REE} =0.19; Fig. 6). The best compromise among the REE and major element fits is the model cumulate from Nuevo Laredo given in Table 5 and Fig. 6; its Δ^2_{REE} = 0.09 is acceptable and its major element fit, Δ^2_{Maj} = 0.01, is marginal in having low FeO.

While Moore County can be modeled adequately as a cumulate from a Nuevo Laredo magma, it is disquieting that the match is not as good as for Serra de Magé above. A possible cause of the problem is sample heterogeneity: the separate samples analyzed for REE and major elements might not have represented identical proportions of cumulus minerals and intercumulus magma. This hypothesis can be easily tested with a complete chemical analysis of a representative sample.

MOAMA

The Moama meteorite is a cumulate eucrite with mineral proportions similar to those of Moore County: 50% plagioclase, 48% pyroxene, 1% silica, and 1% chromite (Lovering, 1975; Delaney *et*
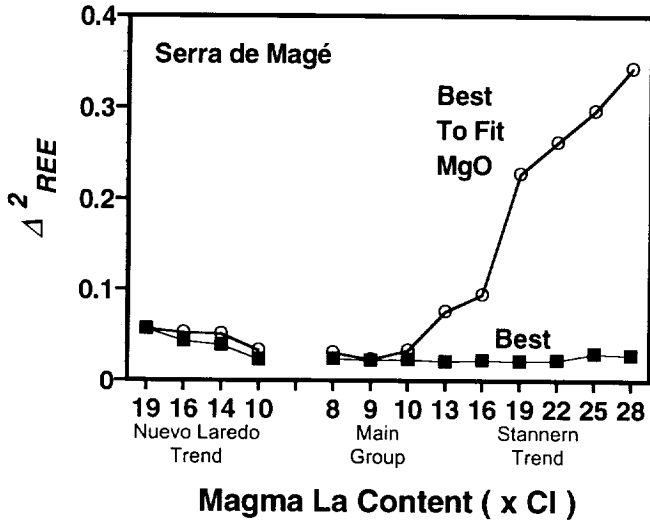
FIG. 5. For models of Serra de Magé, best (lowest) Δ^2_{REE} values (squares), and best (lowest) Δ^2_{REE} values that fit $|MgO_{meas}-MgO_{calc}| < 0.3\%$ (circles), plotted against La contents of parent magmas along Nuevo Laredo–Main Group–Stannern trends.
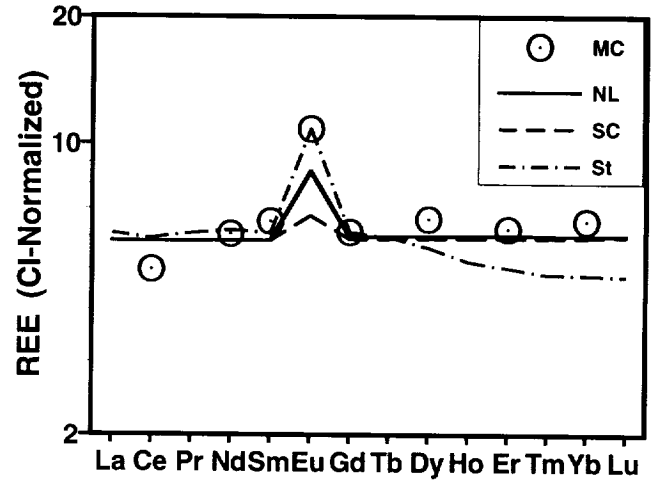

FIG. 6. Rare-earth-element abundances in Moore County (Schnetzler and Philpotts, 1969), circled dots. Lines are calculated REE fits to the measured abundances from Table 5, comparing the calculated and measured abundances. MC = Moore County; NL = best fit cumulate from Nuevo Laredo parent magma; SC = best fit cumulate from Sioux County parent magma; St = best fit cumulate from Stannern parent magma.

al., 1984). Its chemical composition has been analyzed only a few times and is moderately heterogeneous (Lovering, 1975; Hamet *et al.*, 1978; Mittlefehldt, 1979). For instance, the three analyses for MgO are 11.89, 13.26, and 11.42%, for CaO are 9.47, 8.8, and 9.9% (Lovering, 1975; Mittlefehldt, 1979), and for Lu are 0.075, 0.065, and 0.066 ppm (Hamet *et al.*, 1978; Mittlefehldt, 1979; Patchett and Tatsumoto, 1980). Moama is slightly more magnesian than Serra de Magé, with $Mg^* = 0.58$. However, Moama has extremely low abundances of REE, La ~ 0.8 × CI, and distinct enrichment in the heavy REE, Lu/La ~ 3 × CI (Fig. 8). The simple cumulate model was tested using abundances of Ce, Sm, Nd, Eu, Gd, and Yb from Hamet *et al.* (1978) and the major element analysis of Lovering (1975). Unfortunately, these analyses are of different aliquots.

As with Serra de Magé and Moore County, Moama can be modeled adequately as a simple cumulate from a eucrite basalt like Nuevo Laredo (Table 6, Fig. 9). However, this result is strongly dependent on the choice of mineral/magma REE partition coefficients! Using the 'primary' coefficients of Table 1, Moama's composition cannot be fit adequately by any mixture of normal eucritic magma with equilibrium pigeonite and plagioclase (Table 7, Fig. 9). But using the 'alternate' partition coefficients permits Moama's composition to be fit fairly well as a simple cumulate of 4% Nuevo Laredo eucrite magma, 36% cumulus plagioclase, and 60% cumulus pigeonite (Table 7, Fig. 9).

These mass balance calculations on Moama are sensitive to the choice of REE partition coefficient because Moama's bulk REE content is very low compared to those of potential parent magmas. Because the bulk REE content is so low, Moama can contain little trapped melt component, and REE contributions from the cumulus minerals come to dominate the bulk rock abundances. For Serra de Magé or Moore County, this sensitivity to partition coefficients does not arise for because their bulk REE abundances are dominated by their intercumulus magma component.

The 'alternate' D values of Table 1 yield a better fit for Moama because their $D^{pigeonite/magma}$ are higher for the HREE (*e.g.*, Yb) than the "primary' values. This difference allows the calculated REE pattern to approach the HREE-enrichment of Moama itself (Fig. 8). It is, perhaps, gratifying that the 'alternate' values should

work well, because they were determined from a natural eucrite (Pasamonte) that retains its original igneous zoning patterns (Pun and Papike, 1994). It should be remembered that the calculations above for Serra de Magé and Moore County yield essentially the same result using either set of partition coefficients.

If the 'primary' D_{REE} values were shown to be correct, and the 'alternate' values shown to be inapplicable, then Moama could not be explained within the simple cumulate model. Then, one would have to explain why the model fits the major element composition of Moama but not its REE composition. In this hypothetical case,

TABLE 5. Best fits to Moore County:
Lowest Δ^2_{REE} for MgO = 9.3 ± 0.3%.

	Moore County	Best cumulate calculated from given parent magma		
		Nuevo Laredo	Sioux County	Stannern
SiO_2	48.32	49.12	49.32	48.60
TiO_2	0.39	0.41	0.47	0.29
Al_2O_3	13.31	13.89	13.05	17.96
Cr_2O_3	0.44	0.25	0.36	0.32
FeO	17.3	16.00	16.69	11.41
MnO	0.52	0.53	0.54	0.37
MgO	9.36	9.02	9.28	9.08
CaO	9.76	10.09	9.85	11.12
Na_2O	0.42	0.43	0.38	0.50
K_2O	0.02	0.02	0.03	0.03
P_2O_5	0.04	0.04	0.07	0.03
SUM	99.88	99.80	100.04	99.71
Δ^2_{REE}		**0.089**	0.192	0.107
Δ^2_{Maj}		0.010	**0.002**	0.26
X^{magma}		0.35	0.725	0.255
X^{pig}		0.375	0.175	0.325
X^{plag}		0.275	0.1	0.42

Moore County analysis the average of Jeromé (1970) and McCarthy *et al.* (1973).
Values of $\Delta^2_{REE} < 0.1$ and $\Delta^2_{Maj} < 0.005$, shown in **bold**, represent good fits between model cumulate and analyzed rock.
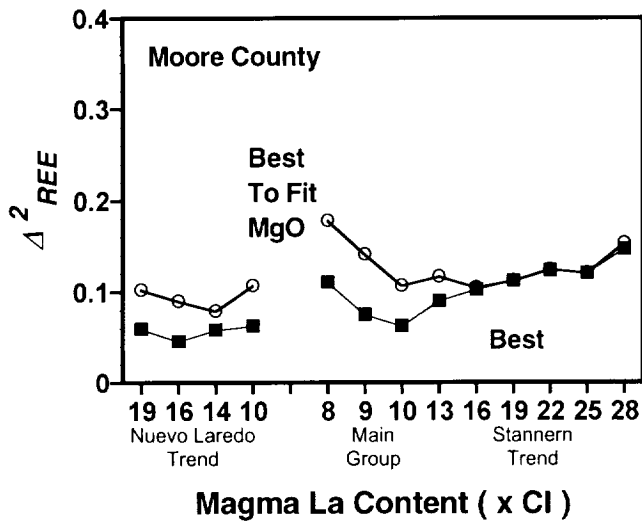
Magma La Content (x CI)

FIG. 7. For models of Moore County, best (lowest) Δ^2_{REE} values (squares), and best (lowest) Δ^2_{REE} values that fit $|MgO_{meas}-MgO_{calc}| < 0.3\%$ (circles), plotted against La contents of parent magmas along Nuevo Laredo–Main Group–Stannern trends.

one would have to invoke magmas beyond the range of known eucrite basalts, or geochemical processing after accumulation (e.g., Sparks et al., 1985; Walker and Agee, 1988).

Yamato 791195

The Y-791195 meteorite is an equigranular, medium-grained monomict eucrite. Although its bulk composition is nearly identical to main-group eucrites (Table 7), Y-790015 is considered a cumulate because of its pyroxene textures and its REE pattern, which is intermediate between those of Moore County and Serra de

FIG. 8. Rare-earth-element abundances in Moama (Hamet et al., 1978). Lines are calculated REE fits from Table 6 to the measured abundances, comparing the calculated and measured abundances. Using the 'primary' D values of Table 1: MC = Moore County; NL = best fit cumulate from Nuevo Laredo parent magma; SC = best fit cumulate from Sioux County parent magma; St = best fit cumulate from Stannern parent magma. Using the 'alternate' D values of Table 1: NL* = best fit cumulate from Nuevo Laredo parent magma.

Magé (Fig. 10; Warren and Kallemeyn, 1992; Mittlefehldt and Lindstrom, 1993). The available major element and REE analyses are of the same sample (Mittlefehldt and Lindstrom, 1993).

The simple cumulate model fails resoundingly for Y-791195. Using the rare earths La, Sm, Eu, Tb, Yb, and Lu (Mittlefehldt and Lindstrom, 1993), the simple cumulate model yields a minimum $\Delta^2_{REE} = 0.19$ from any basaltic eucrite composition as parent magma; the minimum Δ^2_{REE} consistent with MgO = 7.7% is 0.30.

Unfortunately, even these poor REE fits all yield very bad fits to the major elements (as high Δ^2_{Maj}). Use of the alternate D values (Table 1) improves the fits only marginally, and Table 7 reflects use of the primary D. Use of the nominal value for Ce rather than La in Y-791195 improves the model fits significantly (bringing Δ^2_{REE} consistent with MgO down to 0.08) but is not justified given the uncertainties on the Ce analysis (Fig. 10). The underlying problem is that the simple model here cannot yield REE patterns with strong depletions in the LREE.

On the other hand, major element abundances in Y-791159 are very similar to those in Juvinas and Sioux County, suggesting a close affiliation with those meteorites. In fact, the major element composition (Si, Al, Fe, Mg, Ca) can be fit quite closely as simple cumulates from any normal eucritic magma and its equilibrium crystals. Table 7 shows the best matches (i.e., lowest Δ^2_{Maj}) for the full span of eucrite basalt compositions; one need only compare the bulk analysis of Y-791195 (the last three columns of Table 7) to see how close the matches are. Of course, none of these model cumulates has a REE pattern anything like that of Y-791195, as can be seen from the REE pattern of Fig. 10 and the outrageously high values of Δ^2_{REE} for the last three columns of Table 7.

The failure of the simple cumulate model for Y-791195 implies that at least one of its assumptions was violated. This failure appears as an inability to reproduce strong depletions in incompatible elements, like Ti and the

TABLE 6. Best fits to Moama:
Lowest Δ^2_{REE} for MgO = 11.9 ± 0.3%.

	Moama	Best cumulate calculated from given parent magma, using 'Primary' D Values			Best cumulate calculated from given parent magma, using 'Alternate' D values		
		Nuevo Laredo	Sioux County	Stannern	Nuevo Laredo	Sioux County	Stannern
SiO₂	48.58	49.25	49.16	49.26	49.25	49.16	49.27
TiO₂	0.22	0.16	0.11	0.10	0.16	0.11	0.10
Al₂O₃	13.74	13.36	16.80	16.53	13.36	16.79	16.42
Cr₂O₃	0.61	0.25	0.32	0.38	0.25	0.32	0.39
FeO	14.85	15.10	10.70	10.86	15.10	10.70	10.95
MnO	0.50	0.55	0.41	0.39	0.55	0.41	0.39
MgO	11.89	11.57	11.94	11.92	11.57	11.94	11.95
CaO	9.47	9.28	10.29	9.78	9.28	10.29	9.74
Na₂O	0.22	0.33	0.28	0.40	0.33	0.28	0.40
K₂O	0.01	0.01	0.00	0.01	0.01	0.00	0.01
P₂O₅		0.00	0.01	0.00	0.00	0.01	0.00
SUM	100.09	99.86	100.02	99.63	99.86	100.01	99.62
Δ^2_{REE}		0.215	0.490	0.288	**0.089**	0.383	0.132
Δ^2_{Maj}		**0.002**	0.135	0.115	**0.002**	0.135	0.108
χ^{magma}		0.04	0.105	0.02	0.04	0.105	0.025
χ^{pig}		0.60	0.475	0.525	0.60	0.475	0.525
χ^{plag}		0.36	0.42	0.455	0.36	0.42	0.45

Alternate D values from Table 1.
Moama analysis from Lovering (1975).
Values of $\Delta^2_{REE} < 0.1$ and $\Delta^2_{Maj} < 0.005$, shown in **bold**, represent good fits between model cumulate and analyzed rock.
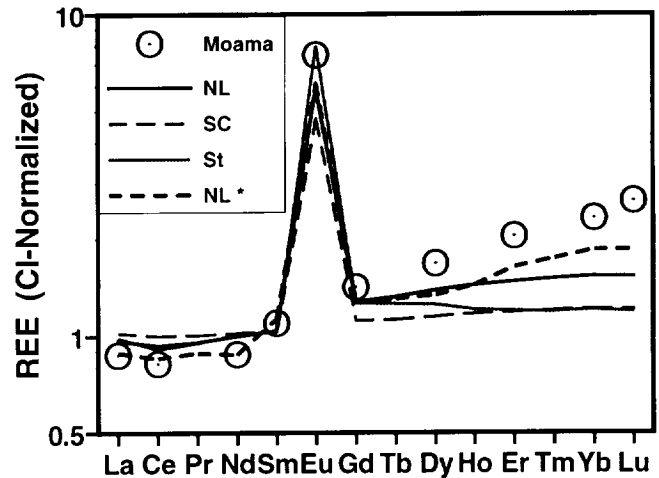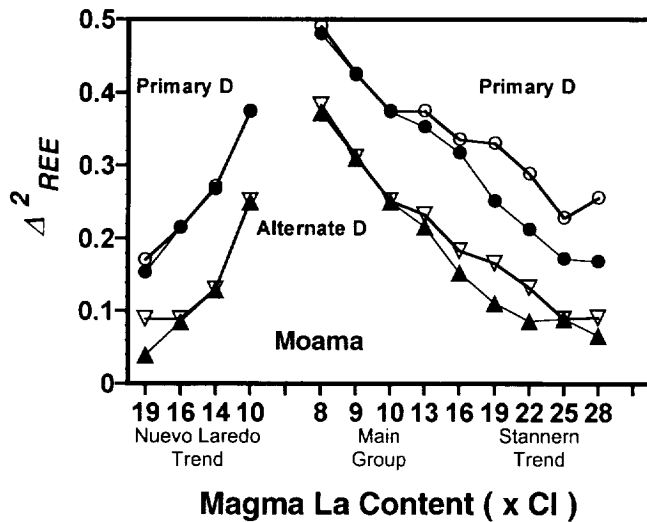
FIG. 9. For models of Moama, best (lowest) Δ^2_{REE} values (filled symbols), and best Δ^2_{REE} values that fit $|MgO_{meas}-MgO_{calc}| < 0.3\%$ (open symbols), plotted against La contents of parent magmas along Nuevo Laredo–Main Group–Stannern trends. Circles and triangles represent results using 'primary' and 'alternate' partition coefficients respectively (Table 1).
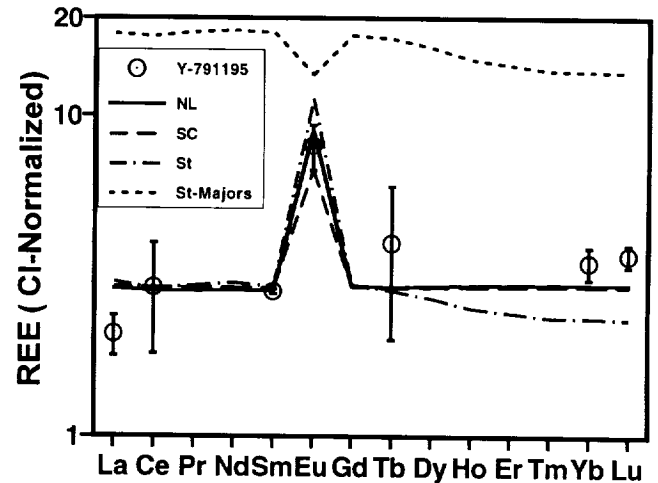
FIG. 10. Rare-earth-element abundances in Y-791195 with 1σ analytical uncertainties (Mittlefehldt and Lindstrom, 1993). Lines are calculated REE fits to the measured abundances from Table 7, comparing the calculated and measured abundances. NL = best REE fit cumulate from Nuevo Laredo parent magma; SC = best fit cumulate from Sioux County parent magma; St = best fit cumulate from Stannern parent magma; St-Majors = best Juvinas parent magma fit to major elements.

REE. It is not clear which of the model's assumptions might have been violated during Y-791195's genesis.

A first suggestion for the failure of the simple cumulate model is that it does not consider the proper parent magma composition. Mittlefehldt and Lindstrom (1993) modeled Y-791195 as a cumulate of plagioclase + pyroxene only from the REE and Mg*. They suggested a parent magma derived from 80% fractional crystallization of a Juvinas-like magma (*i.e.*, La ~ 50 × CI), while Nuevo Laredo

itself only represents 40% fractional crystallization. Warren and Kallemeyn (1992) also suggested formation from a highly fractionated (low Mg*) magma along the Nuevo Laredo trend.

Another possible 'failure mode' is that the distribution coefficients of Table 1 are not relevant to Y-791197. If so, the actual $D^{pigeonite/magma}$ would have to be significantly higher for the heavy REE (*e.g.*, Yb, Lu) than either the 'primary' or 'alternate' values in Table 1.

TABLE 7. Comparison of Juvinas to Y-791195 and best model fits to Y-791195 yielding MgO = 7.7 ± 0.3%.

	Juvinas	Y-791195	Model cumulates with lowest Δ^2_{REE}, from given parent magma*			Model Cumulates with Lowest Δ^2_{Maj}, from given parent magma*		
			Nuevo Laredo	Sioux County	Stannern	Nuevo Laredo	Sioux County	Stannern
SiO$_2$	49.34	49.3	48.28	48.07	48.00	49.20	48.83	48.85
TiO$_2$	0.64	0.25	0.22	0.23	0.15	0.59	0.55	0.78
Al$_2$O$_3$	13.00	13.3	18.45	20.09	21.54	13.38	13.41	13.31
Cr$_2$O$_3$	0.34	0.34	0.19	0.25	0.26	0.26	0.34	0.33
FeO	18.82	17.3	12.09	10.46	8.51	17.27	17.38	17.27
MnO	0.56	0.58	0.41	0.36	0.28	0.53	0.54	0.49
MgO	7.27	7.7	7.94	7.72	7.91	7.66	7.69	7.68
CaO	10.38	10.5	11.69	12.39	12.41	10.29	10.34	10.44
Na$_2$O	0.47	0.40	0.49	0.39	0.55	0.49	0.43	0.55
K$_2$O	0.04	0.03	0.02	0.01	0.02	0.03	0.03	0.07
P$_2$O$_5$	0.09	–	0.02	0.03	0.01	0.06	0.08	0.10
SUM	100.95	99.70	99.79	100.00	99.64	99.76	99.62	99.87
Δ^2_{REE}			0.312	0.338	0.733	23.6	10.26	114.4
Δ^2_{Maj}		0.011	0.255	0.450	0.676	**0.00045**	**0.00040**	**0.00012**
X^{magma}			0.155	0.345	0.1075	0.567	0.873	0.808
X^{pig}			0.370	0.225	0.315	0.238	0.067	0.097
X^{plag}			0.475	0.435	0.5775	0.186	0.060	0.095

*Rare-earth-element calculations use La, Sm, Eu, Tb, Yb, and Lu and use primary D values of Table 1.
Yamoto 791195 analysis from Mittlefehldt and Lindstrom (1993).
Values of $\Delta^2_{REE} < 0.1$ and $\Delta^2_{Maj} < 0.005$, shown in **bold**, represent good fits between model cumulate and analyzed rock.

A final 'failure mode' is that the Y-791195 was affected by a geochemical process beyond those considered by the model. The similarity of major element compositions Y-791195 and Juvinas and Sioux County (Table 7) invites the hypothesis that Y-791195 was a main-group eucrite basalt that was somehow stripped of most of its incompatible elements (*e.g.,* Ti and the REE). Whatever process might strip incompatible elements from a eucrite basalt is not included within the simple model. For instance, it is possible that the missing incompatible elements were in a strongly evolved, late-stage intercumulus magma. This late magma might have been displaced by adcumulus crystal growth, or compaction induced by gravity or a thermal gradient (*e.g.,* Sparks *et al.,* 1985; Walker and Agee, 1988). If so, one might expect small proportions of rock evolved from such an evolved magma (ferroan, incompatible rich) to be encountered occasionally in eucrites. The rare fragments of ferroan troctolite found in a polymict eucrite (Treiman and Drake, 1985) might have originated in this manner. Of course other hypotheses remain valid, as neither the origin of the ferroan troctolites nor Y-791195's depletion in incompatible elements has been completely explained.

CONCLUSIONS

The chemical compositions of the cumulate eucrites Serra de Magé, Moore County, and Moama can be reproduced adequately within an extremely simple model: a mixture of crystals plus intercumulus magma; crystals in equilibrium with the intercumulus magma; and chemical closure after accumulation. For these cumulates, the parent magma compositions and the proportions of cumulus phases can be retrieved, given some general limitations on permitted compositions for parent magmas. However, neither REE alone nor major elements alone may permit retrieval of a unique parent magma composition, for example, the REE pattern of Serra de Magé (Figs. 4, 5; Table 4) and the bulk composition of Y-791195 (Table 7). A unique choice of parent magma can be based only on elements with a wide range of geochemical behaviors (*e.g.,* the REE and major elements).

Of course, the exact quantitative results here should be used with caution, because they are based on a model which is greatly simplified from reality. First, it seems likely that the eucrite parent body produced magmas somewhat beyond the range of 'normal eucrites' considered here (*vis.* Dymek *et al.,* 1976; Mittlefehldt, 1979; Smith, 1982; Hewins and Newsom, 1988; Buchanan and Reid, 1996). Second, it is quite possible (even probable) that cumulus mineral grains would not have been chemically homogeneous, as required by the model. Third, it is unlikely that any cumulate rock would experience no postcumulus processing.

And fourth, it is likely that the distribution coefficients of Table 1 are not completely accurate, and so calculations based on them remain somewhat uncertain. The mass-balance modeling as done here is insensitive to the exact choice of mineral/magma partition coefficients, except if the cumulate had relatively little intercumulus magma (*e.g.,* Moama with only 4% intercumulus magma). Thus, cumulates with less intercumulus magma may provide tighter constraints on which partition coefficients are most appropriate for the system. For the eucrites, the $D_{REE}^{pigeonite/magma}$ of Pun and Papike (1994), derived from an unequilibrated eucrite, appear the most suitable. Even Moama is not modeled extremely well with the $D_{REE}^{pigeonite/magma}$ of Pun and Papike, 1994 (see Fig. 8), and one might hope for larger $D^{pigeonite/magma}$ for the heavy REE.

The Y-791195 cumulate eucrite cannot be accommodated within this simple model. Its bulk composition, but not its REE or Ti

abundances, can be modeled adequately as simple cumulates from known eucrite basalt magmas. Compared to cumulates that are modeled successfully, Y-791195 has lower REE abundances and a much lower La/Lu ratio. Yamato 791195 could have formed from a magma composition beyond those considered here, or it may have lost a component enriched in incompatible elements (*i.e.,* a late-stage intercumulus magma). Further analyses and modeling may be helpful in understanding Y-791195.

Cumulate Eucrite Parent Magmas

All of the cumulate eucrites considered here could reasonably have formed from parent magmas like the known eucrite basalts, and all but Y-791195 can be modeled as simple cumulates. The range of magmas required here is actually only the Main Group (*e.g.,* Sioux County or Juvinas for Y-791195) and the Nuevo Laredo itself (for Serra de Magé, Moore County, and Moama). No cumulates studied here could have formed from Stannern Trend magmas, although the Pomozdino eucrite may be such a cumulate (Warren *et al.,* 1990).

From this work's mass-balance modeling, there is no need to invoke extremely fractionated magmas (*e.g.,* La to 5000 × CI and La/Lu to 100 × CI) as parent magmas for the cumulate eucrites. Such extreme fractionates are not among the known eucrite basalts but have been suggested in many previous studies. Invoking Occam's Razor, I would suggest that the cumulate eucrites formed from known eucrite magma types, and that extreme or unknown magma types are not needed.

Vesta Geology

The results of this study present intriguing questions about the geology of the eucrite parent body, probably the asteroid 4 Vesta (Drake, 1979; Binzel and Xu, 1993). First, there is no unequivocal evidence here for magma compositions beyond the range of the known basaltic eucrites. This limited range of parent magmas is consistent with very simple petrogenetic processes on the eucrite parent body and may militate (in general terms) against complex petrogenetic schemes that may be required to derive eucrites and diogenites from the same magmatic system.

Second, the cumulate eucrites studied here present a wide range of proportions of intercumulus magma, 35% to 4%. The higher proportions are consistent with simple accumulation of cumulus crystals, but the lower proportions require some sorts of postcumulus compaction or grain overgrowth processes. Are gravitational forces within a eucrite parent asteroid strong enough to drive igneous crystal accumulation and postcumulus compaction, or are other forces required?

And finally, it is intriguing that most of the cumulate eucrites (Moore County, Serra de Magé, Moama) are consistent with a parent magma like Nuevo Laredo. Could these cumulate eucrites represent fragments, or outcrops, of a single gabbroic intrusion? Could magmas like Nuevo Laredo have been preferentially retained within 4 Vesta and not emplaced near or at its surface? Or could the rarity (or absence) of cumulate eucrites from Main Group or Stannern Trend eucrite magmas merely reflect uneven sampling of lithologies from 4 Vesta?

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APPENDIX

Following are chemical compositions of magmas and minerals used as input to the calculations in the paper. Bulk major element compositions are from the literature and from laboratory experiments on eucrites. Bulk rare earth abundances are idealized for Sioux County and Juvinas, from the literature for Stannern and Bouvante, and calculated from D values of Table 1

for magmas along the Nuevo Laredo trend. Mineral compositions are from laboratory experiments on eucrites, from the core compositions of natural eucrites, or calculated based on mineral/magma D values from Stolper (1977), Jurewicz *et al.* (1993), and Jones (1995).

TABLE A1. Magma compositions.

	SC	JV-SC	JV	ST-22	BV-25	NL-14	NL-16	NL-19
SiO_2	49.03	49.25	49.34	48.81	50.22	49.12	49.46	49.42
TiO_2	0.62	0.79	0.64	0.95	1.00	0.73	0.95	1.07
Al_2O_3	12.84	12.31	13.00	12.28	10.5	12.36	11.78	10.95
Cr_2O_3	0.35	0.32	0.34	0.32	0.31	0.15	0.29	0.13
FeO	18.58	19.34	18.82	18.97	19.42	19.18	20.10	21.1
MnO	0.56	0.56	0.56	0.52	0.53	0.64	0.56	0.62
MgO	7.11	6.29	7.27	6.81	6.47	6.07	5.46	4.32
CaO	10.35	10.38	10.38	10.49	10.42	10.31	10.40	10.32
Na_2O	0.45	0.51	0.47	0.58	0.51	0.52	0.57	0.57
K_2O	0.04	0.05	0.04	0.08	0.06	0.04	0.05	0.06
P_2O_5	0.09	0.10	0.09	0.12	–	0.10	0.11	0.12
Total	100.02	99.88	100.95	99.93	99.44	99.22	99.73	98.68
Rare earth elements (× CI)								
La	8.0	9.0	10.0	22.0	24.6	14.0	16.0	19.0
Ce	8.0	9.0	10.0	21.6	25.4	14.0	16.0	19.0
Pr	8.0	9.0	10.0	22.2	24.9	14.0	16.0	18.8
Nd	8.0	9.0	10.0	22.5	24.4	14.0	16.0	18.6
Sm	8.0	9.0	10.0	22.2	25.0	14.0	16.0	18.2
Eu	8.0	9.0	10.0	14.6	15.0	11.9	12.8	13.3
Gd	8.0	9.0	10.0	21.8	24.5	13.9	15.9	17.8
Tb	8.0	9.0	10.0	21.3	24.0	13.9	15.9	17.5
Dy	8.0	9.0	10.0	19.9	23.0	13.9	15.8	17.0
Ho	8.0	9.0	10.0	18.3	22.7	13.8	15.7	16.6
Er	8.0	9.0	10.0	17.6	22.7	13.8	15.7	16.2
Tm	8.0	9.0	10.0	16.9	22.7	13.8	15.6	15.8
Yb	8.0	9.0	10.0	16.8	18.9	13.7	15.5	15.5
Lu	8.0	9.0	10.0	16.7	18.8	13.7	15.5	15.5

SC = Sioux County. Major elements from McCarthy *et al.* (1973), rare earths idealized.

SC-JV = Average of Sioux County and Juvinas, rare earths idealized.

JV = Juvinas. Major elements from McCarthy *et al.* (1973), rare earths idealized.

ST-22 = Stannern. Major elements and rare earths as compiled by Warren *et al.* (1990).

BV-25 = Bouvante. Major elements and rare earths as compiled by Warren *et al.* (1990).

NL-14 = Major elements are glass SC68 of Stolper (1977); rare earths calculated.

NL-16 = Nuevo Laredo. Major elements and rare earth from Warren and Jerde (1987).

NL-19 = Major elements are glass SC64 of Stolper (1977); rare earths calculated.

TABLE A2. Pigeonite compositions.

wt%	SC52	JV18	SC68	SC66	SC64
SiO$_2$	53.14	52.7	52.21	51.61	51.42
TiO$_2$	0.10	0.15	0.1	0.2	0.2
Al$_2$O$_3$	1.00	1.3	1.2	0.9	0.9
Cr$_2$O$_3$	0.60	0.72	0.5	0.4	0.5
FeO	18.42	19.42	21.23	23.45	24.82
MnO	0.74	0.72	0.78	0.88	0.93
MgO	23.56	22.13	21.02	18.7	16.98
CaO	2.48	2.45	2.92	3.86	4.25
Total	100.04	99.59	99.96	100.	100.
En	66	64	60	54	50
Fs	29	31	34	38	41
Wo	5	5	6	8	9

All pigeonite compositions from Stolper (1977).
SC52 used for SC, SC-JV, and JV magmas.
JV18 used for ST-22 and BV-25 magmas.
SC68 used for NL-14 magma.
SC66 used for NL-16 magma.
SC64 used for NL-19 magma.

TABLE A3. Plagioclase compositions.

wt%	An$_{95}$	Juv
SiO$_2$	44.71	45.3
Al$_2$O$_3$	35.64	34.3
FeO	0	0.62
MgO	0	0.36
CaO	19.10	18.2
Na$_2$O	0.55	0.85
K$_2$O	0.00	0.02
Total	100.00	99.65
An	95	92

Anorithrite$_{95}$ composition calculated, used for SC, SC-JV and JV magmas. Juv plagioclase is average from Juvinas eucrite, used for all other magmas.

TABLE A4. Magnesium oxide and REE abundances of other magmas.

Magma	MS-13	MS-16	MS-19	MS-22	MS-25	MS-28
MgO%	7.20	7.20	7.20	6.81	6.47	6.47
Rare earth elements ($\times$ CI)						
La	13.00	16.00	19.00	22.00	25.00	28.00
Ce	13.00	16.01	19.01	22.02	25.02	28.03
Pr	12.92	15.85	18.76	21.65	24.52	27.37
Nd	12.85	15.72	18.55	21.34	24.10	26.83
Sm	12.72	15.47	18.16	20.78	23.34	25.85
Eu	10.96	12.26	13.32	14.20	14.94	15.57
Gd	12.59	15.23	17.78	20.24	22.62	24.92
Tb	12.48	15.02	17.45	19.77	21.99	24.12
Dy	12.32	14.73	17.01	19.16	21.19	23.11
Ho	12.17	14.46	16.59	18.58	20.43	22.17
Er	12.02	14.19	16.19	18.03	19.73	21.31
Tm	11.87	13.94	15.81	17.52	19.07	20.51
Yb	11.73	13.69	15.45	17.03	18.46	19.76
Lu	11.73	13.69	15.45	17.03	18.46	19.76
Pigeonite MgO%	23.8	23.8	23.8	22.7	21.55	21.55

Full magma and mineral compositions were not calculated or used for these hypothetical systems. Magma and pyroxene MgO are based on experiments of Stolper (1977) and Jurewicz *et al.* (1993). Rare-earth-element abundances are calculated.