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ACHONDRITES AND IGNEOUS PROCESSES ON ASTEROIDS

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INTRODUCTION

Partial melting and fractional crystallization are generally believed to be the most fundamental processes in the petrogenesis of terrestrial igneous rocks. Partial melting generates magmas representing the low-temperature melting fractions of source rocks, leaving behind refractory residues ("restites"). The progressive separation of crystals from melt that we call fractional crystallization induces changes in magma compositions and produces accumulations of separated crystals ("cumulates"). Varying degrees of partial melting, together with magmatic fractionation, result in the enormous variety of igneous rocks found on Earth.

Much of modern igneous petrology consists of attempts, using data from experiments, geochemical analyses, and petrographic observations, to sort out the effects of these processes and to quantify their roles in specific igneous systems. It is reasonable to expect that these same processes were also important in producing igneous rocks on extraterrestrial bodies. The study of *achondrites*, which are meteorites of magmatic origin, allows us to explore the generality of our understanding of igneous processes. This is because magmatic processes within achondrite parent bodies occurred under different conditions from those operating within the Earth (e.g. different gravitational fields, source region compositions, heat sources, and time scales for magmatic evolution). By comparing the products of magmatic activity on different solar system bodies, we may be able to isolate the effects of different petrogenetic processes and identify some of the factors that determine the relative roles of these processes. It is crucial to recognize physical and chemical constraints on the processes of partial melting and fractional crystallization if we hope to use our

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knowledge of terrestrial igneous processes as a foundation for planetary geology. Achondrites greatly extend the limited information of this kind we already have from studies of lunar rocks to smaller bodies with different compositions.

Petrogenetic studies of terrestrial igneous rocks are, of course, not without controversy, even where sampling is adequate and field relationships are known. Uncertainties in the interpretations of achondrite origins are exacerbated by the small number of samples available for study, none of which can be confidently placed into a geologic context. However, these meteorites commonly have distinctive geochemical and petrographic "fingerprints" that allow their classification into kindred groups, and comparisons of such related meteorites have provided insights into the igneous processes that produced them. It seems likely that all members of each group were liberated from a single parent body, although this point is arguable. Here, we consider two important achondrite groups—the eucrites and the ureilites. Both groups were apparently derived from small planetesimals, i.e. asteroids, although there are other achondrites that may have had planetary origins (McSween 1985, and references therein).

THE EUCRITE GROUP

The eucrites and their relatives (sometimes referred to as the HED group, for *h*owardites, *e*ucrites, and *d*iogenites) constitute the largest group of achondritic meteorites. Studies of these meteorites illustrate how relatively simple initial petrogenetic models can become complex and sophisticated as the amount of information about them increases.

Petrography, Geochemistry, and Chronology

Eucrites are basaltic rocks, consisting predominantly of pyroxene (pigeonite) and plagioclase, with minor amounts of silica polymorphs, ilmenite, chromite, troilite (FeS), kamacite (Fe-Ni alloy), phosphates, zircon, and occasionally olivine (Duke & Silver 1967, Lovering 1975, Wilkening & Anders 1975, Takeda et al 1983, Treiman & Drake 1985). Many eucrites are fine grained and have vitrophyric or subophitic textures comparable to terrestrial basalts, but most are monomict breccias. Many eucrites have been recrystallized during thermal annealing, which is reflected in homogenization of the compositions of originally zoned pyroxenes (Miyamoto et al 1985a) and in clouding of both pyroxene and plagioclase grains by finely disseminated inclusions (Harlow & Klimenditis 1980). A few coarse-grained eucrites have preferred orientations of mineral grains, and their pyroxenes have higher Mg/(Mg+Fe) ratios and show exsolution textures; these are called *cumulate eucrites*. *Polymict eucrites* contain clasts of a variety of eucrite and cumulate eucrite lithologies (Delaney et al 1984, Treiman & Drake 1985). Meteorites closely related to the eucrites are the *diogenites*, which are usually brecciated orthopyroxenites commonly containing minor olivine (Mason 1963, Gooley & Moore 1976, Hewins 1981) and the *howardites*, which are polymict breccias containing clasts of eucrites, diogenites, and other related rocks (Bunch 1975, Dymek et al 1976, Desnoyers & Jerome 1977, Ikeda & Takeda 1985). Relative to polymict eucrites, howardites contain a larger diogenite component [estimates for seven howardites range from 23 to 68 vol% (Labotka & Papike 1980, Fuhrman & Papike 1981)], but there is probably a continuum between these kinds of breccias (Delaney et al 1983). *Mesosiderites* are breccias containing a significant metal fraction mixed with diogenitic and gabbroic material (Floran 1978, Mittlefehldt 1979, Prinz et al 1980); their connection with the eucrite group is uncertain, however, so they are not considered further here.

All of these meteorites are anhydrous and equilibrated under highly reducing conditions (Hewins & Ulmer 1984), comparable to lunar basalts. Another important chemical characteristic shared among them is a similarity in oxygen isotopic composition. This parameter is commonly used to distinguish meteorite samples originating on different parent bodies. Any igneous process that discriminates between oxygen isotopes will affect the $^{18}O/^{16}O$ ratio by twice as much as the $^{17}O/^{16}O$ ratio, resulting in a smearing of rock compositions along a line of slope 1/2 on a plot of $\delta^{17}O$ versus $\delta^{18}O$. As shown in Figure 1, the eucrite group defines a line parallel to but clearly displaced from the terrestrial mass-fractionation line (Clayton & Mayeda 1983). The oxygen isotopic compositions of eucrite group

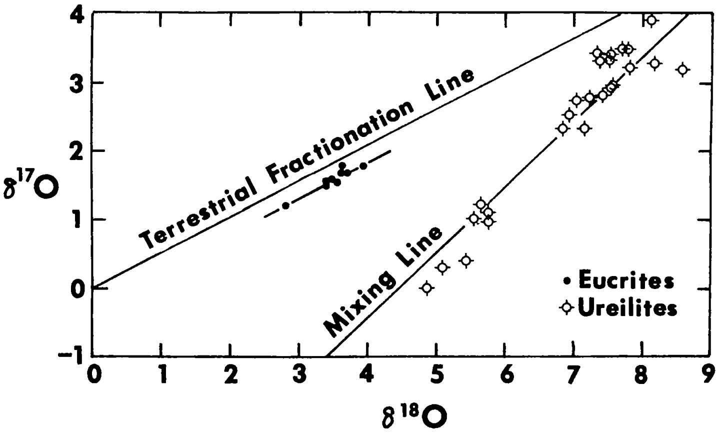

Figure 1 Oxygen isotopic compositions (per mil relative to standard mean ocean water) for eucrites (Clayton & Mayeda 1983) and ureilites (Clayton & Mayeda 1988). The terrestrial mass-fractionation line and a mixing line for components of the Allende carbonaceous chondrite are shown for reference.

samples are thus consistent with their formation on the same parent body. (However, lunar samples fall along the terrestrial mass-fractionation line. This fact points to an obvious problem in using oxygen isotopes as fingerprints of one specific body. It does provide evidence, however, of a close genetic link between the Earth and Moon.)

The crystallization behavior of eucrite melts was investigated by Walker et al (1978a) and Powell et al (1980), who concluded that these magmas cooled from liquidus to solidus temperatures in times ranging from hours to tens of years. Miyamoto & Takeda (1977) and Takeda (1979) inferred the subsolidus cooling histories of various members of the eucrite group based on the widths of pyroxene exsolution lamellae. Subsolidus cooling rates were apparently slower than those through the crystallization interval.

Two basalt fractionation trends have been recognized among eucrites (Stolper 1977) and have been identified in the clast populations within howardites (Delaney et al 1981) and polymict eucrites (Delaney et al 1984, Ikeda & Takeda 1985). These trends differ primarily in their alkali contents, which results in differences in plagioclase composition for a given pyroxene Mg/(Mg+Fe) ratio (Figure 2). Most noncumulate eucrites plot in a cluster (the "main group" eucrites) in this diagram along trend A (also called the "Nuevo Laredo" trend after one prominent member); trend B has been called the "Stannern" trend. Meteorites in trend A are depleted in incompatible trace elements relative to those in trend B. Delaney (1987) explained these trends as originating by melting of different sources, followed by

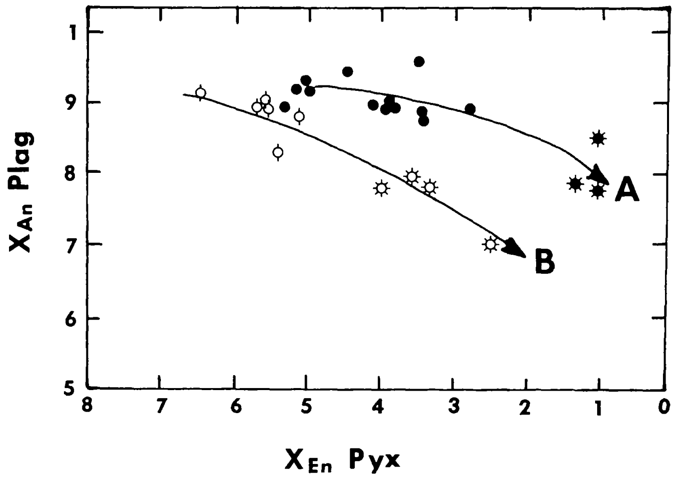

Figure 2 Plot of mole fraction of anorthite in plagioclase versus mole fraction of enstatite in pyroxene, showing two distinct groups of basalts (indicated by open and filled symbols) in eucrites and howardites (Delaney et al 1981, Ikeda & Takeda 1985). All analyses are bulk-rock compositions except for stars, which are calculated liquid compositions in equilibrium with cumulates.

fractional crystallization; he envisioned a complex parent body with a serial pattern of magmatism. Ikeda & Takeda (1985) argued for fractionation in different parts of a magma ocean that was compositionally stratified by escape of volatiles from its top.

Rb-Sr, Sm-Nd, and U-Pb ages for the eucrite group mostly fall in the range 4.4–4.6 Gyr, with very primitive initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios [Papanastassiou & Wasserburg 1969, Tatsumoto et al 1973, Allègre et al 1975, Lugmair & Scheinin 1975, Unruh et al 1977, Birck & Allègre 1978, Basaltic Volcanism Study Project 1981 (Chap. 7), Jacobsen & Wasserburg 1984, Nyquist et al 1986], although a few ages are as young as 2.6 Gyr. The 4.4–4.6 Gyr ages are generally interpreted as the time of crystallization, and younger ages are thought to reflect resetting by shock, as corroborated by a wide spectrum of $^{40}Ar/^{39}Ar$ ages (e.g. Bogard et al 1985). Sm-Nd crystallization ages for cumulate eucrites appear to be younger (approximately 4.4 Gyr) than those for noncumulate eucrites (4.5–4.6 Gyr) (Carlson et al 1988); however, these apparently younger ages may have resulted from slow cooling at depth (Nyquist et al 1986).

Parent Body

The ancient crystallization ages just discussed and the very primitive initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of eucrites indicate that the parent body had a short and relatively simple igneous history, such as that expected for an asteroid. Most geochemical models for eucrite source regions (Consolmagno & Drake 1977, Dreibus et al 1977, Hertogen et al 1977, Morgan et al 1978) are consistent with this idea, as the inferred sources appear to have had compositions that were approximately chondritic rather than having been previously differentiated. However, other data on the siderophile element concentrations in eucrites suggest that this body may have experienced core formation (Palme & Rammensee 1981, Newsom 1985).

By assuming that subsolidus crystallization of pyroxenes reflects relative cooling rates at different depths, Miyamoto & Takeda (1977) and Takeda (1979) constructed a "layered crust" model for the eucrite parent body, in which diogenites and cumulate eucrites formed at deeper levels than eucrites. In this scenario, howardites and polymict eucrites are impact breccias that sampled materials from various levels. Nyquist et al (1986) suggested that polymict eucrites were deposited in ejecta blankets, whereas monomict eucrites, which are commonly thermally annealed, were samples from crater floors or walls.

Asteroid 4 Vesta has spectral reflectance characteristics that are very similar to those of the eucrite group (McCord et al 1970, Larson & Fink 1975, Feierberg et al 1980, Gaffey 1983) and has been suggested to be the eucrite parent body (Consolmagno 1979, Drake 1979). The maximum pressures within the interior of this asteroid are estimated to be less than 2 kbar. The small, near-Earth asteroids 3551 RD (Bell 1988) and 1915 Zuetzalcoatl (McFadden et al 1985) have spectral signatures similar to eucrites and diogenites, respectively, and could be fragments of Vesta or some similar body.

Partial Melting or Crystal Fractionation?

Nowhere do competing arguments for partial melting versus fractional crystallization as the dominant process come more into focus than in discussions of the origin of the eucrite group. The principal challenge in interpreting these meteorites is to understand how relatively iron-rich basaltic liquids, which crystallized to form the eucrites, are related to the more magnesian pyroxenes and olivines in diogenites and howardites. It seems clear that diogenites cannot be refractory residues from partial melting, because residual solids formed during low-pressure melting have higher olivine/pyroxene ratios than the starting material (Warren 1985). If the starting material were chondritic, as is appropriate for an asteroidal body, it would consist dominantly of olivine. Residues from partial melting would thus have very high olivine/pyroxene ratios, unlike the pyroxene-rich mineralogy of diogenites. Diogenites, then, must be cumulates rather than residues, but how are they related to eucrites?

One-atmosphere melting experiments (Stolper 1977) indicate that eucrite compositions are multiply saturated with olivine, pigeonite, plagioclase, spinel, and metal. In other words, eucrite compositions cluster near the low-pressure peritectic involving these phases, as illustrated in the projection in Figure 3. The significance of this peritectic is that it is the locus of liquids produced by partial melting of plagioclase-bearing peridotite (which is basically what chondrites are). So long as olivine, low-Ca pyroxene, and plagioclase remain in the source region, the compositions of derived melts will remain on this peritectic. When plagioclase is finally exhausted from the residue, the liquid will advance along the olivine-pyroxene cotectic (Figure 3) as melting proceeds. When low-Ca pyroxene is finally lost as a residual phase, the liquid then moves into the olivine primary phase field. Stolper (1977) viewed most eucrites as nearly primary magmas generated by varying but generally low degrees of partial melting of the same source region. This model not only explains why eucrite compositions cluster around the peritectic, but it is also consistent with observed incompatible element trends. By modeling incompatible element concentrations, Consolmagno & Drake (1977) calculated that eucrite magmas required 5–15% melting of a chondritic source. Magmas produced by higher degrees of melting, although lying along the olivine-pyroxene cotectic and thus saturated with olivine, would crystallize only

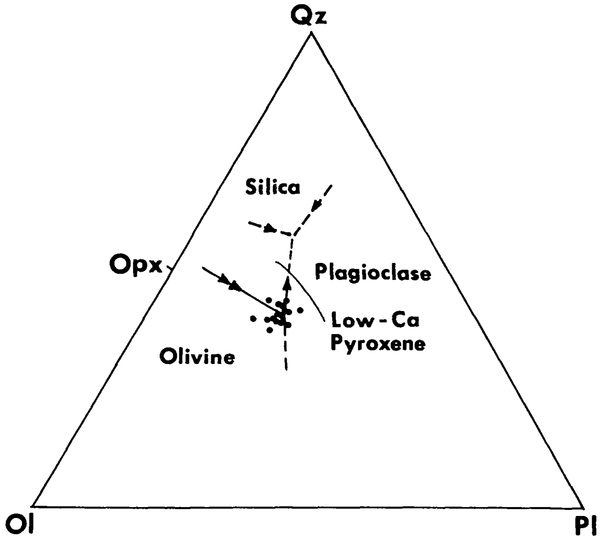

Figure 3 Pseudoliquidus diagram for the olivine-plagioclase-silica system, projected from diopside. Phase boundaries are based on multiply saturated liquid compositions from experiments by Stolper (1977). Circles are compositions of noncumulate eucrites (Basaltic Volcanism Study Project 1981, Chap. 3).

magnesian pyroxene when separated from their source region. In Stolper's model, fractional crystallization of such liquids produced the cumulate orthopyroxenes in diogenites. A few magnesian basaltic clasts in polymict breccias (Smith 1982) could be representative of such parental magmas for diogenites.

It has also been argued that magnesian parental magmas underwent fractional crystallization to produce cumulate diogenites and ultimately eucritic residual liquids (Mason 1962, McCarthy et al 1973). The near-continuum in pyroxene compositions among diogenites, cumulate eucrites, and eucrites is consistent with this petrogenetic model. On the other hand, this model requires that the olivine-pyroxene cotectic in Figure 3 be either a subtraction curve or a reaction curve that remains tangential to pyroxene, so that fractionating liquids reaching this curve from the olivine primary phase field would follow it to the reaction point. Stolper (1977) suggested that this boundary is a reaction curve at 1 atm, and calculations by Longhi & Pan (1988) corroborate this reaction relationship. Consequently, fractionating liquids reaching this curve would immediately cross into the low-Ca pyroxene primary phase field and then move directly away from the pyroxene composition to intersect the pyroxene-plagioclase boundary, bypassing the reaction point. Nevertheless, the fractionation model has recently been revived by considering other factors that might alter the nature of the olivine-pyroxene boundary curve. Warren (1985) suggested that the boundary, although a reaction curve, is so nearly radial to pyroxene that fractionation of low-Ca pyroxene produces eucritic residual liquids anyway. It has also been noted that the projection in Figure 3 suppresses any effect that changing the Mg/(Mg+Fe) ratio of the fractionating liquid might have on this curve. A number of workers (Jones 1984, Ikeda & Takeda 1985, Delaney 1987, Hewins 1987) have argued that a changing Mg/(Mg+Fe) ratio causes this boundary to be, at least in part, a subtraction curve. However, further experiments (Beckett & Stolper 1987) and calculations (Longhi & Pan 1988) reaffirmed that this is a reaction curve at 1 atm for liquids that could generate eucrites, and that fractionation of proposed parental magmas for diogenites cannot produce eucrites. These magmas could produce orthopyroxenes of similar composition to those in diogenites, but there is no obvious way to relate diogenites and eucrites by a single-stage fractionation process at low pressure.

One factor that might alter the character of the olivine-pyroxene boundary is increased pressure. Although pressures within the interiors of even the largest asteroids are only a few kilobars, they may be sufficient to allow diogenite pyroxenes and eucrite liquids to form along a common liquid line of descent. Longhi & Pan (1988) calculated that fractional crystallization could produce both meteorite types if it occurred at about 2 kbar, although the pressure uncertainty (±1 kbar) in their algorithm is considerable. This hypothesis has yet to be established experimentally, but if it is true, the fractional crystallization model may become a more attractive alternative.

The existence of two distinct trends among eucrites (Figure 2) can be explained by either petrogenetic model. Advocates of the partial-melting model would appeal to varying degrees of partial melting, which either exhausted plagioclase (trend B) or left it behind (trend A) in the source residue. In the fractionation model, these trends could be accounted for by derivation of melts from distinct source regions, followed by fractional crystallization and possibly magma mixing (Hewins 1987). Alternatively, one trend could represent fractional crystallization and the other a partial-melting sequence (Warren & Jerde 1987).

A potential problem for the partial-melting model is the argument, based on low siderophile element abundances, that the eucrite parent body experienced core formation before production of eucrites. Newsom (1985) suggested that this evidence favored the fractional-crystallization model because metal segregation would require a higher degree of melting than that hypothesized for the origin of eucrite primary magmas.

The fractional-crystallization model suffers from the need to have a fairly large (500–1000 km radius) parent body to provide the required pressures. The absence among meteorites of volcanic equivalents of the magmas that produced diogenites is also perplexing (Stolper 1977, Longhi & Pan 1988) because these would have been less dense than eucritic melts and should have erupted preferentially if present in the same magma chambers.

UREILITES

As in the case of the eucrites, the respective roles of fractional crystallization and partial melting in ureilite petrogenesis are contested. However, the situation with ureilites is even more complex; the ureilites are arguably the most perplexing group of achondrites.

Petrography, Geochemistry, and Chronology

Ureilites are relatively coarse-grained ultramafic rocks consisting of olivine and pyroxene (pigeonite) in various proportions (usually with olivine predominant) and in some cases also containing augite and orthopyroxene (Vdovykin 1970, Neuvonen et al 1972, Berkley et al 1976, 1980, Berkley 1986, Takeda 1987, Goodrich et al 1987a). Interstitial to these phases is an opaque, fine-grained, heterogeneous assemblage consisting mostly of graphite (and its polymorphs, diamond and lonsdaleite, in highly shocked samples), along with kamacite, troilite, and other accessory minerals. Most of this carbonaceous matrix is distributed between silicate grains, but it also occurs along fractures and cleavage planes within silicates. Some workers have suggested that carbon was mixed with silicates in the nebula (Takeda et al 1980, Janssens et al 1987) or was injected late into the solid ureilite silicate assemblage (Boynton et al 1976, Wasson et al 1976, Higuchi et al 1976), but recent petrographic observations indicate that graphite was a primary magmatic phase (Berkley et al 1980, Berkley & Jones 1982). In further support of this idea, Goodrich & Berkley (1986) noted the presence of cohenite- and sulfide-bearing metallic spherules as inclusions in olivine and pigeonite, presumably crystallization products of immiscible, carbon-saturated melts of Fe-Ni-C-S composition that were present in the ureilite parent magma.

Pyroxene geothermometry for ureilites yields equilibration temperatures above 1200°C (Takeda 1987). The large grain size and chemical homogeneity of olivine and pyroxene in ureilites suggest that they crystallized relatively slowly. On the other hand, the absence of exsolution lamellae in pigeonite may suggest that these achondrites were quenched from above the solvus (Berkley et al 1980, Takeda 1987). The high Ca content of ureilite olivine has also been cited as evidence for quenching, but this may have resulted from crystallization of this phase at high temperature prior to the appearance of Ca-bearing minerals (Goodrich et al 1987b). The outer rims of olivine and pigeonite grains are more magnesian than the cores and contain disseminated metallic Fe. This feature has commonly been interpreted to result from reduction of Fe in silicates by reaction with graphite (Marvin & Wood 1972, Wlotzka 1972, Berkley et al 1976). Correlations of Fe/Mn, Fe/Cr, and Fe/Ca with Fe/Mg in olivines support this idea (Goodrich et al 1987b, Takeda 1987); however, the importance of reduction in establishing ureilite compositions has been questioned by Clayton & Mayeda (1988), as discussed below. Taken together, these observations suggest that ureilites had a two-stage cooling history. One possible scenario is that ureilites began to cool slowly at depth but were rapidly quenched by impact excavation (Wasson et al 1976, Berkley et al 1980, Miyamoto et al 1985b).

Berkley et al (1980) recognized three distinct compositional groups of ureilites, based on the molar FeO/MgO ratios in olivine cores. Average olivine compositions for these groups are 79, 84, and 91 mol% forsterite. It is unclear if these groups represent either an incompletely sampled continuum of ureilite compositions within one planetesimal or samples from several parent bodies of different composition.

The most unusual feature of ureilites is their oxygen isotopic compositions. In contrast to the eucrite group, these meteorites do not define a single mass-fractionation line (Clayton & Mayeda 1988), as shown in Figure 1. This implies that either these meteorites did not come from the same parent body or else the parent body was never homogenized isotopically. Ureilite oxygen isotopic compositions resemble those of carbonaceous chondrites, in that they fall along a mixing line defined by components and bulk compositions of such meteorites. Clayton & Mayeda also noted an apparent relationship between oxygen isotopic composition and FeO/MgO group.

Many of these meteorites are heavily shocked, and Vdovykin (1970) based his ureilite classification scheme on shock features. The most prominent shock features are mosaicism of olivines and the production of high-pressure polymorphs of carbon. Some of the more highly shocked ureilites are polymict breccias, containing a variety of feldspathic clasts (Jaques & Fitzgerald 1982, Prinz et al 1988).

Ureilites contain significant quantities of trapped, planetary noble gases, most of which are contained in diamond (Gobel et al 1978, Begemann & Ott 1982). These gases presumably resided in graphite prior to shock (Janssens et al 1987). The isotopic composition of carbon in analyzed ureilites falls into two groups, with $\delta^{13}C$ of approximately 2 and 10 (Grady et al 1985). Unlike the oxygen isotopes, these groups do not correlate with any FeO/MgO groups.

The only radiometric age data for ureilites were reported by Goodrich et al (1988). The isotopic compositions of Rb and Sr are inhomogeneous in three analyzed meteorites and do not yield isochrons. On a Sm-Nd isochron plot, whole-rock samples define a line with slope corresponding to an age of 3.74 Gyr. There is no correlation between $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$. If this line is an isochron, the age is surprisingly young. It seems more likely that it is a mixing line between one end member representing the ultramafic assemblage and another enriched in light rare earth elements (REE). If the ultramafic assemblage formed at 4.55 Ga and the light REE-enriched component is a differentiate of similar material, the latter's age is 3.74 Gyr.

Parent Planetesimal(s)

There is little evidence on which to speculate about the nature of the ureilite parent body (or bodies). Most researchers accept that ureilites are derived from an asteroidal source. The oxygen isotopic diversity exhibited by the ureilite group is also seen within single, brecciated ureilites (Clayton & Mayeda 1988), which suggests that these meteorites were likely derived from a single parent body that was not homogenized by igneous differentiation. Geochemical modeling (Janssens et al 1987, Goodrich et al 1987b) is most compatible with a carbonaceous chondrite bulk composition, and the near-chondritic concentrations of siderophile elements suggest that the parent object had not experienced metal segregation to form a core (Janssens et al 1987). Goodrich et al (1987b) suggested that the ureilite parent body was fairly large (minimum radius of 235 km, as discussed below). However, this size constraint may be somewhat elastic (Walker & Agee 1988), permitting smaller parent bodies to be considered.

Although no ureilitelike body has been recognized among spectrally analyzed asteroids, the petrographic variations seen in ureilite polymict breccias, the wide range of shock features observed in ureilite samples, and the relatively featureless spectra of ureilites (Gaffey 1976) make it difficult to know what characteristics might be diagnostic in asteroid spectra. Goodrich et al (1987b) suggested that the ureilite parent body may have been disrupted, and fragments may be unrecognizable because of spectral diversity.

Cumulates or Residues from Partial Melting?

The origin of ureilites has been debated for many years. Three principal lines of evidence, based on textures, modal mineralogy, and trace element geochemistry, have been employed to advance one preferred model or another.

Compact polycrystalline aggregates of interlocking grains with triple junctions seen in many ureilites could be consistent with their formation either as adcumulates or as residues from partial melting (Boynton et al 1976, Higuchi et al 1976, Takeda 1987). Analyses of the optical orientations of olivine and pigeonite grains in ureilites (Berkley et al 1976, 1980) demonstrate that these meteorites display strong mineral lineations and layering. Berkley et al argued that cumulate processes produced these textural features. They suggested that these textures are more like those of terrestrial adcumulate rocks than of restites, in which triple-junction interfacial angles are generally rounded. Moreover, a few ureilites contain unusual features, such as euhedral crystals and size-graded layering, that are more compatible with a cumulate origin than with a recrystallized residue from partial melting.

Walker & Agee (1988) performed melting experiments in a thermal gradient on the Allende carbonaceous chondrite, a plausible source material for ureilites considering their oxygen isotopic and siderophile trace element compositions. They were able to produce compact crystalline aggregates of silicate crystals, largely free of interstitial liquid, that resembled ureilites in texture. However, sulfide melts in their experimental charges were unable to disentangle themselves from olivines and could not migrate in the thermal gradient, as interstitial silicate liquids were able to do. This difference in behavior apparently results from the distinct wetting properties of sulfide and silicate melts against olivine, and its result is that melting residues cannot purge themselves of sulfide liquid. Walker & Agee (1988) suggested that the sulfide-poor ureilites are thus unlikely to be compacted residues from the melting of a carbonaceous chondrite source unless sulfide was removed by some other process; for this reason, they favored a cumulate origin.

The simple mineralogy of ureilites is consistent with either an adcumulate or melting residue origin, and in fact the relative proportions of olivine, pigeonite, and augite among different ureilites have been cited as evidence for both models. The overall assemblage of olivine + pigeonite + graphite is a plausible crystal extract from liquids produced by melting of carbonaceous chondrites (Walker & Agee 1988). Berkley et al (1980) suggested that observed modal variations are difficult to reconcile with the formation of ureilites as residues from partial melting. Different degrees of partial melting would certainly be expected to cause variations in modal olivine/pyroxene ratios but possibly not of such a wide range. Ryder (1981) and Warren & Kallemeyn (1988) claimed that the pyroxene/olivine ratio in ureilites is too low for cumulates but is in the range expected for melt residues. Their argument, however, assumes cotectic crystallization of olivine and pyroxene, and as Berkley (1986) has pointed out, pigeonite may be a postcumulus phase in at least some ureilites.

The presence of millimeter-sized, euhedral graphite crystals in unshocked ureilites, which would necessarily be cumulus grains in the adcumulus model, may be difficult to reconcile with conventional mechanisms for crystal accumulation, such as gravitational settling (Walker & Agee 1988). There is no apparent reason why low-density graphite should be concentrated along with olivine and pigeonite, which have higher densities than their parent liquids. However, other concentration mechanisms not involving buoyant forces have been envisioned for terrestrial cumulate rocks and could apply to ureilites. In fact, the occurrence of mineral lineations in ureilites may suggest accumulation in a dynamic flow regime (Berkley et al 1980).

Another peculiarity of the ureilites is the unusual V-shaped REE pattern, the meaning of which is still disputed. The light REE appear to be concentrated in an as yet unidentified phase that may be unrelated to the primary silicate assemblage, possibly introduced at some later stage (Spitz & Boynton 1986). Boynton et al (1976) suggested that fractionation of olivine from a magma with chondritic-relative REE abundances could not produce the steep slope of the heavy REE pattern, and thus they favored a restite origin. However, new olivine/liquid distribution coefficients for REE (McKay 1986) produce patterns much steeper than previously thought, and fractionation models using these coefficients appear to reproduce ureilite heavy REE patterns (Spitz & Boynton 1986). Spitz & Goodrich (1987) have also shown that partial melting cannot reproduce negative Eu anomalies in residues like those seen in ureilites.

On balance, the evidence presented above seems to favor a cumulate origin for ureilites, although no clear consensus on this point has emerged. If these meteorites are adcumulates, they presumably formed by enlargement of cumulus crystals through reaction with intercumulus liquids in contact with the main magma reservoir. Almost none of the intercumulus material remains, as corroborated by the low incompatible element abundances in these meteorites. Berkley & Jones (1982) suggested that an immiscible metallic liquid may have sunk through the cumulus pile, facilitating the expulsion of interstitial silicate liquid, although the wetting properties of sulfide melts may suggest that such a process is unlikely. If, on the other hand, ureilites are residues, the melt fraction has been very effectively removed. Walker & Agee's (1988) melting experiments suggest that almost complete removal of interstitial silicate melt from crystalline residues is possible in a thermal gradient. Takeda (1987) proposed a fractional fusion process in which the amount of melt present at any time was very small. His model has the advantage of preserving grain orientations during recrystallization, but it cannot account for the removal of sulfides.

Origin of Ureilites

If we accept the argument that ureilites are cumulates, the first question we might ask is whether or not all of these meteorites could have been derived from one parent magma. The oxygen isotopic data already discussed apparently require that ureilites cannot in general be comagmatic. Goodrich et al (1987b) noted that CaO/Al_2O_3 ratios in ureilite olivines and pyroxenes are correlated, but that significant variations in these ratios occur between different ureilites. Because these variations cannot be produced by olivine fractionation, Goodrich et al inferred that these meteorites must have crystallized from several distinct magmas.

Using pigeonite/liquid distribution coefficients, Goodrich et al (1987b) estimated the molar CaO/Al_2O_3 ratios for ureilite parent magmas to be significantly higher than the chondritic ratio. They argued that partial melts with nonchondritic CaO/Al_2O_3 ratios could not be derived from a chondritic source because of the empirical observation that eucrites have essentially chondritic CaO/Al_2O_3 ratios. (This argument assumes that eucrite compositions represent direct partial melts, not fractionation products.) Instead, ureilites require plagioclase-depleted sources, which implies that some earlier differentiation had occurred. The model developed by Goodrich et al thus involves several steps. (*a*) Chondritic material undergoes a high degree of partial melting, leaving a plagioclase-depleted residue; (*b*) fractional crystallization of the liquids generated in step (*a*) produces ultramafic and feldspathic cumulates; and (*c*) remelting of these mafic cumulates [or of the residue in stage (*a*)] produces ureilite parent magmas.

There are several major objections to this model. For their calculation, Goodrich et al (1987b) assumed 10% melting in stage (*a*), 10% fractionation of this magma to produce the cumulate source in stage (*b*), 3% remelting in stage (*c*), and 1% crystallization of this parental magma to produce ureilite cumulates. Ureilite production by this model is clearly an inefficient process. Multiplying through all of these percentages, we see that ureilites represent only 3 ppm of the original parent body source. It is hard to believe that such rare samples should occur so frequently without sampling other related rocks from this parent body. Another objection stems from the oxygen isotopic data. Several stages of parent body differentiation should have homogenized its oxygen isotopes. If all ureilites are derived from the same body, it must have been undifferentiated at the time that ureilite parent magmas were formed.

Takeda (1987) and Prinz et al (1988) suggested that impacts into a primitive, carbonaceous chondritelike asteroid would cause melting in localized pockets, and that ureilites represent the residues from these events after separation of melt. This model might also explain the diversity of oxygen isotopic compositions.

Warren & Kallemeyn (1988) suggested that catastrophic disruption of multiple ureilite parent bodies by impact, followed by incomplete reassembly, may explain the characteristics of these meteorites. If the parent bodies were largely molten when impacted, the reaccreted crystalline material and carbon-rich fluid might mimic the properties of ureilites.

Heating or cooling in a thermal gradient removes the necessity of a gravity field for producing cumulate textures (Walker & Agee 1988). Planetesimal heating could cause segregation of melt inward, forming a ureilite outer shell near the exterior surface. If such a process occurred on numerous small bodies of slightly different composition, it could explain the complexity in oxygen isotopes.

Goodrich et al (1987b) proposed that ureilites experienced various degrees of reduction, presumably by reaction with graphite, after their formation. The graphite fO_2 buffer is pressure dependent, so this variable reduction may have occurred by means of equilibration at different pressures. Goodrich et al suggested that ureilite parent magmas crystallized at various depths, but that none were near the surface because at least 50–200 bars pressure is necessary to stabilize FeO relative to metallic Fe. They estimated that the minimum radius for the ureilite parent body was 235 km, based on the requirement that the graphite buffer be above iron-wustite fO_2 at 1200°C. Clayton & Mayeda (1988), however, found a correlation between oxygen isotopic composition (a primary feature) and bulk Fe content in ureilites. From their observations, it appears that original parent body characteristics, which were presumably established in the nebula, may explain these features better than reduction on the ureilite parent body. Clearly, many aspects of the petrogenesis of ureilites have not been resolved.

IMPLICATIONS FOR PLANETARY MAGMATISM

What insights can be drawn from this examination of igneous petrogenesis on several small, asteroidal bodies? It is clear from the abundance of undifferentiated meteorites (chondrites) in our collections that many asteroids must have escaped thermal processing, and understanding the possible compositional differences between geologically processed and unprocessed parent bodies may help explain this distinction. Achondrites provide important insights into the chemical compositions of their parent asteroids, but it is necessary to distinguish between rival petrogenetic models to obtain this information. To use the eucrite parent body as an example, the partial-melting hypothesis requires a much lower molar MgO/(MgO + FeO) ratio (0.68, as typified by the parent body composition calculated by Hertogen et al 1977) than the fractional crystallization hypothesis (0.80, as in the model of Dreibus et al 1977). Chronologic data and constraints on asteroid size that are provided by achondrites may also aid in understanding why some asteroids have experienced melting.

A second point is that primary (unfractionated) magmas are thought to be rare among erupted lavas on the Earth (Basaltic Volcanism Study Project 1981, Chap. 1), possibly because the crust acts as a density filter for primary compositions (Stolper & Walker 1980). Does fractional crystallization also modify most magmas on small bodies? If the partial-melting model for eucrite petrogenesis is ultimately proven to be correct, it suggests that ascending primary magmas may be less likely to undergo extensive fractionation within small planetesimals than within large planets. On the other hand, if fractionation at very modest pressures is demonstrated to have produced eucrites, we may assume that fractional crystallization is a pervasive process that probably affects primary magmas generated within bodies of virtually any size.

The evidence for crystal fractionation in ureilites seems less equivocal, although the origin of these meteorites is still contested. If we accept that they formed as adcumulates, this may lend credence to the idea that fractionation is an important process even on small bodies. This conclusion holds in spite of the fact that the inferred parental magma compositions for ureilites were rather different from those of terrestrial cumulates. The significance of magma compositions in affecting mechanisms of crystal accumulation must await a better understanding of the crystal segregation process that may have actually formed ureilites.

Walker et al (1978b) constructed numerical models of crystal settling and melt segregation within the eucrite parent body, but their results are probably applicable to any planetesimal. Their calculations confirm that a small gravitational acceleration decreases the accumulation efficiency of crystals, but *g* values appropriate to asteroids even 1 km in radius appear to allow separation of crystals from melt. Separation of a small amount of melt dispersed throughout the source region, as implied by the low degrees of partial melting envisioned for eucritic magmas, is a more challenging problem. The calculations of Walker et al require larger bodies, perhaps 10–100 km in radius, to segregate and remove small percentages of melt before they solidify in place. However, *g* is not the limiting factor in this case, but it is rather the necessity of having a compacted interior.

A third conclusion from the study of achondrites is that magmatic activity on both the eucrite and the ureilite parent bodies appears to have been more complex than has been generally appreciated. The ancient crystallization ages for eucrites and geochemical constraints on source "feedstocks" have been used to argue for a one-stage heating model of chondritic material, possibly by decay of short-lived radionuclides or other heat sources unique to the early solar system. However, it is doubtful that eucrites and diogenites are related by a simple fractionation process, even at elevated pressures, and a multistage melting or fractionation history may be required. The apparent difference in crystallization ages for cumulate and noncumulate eucrites may also indicate a more complex thermal evolution. Fractionation models involving pervasive melting to produce a magma ocean on the eucrite parent body are probably too simplistic, and advocates of these models must continually adjust them to fit new, complicating observations. If, instead, eucrites are primary magmas, melting of several different sources may be necessary to account for their compositional diversity. Differing source regions could have been produced by serial magmatic activity, as plutons were added to previously unmelted source regions, which were then melted at a subsequent stage.

It seems likely that ureilites likewise were produced by melting of chondritic sources soon after their accretion into planetesimals, but complications can be seen in this case as well. The biggest surprise from the study of ureilites is that partial melting may not automatically produce parent body–wide homogenization of oxygen isotopes. (This is obviously true only if a single parent body was involved.) This difference may be related to the range of isotopic diversity in the source regions of this body, but it is nonetheless unexpected and may have implications for other isotopic systems, such as those used for chonology. Alternatively, if ureilites were derived from multiple parent bodies, they all experienced the same igneous processes, despite slightly different bulk compositions.

A final conclusion has to do with representative sampling. Why are ureilites so mineralogically similar when related clasts in polymict ureilites hint at a much more petrologically diverse parent body? And if the fractional crystallization model for eucrites is ultimately shown to be correct, why are there few if any representatives of primitive parental magmas for eucrites preserved as meteorites? This situation parallels that for midocean ridge basalts. If, as some suggest, most of these basalts are derived from fractionation of primitive picritic magmas, then some explanation is required for why they are so rarely sampled.

In the case of the eucrite parent body, the available samples—basalts, lesser amounts of cumulates, and regolith breccias composed of both components—make sense from a geological perspective. Gaffey (1983) has produced a spectral map of asteroid 4 Vesta that shows a surface dominated by eucritelike material, punctuated with round areas (presumably craters) containing diogenitelike material. The clear implication is that this is igneous stratigraphy (basalts overlying cumulate rocks) exposed by impacts. With that background, it is somewhat surprising that we have only cumulate, or possibly restite, samples from the ureilite parent body. Where are the volcanic rocks? Walker & Agee (1988) have made an intriguing suggestion that the ureilite accumulation process may have occurred near the outside cooling surface of the parent body, with liquids segregating in the interior; however, much work remains to be done before this radical hypothesis is generally acceptable.

It is also perplexing that we have no samples of the source regions in the interiors of either of these parent bodies (if the ureilites are adcumulates), particularly in light of suggestions that asteroids have commonly been catastrophically disrupted and reassembled into gravitationally bound rubble piles (Taylor et al 1987). Surface impacts into such bodies should sample all kinds of materials originally formed throughout the interiors, but for achondrites this does not seem to be the case. Petrographic sampling of igneous source regions may be as difficult on asteroids as it is on the Earth.

From this survey, it is clear that studies of achondrites have not achieved a consensus regarding the melting and crystallization histories of asteroids. Nevertheless, progress is being made, and it is encouraging to see that petrological principles gained from terrestrial experience can be extended to other solar system bodies.

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