INVITED REVIEW

Ureilite breccias: clues to the petrologic structure and impact disruption of the ureilite parent asteroid

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Abstract

The majority of the ~143 ureilite meteorites are monomict (unbrecciated) ultramafic rocks, which represent the mantle (olivine + low-Ca pyroxene residues and less abundant cumulates) of a partially melted (~25–30%), carbon-rich asteroid ≥125 km in radius. Accumulated petrologic and geochemical studies of these meteorites have led to a picture of a ureilite parent body (UPB) that was stratified in mg#, pyroxene abundance and pyroxene type, due to the pressure dependence of carbon redox control, and which preserved a pre-magmatic heterogeneity in Δ17O. The absence, however, of ureilite crustal rocks (i.e. basalts) in the meteorite record, leads to significant gaps in our knowledge of the geologic history of the UPB.

Ureilite breccias provide considerable information that cannot be obtained from the monomict samples, and help to fill in those gaps. Fourteen ureilites are polymict breccias (at least three of which contain solar wind gases) that formed in a regolith. They contain a variety of clast types representing indigenous ureilite lithologies not known among the monomict samples, as well as several types of non-indigenous impactor materials. In addition, one
ureilite (FRO 93008) is a dimict breccia, consisting of two ultramafic lithologies that could not have formed in close proximity on the UPB.

Several feldspathic lithologies representing melts complementary to the monomict ureilite residues or cumulates have been recognized in polymict ureilites. From these lithologies we infer that melt extraction on the UPB was a rapid, fractional process in which trace element and oxygen isotopic equilibrium was not achieved. The majority of melts that reached the surface erupted explosively (due to high contents of CO/CO₂) and were lost into space. Thus, it is likely that the UPB never had an extensive basaltic crust. Melts generated at the shallowest depths and late fractionates, in which carbon had largely been consumed by reduction, were the most likely to have been preserved. Our sample of the UPB is limited to depths equivalent to ~100 bars pressure or less, but minor augite-bearing feldspathic lithologies and related cumulates may represent melts derived from deeper.

In addition, we infer that the UPB was catastrophically disrupted, while still hot, by an impacting projectile. Meter-sized ejecta from this impact reaccreted into one or more daughter bodies, on which the brecciated ureilites formed. Ureilite meteorites are derived from these offspring, rather than from the UPB. The remnant of the original UPB may consist largely of olivine plus augite, and thus not resemble the majority of ureilites.

1. Introduction

Ureilites comprise the second largest group (next to the HED group) of achondritic meteorites, with 143 currently (as of Russell et al., 2004) recognized samples (known pairings reduce the number of distinct samples to ~100, but the extent of pairing among the more recently classified ureilites is not known). The majority of ureilites are unbrecciated monomict rocks with coarse-grained igneous textures, and are thought by most workers to represent the mantle of a partially melted, carbon-rich asteroid (see reviews by Goodrich, 1992; Mittlefehldt et al., 1998). However, 14 (some of which may be paired) are polymict breccias, and one (possibly paired with ten others) is a dimict breccia. Since the earliest studies of polymict ureilites (Jaques and Fitzgerald, 1982; Prinz et al., 1986, 1987, 1988), it has been known that they contain a large variety of clast types, some of which are unlike monomict ureilites. Recent studies (Ikeda et al., 2000, 2003; Kita et al., 2003a; Cohen et al., 2004) have provided comprehensive surveys of these materials, and greatly enhanced our knowledge of their properties. Dimict ureilites have only recently been recognized (Smith et al., 2000; Fioretti and Goodrich, 2001), and are breccias of a different type. Our purpose in this paper is to provide an up-to-date review of ureilitic breccias, and to draw attention to the importance of these comparatively few samples. In Section 2, we summarize the major characteristics of monomict ureilites, and a model (presented in Goodrich et al., 2002a and developed more fully here) for the petrologic structure of the UPB that is based on the monomict samples. In Section 3 and 4, we review petrologic, chemical, and isotopic characteristics of the major lithologic components of polymict and dimict ureilites, and discuss interpretations of their origin. In the final section, we discuss the breccias in the
context of our petrologic model, and show that they provide important information
about the differentiation history of the ureilite parent body (UPB) that cannot be
obtained directly from monomict ureilites; they also offer clues to a history of
breakup and reassembly for this body, and to the current provenance of ureilites.

2. Monomict ureilites and the UPB

2.1. Petrologic structure of the UPB

All monomict ureilites are coarse-grained, ultramafic (olivine–pyroxene) rocks
characterized by high abundances (up to ~5 vol%) of carbon (graphite and
secondary, shock-produced diamond), with metal and sulfide as the only other
common accessory phases (Goodrich, 1992; Mittlefehldt et al., 1998). They have
highly equilibrated olivine and pyroxene compositions (homogeneous within each
rock), which reflect high-temperatures (~1100–1300 °C) of equilibration. Olivine–
pyroxene ureilites, which are the most abundant type, have equilibrated textures
(gently rounded grain boundaries and abundant triple junctions) and uninverted
pyroxene (Wo7–13) as the only pyroxene. They show an extremely large range of
\( mg\# \) (Fo of olivine), from ~76 to 92, and an Fe/Mg vs. Fe/Mn trend of near-
constant, chondritic Mn/Mg (shown in Fig. 1a for their olivine) that suggests that
they are residues and are related to one another principally by various degrees of
reduction of common precursor material (Goodrich and Delaney, 2000). This
reduction relationship is thought to be due to carbon redox control (smelting), over
pressures ranging from ~15 to 100 bars (Berkley and Jones, 1982; Goodrich et al.,
1987; Warren and Kalamene, 1992; Walker and Grove, 1993; Sinha et al., 1997;
Singletary and Grove, 2003), thus indicating that they are derived from a range of
depths (Fig. 2a). Olivine–orthopyroxene ureilites, which are a less abundant type (6
unpaired meteorites) contain orthopyroxene (Wo 4.5–5.0) instead of, or in addition
to, pigeonite, and occur only among the most magnesian (Fo~86–92) samples. Their
Fe/Mg–Fe/Mn compositions fall on the same trend as the olivine–pigeonite ureilites
(Fig. 1a), suggesting that they too are residues. The occurrence of orthopyroxene is
consistent with the increased stability of orthopyroxene relative to pigeonite at high
\( mg\# \) (Longhi, 1991). Petrologic modeling indicates that approximately 25–30%
partial melting (beyond the point of plagioclase depletion) of chondritic-like
precursor materials, at various degrees of reduction, could produce residues similar
to the olivine–pigeonite and olivine–orthopyroxene ureilites (Fig. 3), although those
precursors must have been enriched in Ca relative to Al to produce pigeonite as the
dominant pyroxene (Goodrich, 1999a).

Two unusual magnesian samples, EET96328 (and 5 paired meteorites) and
EET90019, have poikilitic textures in which the pyroxene (orthopyroxene of \( mg\# 87 \) in
EET96328 and pigeonite of \( mg\# 92 \) in EET90019) occurs as large oikocrysts enclosing
olivine and contains abundant melt inclusions (Goodrich, 2001), suggesting that it
crystallized from a melt. Nevertheless, the olivine in these samples falls on the
Fig. 1. Molar Fe/Mg vs. Fe/Mn of olivine and pyroxene in ureilites. (a) Monomict ureilite olivine. Olivine–pigeonite and olivine–orthopyroxene ureilites plot on a single trend of near-constant, chondritic Mn/Mg ratio, which suggests that they are residues, and are related to one another principally by reduction rather than different degrees of melting (Goodrich and Delaney, 2000). The data are fit here by the power law relationship Fe/Mn = 139.7*(Fe/Mg)^0.865. Augite-bearing ureilites plot to right of the residue fit, suggesting that they contain a melt component (Goodrich and Delaney, 2000). All data (Goodrich et al., 1987; Goodrich et al., 2001; unpublished data of the first author) are of high precision (both analytical error and internal variation is on the order of the size of the symbols) and self-consistent. (b) Augite-bearing monomict ureilite-like clasts in polymict ureilites plot to the right of the monomict ureilite residue trend, demonstrating their affinity to augite-bearing monomict ureilites. Data for monomict ureilites as in (a). (c) Pyroxenes in the major populations of feldspathic clasts in polymict ureilites show normal igneous fractionation trends of near-constant Fe/Mn ratio over large ranges of Fe/Mg ratio extending to much higher values than seen in monomict ureilites. Near-linear trend shown for monomict ureilite pigeonite (Goodrich et al., 1987) is similar to that shown in (a) for olivine. (d) Olivines in relatively rare olivine–augite feldspathic clasts in polymict ureilites have Fe–Mg–Mn compositions consistent with normal igneous fractionation. Three clasts form one coherent trend; a fourth (C24) is distinct. The primary Fe–Mn–Mg composition (before exsolution of chromite) inferred for olivine in the unusual clast 1 in DaG 165 is consistent with compositions of ferroan olivine–pigeonite ureilites (see text). Data for olivine–pigeonite and olivine–orthopyroxene monomict ureilites as in (a).
Fe–Mn–Mg trend of other ureilitic olivine–pigeonite and olivine–orthopyroxene ureilites interpreted to be residues (Fig. 1a). These ureilites may be paracumulates (this term was introduced by Warren and Kallemeyn (1989)) to describe “mushy, cumulate-like partial melt residues”) – mixtures of residual (olivine) and cumulus (pyroxene) material (Fig. 2a).

Monomict ureilites of a third type (augite-bearing), which is also relatively rare (9 unpaired meteorites) are characterized by the presence of augite, and have more complex textures than the olivine–pigeonite and olivine–orthopyroxene ureilites. Most of them have poikilitic areas, consisting of large (mm to cm-sized) oikocrysts of orthopyroxene or pigeonite enclosing rounded grains of olivine and augite, though other areas of the same rocks may show the typical, equilibrated texture seen in the olivine–pigeonite and olivine–orthopyroxene ureilites, but with the dominant (usually the only) pyroxene being augite. They commonly show textural evidence that both olivine and augite were in reaction relationship with melts, from which the low-Ca pyroxene oikocrysts grew (Goodrich, 1999b; Goodrich and Keller, 2000; Berkley and Goodrich, 2001). In addition, many of them have melt inclusions in their olivine, and in some cases also in low-Ca pyroxene and augite (Fioretti and Goodrich, 2000; Goodrich and Fioretti, 2000; Goodrich et al., 2001; unpublished data of the first author). Such textural indications that these ureilites crystallized from melts are strongly augmented by the compositions of their olivine, which show a large range of \( \text{mg}^\# \) (~75–95) similar to that of the olivine–pigeonite and olivine–orthopyroxene ureilites but are invariably displaced from the Fe/Mg–Fe/Mn trend of olivine–pigeonite–orthopyroxene ureilites to higher Mn/Mg ratios (Fig. 1a), consistent with the fractionation expected between melts and residues (Goodrich and Delaney, 2000). Nevertheless, the degree to which their Fe/Mg–Fe/Mn compositions deviate from the olivine–pigeonite–orthopyroxene ureilite trend varies widely (Fig. 1a), which suggests that the degree to which they represent melts varies; that is, to various extents they are may be paracumulates, rather than pure cumulates, with some of their olivine being residual and some having crystallized from melts (and their present homogenous olivine compositions reflecting high-T equilibration between the two types of grains). In support of this interpretation, three augite-bearing ureilites (META78008, HH064 and Y74130) that have only slightly displaced Fe–Mn–Mg compositions contain rare olivine–pigeonite chadocrysts in augite oikocrysts, suggesting that residual olivine–pigeonite assemblages were invaded by augite-saturated melts (Berkley and Goodrich, 2001; unpublished data of the first author).

Petrologic considerations suggest that these melts were not complementary to the olivine–pigeonite or olivine–orthopyroxene ureilites. First, melts in equilibrium with olivine–pigeonite and olivine–orthopyroxene ureilites are in reaction relationship with olivine (Goodrich, 1999a), and so would not crystallize olivine. Second, the dominance of augite, particularly in the typical-textured areas where it appears to have co-crystallized with olivine, suggests crystallization at higher \( f_O^2 \) (lower degrees of reduction) than shown by the olivine–pigeonite ureilites, if common precursor material having a bulk iron content similar to carbonaceous chondrites (25–29% Fe as FeO, or \( \text{mg} \sim 62–65 \)) is assumed (Fig. 3). The smelting model (pressure-dependent...
carbon redox control) implies, then, that these melts were derived from greater depths than the olivine–pigeonite ureilites (Fig. 2a). However, the observation that their mg#s span the same range as the olivine–pigeonite ureilites (Fig. 1a) implies that the rocks are products of crystallization of these melts after they migrated to shallower depths; that is, they must have been smelted during ascent (assuming that all ureilite precursor material had high carbon contents and the melts transported carbon with them) and their final mg#s must have been controlled by their final depths. Fig. 3 illustrates qualitatively that, to various degrees, such melts could be reduced during ascent without leaving the augite stability field. This diagram also illustrates a possible explanation for the late augite→low-Ca pyroxene reaction textures seen in most augite-bearing ureilites, as further reduction (ascent) would result in movement into the low-Ca pyroxene stability field.

In general, bulk chemical compositions of monomict ureilites reflect their ultramafic mineralogy (Goodrich, 1992; Mittlefehldt et al., 1998). However, rare
earth element (REE) patterns of many olivine–pigeonite and olivine–orthopyroxene ureilites are V-shaped (Fig. 4a), and reflect the presence of two components (Fig. 4b): (1) their olivine+pyroxene assemblages, which are highly LREE-depleted and have negative Eu-anomalies, consistent with their residue origin and loss of a feldspathic component, and (2) a cryptic (not associated with any distinct phase) LREE-enriched component, which is volumetrically minor and heterogeneously distributed (principally in C-rich areas along grain boundaries), and can be easily removed by leaching with weak acids (Boynton et al., 1976; Spitz and Boynton, 1991; Goodrich and Lugmair, 1995). The identity of the latter is unknown. It may represent a metasomatic fluid that was introduced at \( \sim 3.79 \) Ga (Goodrich and Lugmair, 1995; Goodrich et al., 1995). Alternatively, it may be a terrestrial contaminant (Torigoye-Kita et al., 1995a,b). The augite-bearing ureilites tend to have elevated, LREE-depleted patterns (Fig. 4a), which probably reflect higher distribution coefficients for REE in augite (compared to low-Ca pyroxene), and possibly also their origin as melts (a few of them have V-shaped REE patterns, indicating the presence of the LREE-enriched component).
2.2. Oxygen isotopes of ureilites and the differentiation history of the UPB

Ureilites are characterized by oxygen isotopic compositions that range along a δ^{17}O–δ^{18}O line of slope ~1 (Fig. 5a), nearly coincident with to the CCAM line defined by Allende CAIs and C2–C3 materials (Clayton and Mayeda, 1988, 1996). This pattern is unique among achondrite groups, and reflects oxygen isotopic heterogeneity of ureilite precursor materials. Their oxygen isotopic compositions (Δ^{17}O) are also correlated with mg#, which implies that they are correlated with depth (Fig. 5d). Although the slope ~1 oxygen isotopic trend of ureilites may have a nebular origin (Clayton and Mayeda, 1988), it is difficult to explain the depth correlation in this model. Goodrich et al. (2002a) suggested that the oxygen isotopic heterogeneity was established by water-rock mixing during pre-igneous aqueous alteration of a CV-like parent body, which could explain a depth correlation if heating began in the center and alteration proceeded radially (Young et al., 1999). Regardless of the origin of this oxygen isotopic heterogeneity, it was preserved during high-temperature igneous processing. This has led some authors (e.g. Warren and Kallemden, 1992; Scott et al., 1993) to suggest that ureilites are relatively primitive residues from a parent body that experienced only a limited degree of igneous processing, and is most easily reconciled with our petrologic model if melt extraction on the UPB was a rapid, fractional process in which migrating melts did not interact significantly with the rocks through which they migrated.

At the same time, it is notable that the augite-bearing ureilites, which represent melts that must have moved upwards from their source regions and pooled at various shallower depths, show the same range of heterogeneous oxygen isotopic compositions and correlation of mg# with Δ^{17}O as the olivine–pigeonite and olivine–orthopyroxene ureilites (Fig. 5a and d). This suggests that, as high-temperature cumulates, they had sufficient time to equilibrate both mg# and oxygen isotopes with their surroundings.

2.3. Impact disruption and shock history of the UPB

All monomict ureilites show evidence of extremely rapid cooling (on the order of 10°C/h through the range 1100–650°C) accompanied by a sudden drop in pressure, during which characteristic reduction rims (highly magnesian compositions riddled with tiny grains of metal) formed on their olivine and pyroxenes (Mittlefehldt et al., 1998; Goodrich et al., 2001). This common P–T history suggests that they are all derived from a single UPB, and were excavated, while still hot, by a single, major impact, possibly involving catastrophic disruption of the whole body (Takeda, 1987; Warren and Kallemden, 1992). It is unlikely that this impact was responsible for delivery of ureilites to Earth, since ureilites show young (~35 Ma) cosmic ray exposure ages (Eugster, 2003). Thus, the disrupted material must have reassembled, either onto a layer of rubble on the original asteroid, or into an offspring body that assembled from debris created by the impact.
Although monomict ureilites show a nearly continuous range of $mg\#$, from $\sim 75$ to $95$, there is a strong peak in the distribution at $mg \sim 78–80$ (Fig. 6a). In terms of our petrologic model, this implies that a large percentage of the material we are sampling from the UPB was derived from very similar depths (Fig. 2a). If the ureilite material
reaccreted to the original body, we would expect to see a less biased sample, with the various depths from which materials were derived more equally represented. Thus, this peak in the distribution supports the suggestion (Goodrich et al., 2002a) that we are sampling an offspring body, which formed principally from a subsample of the ejected materials.

Shock states among monomict ureilites vary widely – from very low-shock samples (showing only minor undulatory extinction in olivine and euhedral laths of crystalline graphite) to very high-shock samples (in which olivine is completely mosaiced and carbon occurs as diamond and/or fine-grained, poorly crystalline graphite). They are not strongly correlated with $mg\#$ (Fig. 6c), although the highest shock levels occur only at $mg\# < 85$ (we caution, however, that shock levels may not be consistently quantified; more recently discovered ureilites have been classified on the S1–S6 shock scale of Stöffler et al. (1991), but others have been classified only as low, medium or high shock (Goodrich, 1992; Mittlefehldt et al., 1998). Although some ureilites clearly show multiple deformation events, it is likely that a single event was responsible for their major shock features, given that highly shocked achondrites are rare. Was this event the major impact that disrupted and quenched ureilite material? Certainly it could not have occurred before the disruptive impact, as shock features acquired before ureilites were quenched would have been quickly obliterated by recrystallization. There are, however, indications that it occurred while ureilite material was hot ($> 1100 \, ^\circ C$). For example, Cr-rich garnet, which has been observed around chromite in LEW 88774 and NWA 766 (Goodrich and Harlow, 2001; Sikirdji and Warren, 2001) and is a unique shock product in ureilites, appears to have crystallized above $1700 \, ^\circ C$. To raise temperatures to $> 1700 \, ^\circ C$ (from $< 600 \, ^\circ C$) would require shock pressures of $> 80 \, GPa$, which would have caused recrystallization and melting of olivine that are not observed. In addition, Bischoff et al. (1999) argued that the mosaicism of olivine seen in the most highly shocked ureilites reflects lower shock pressures than the scale of Stöffler et al. (1991) would indicate, as a

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**Fig. 4.** REE in ureilites. (a) Shaded area = range of olivine–pigeonite and olivine–orthopyroxene ureilites. Square symbols = augite-bearing ureilites. (b) Leaching experiments (Boydton et al., 1976; Spitz and Boynton, 1991) have shown that the V-shaped patterns of ureilites reflect the presence of a cryptic LREE-enriched component (leachate). Leached samples show a LREE-depleted pattern that is nearly identical to that reconstructed in modal proportions from in situ (SIMS) measurements of olivine and pyroxene (data from Guan and Crozaz, 2000). (c) REE of individual minerals in monomict ureilites, from in situ (SIMS) measurements of Guan and Crozaz (2000). (d) Bulk REE of four polymict ureilites. LREE-enriched patterns reflect the presence of feldspathic material and of the LREE-enriched component. (e) REE of mafic minerals in polymict ureilites, from in-situ (SIMS) measurements of Guan and Crozaz (2001). (f) Plagioclase grains in polymict ureilites (solid symbols) show a typical plagioclase pattern, with large positive Eu anomalies; REE abundances are not correlated with An content, indicating that not all grains are derived from a common magma. Bulk feldspathic clasts in polymict ureilites show relatively flat REE patterns. Data from Guan and Crozaz (2001).

Monomict ureilites and monomict ureilite-like clasts in polymict ureilites shown a correlation of $\Delta^{17}O$ with $mg$# (d), which implies a correlation with depth in the UPB. Range of bulk oxygen isotopic compositions of polymict ureilites is similar to that for monomict ureilites with $mg < \sim 83$, indicating a preponderance of low-$mg$ material.
result of the shock occurring at near-magmatic temperatures. Therefore, it is likely that the principle shock features of ureilites were established during the disruptive impact, and were quenched into place at that time.

2.4. Missing lithologies

Our petrologic model implies that several lithologies that formed on the UPB are not represented among monomict ureilites. This includes, most notably, the basaltic component of all melts (the case of the “missing basalts” has been discussed by a number of authors). The absence of basaltic ureilites has been attributed by Warren
and Kallemeyn (1992) and Scott et al. (1993) to the fact that melts generated on the UPB would have been extremely rich in CO and CO₂ (generated by smelting), and therefore probably erupted explosively (Wilson and Keil, 1991) at velocities sufficient to escape their parent body and be lost (Fig. 2a).

Although the augite-bearing ureilites (and a few rare olivine–pigeonite and olivine–orthopyroxene ureilites) appear to represent a melt component, they are nevertheless ultramafic rocks (i.e. none contain plagioclase). The melts they represent may have been basaltic (in which case the augite-bearing ureilites are early cumulates). Alternatively, they may have been generated late in a fractional (incremental batch) melting process, and were highly refractory. The latter interpretation is more consistent with the constraint that oxygen isotopic heterogeneity was preserved on the UPB.

It is also notable that there are no monomict ureilites representing residues derived from deeper in the UPB than the most ferroan olivine–pigeonite ureilite. Our model implies that such residues would consist predominantly of olivine + augite and have mg#s < 75 (some olivine–pigeonite or olivine–pigeonite–augite assemblages with mg# < 75 might also be expected).

In addition, although ureilites have near-chondritic abundances of trace siderophile elements, indicating that core formation did not occur on the UPB (Janssens et al., 1987; Goodrich et al., 1987), if the original UPB was homogeneous in bulk Fe content then various amounts of metal, in accordance with degree of reduction, must have been formed. Silicate materials that can produce the olivine–pigeonite and olivine–orthopyroxene ureilites as residues contain ~5–15 wt% FeO (Goodrich, 1999a), indicating loss of ~15–24 wt% FeO relative to CI. However, all ureilites have similar, low abundances of metal, on the order of a few percent. Some metal occurs interstitially, although its original abundance is often difficult to determine due to terrestrial weathering. In addition, Singletary and Grove (2003) pointed out that the pigeonites in most olivine–pigeonite ureilites contain trains of fine-grained metal inclusions, which are not surrounded by reduction rims and therefore may be a product of primary smelting. They also observed a correlation between degree of secondary reduction of olivine and modal abundance of pigeonite, and argue that this results because smelting both increases pigeonite content (relative to olivine) and decreases carbon content (leaving less carbon available for late, secondary reduction). However, if the fine-grained metal grains in pigeonite represent the entire budget of metal produced in primary smelting, there should also be a correlation between the abundance of such metal and mg (or pigeonite abundance), which there is not (see data in Table 1 of Singletary and Grove, 2003). Therefore, it appears that metal was lost, most likely in the form of metallic Fe–S melts. Trace siderophile element patterns do, indeed, show an imprint of solid metal/liquid metal fractionation (Janssens et al., 1987; Goodrich et al., 1987). However, currently available data for olivine–pigeonite and olivine–orthopyroxene ureilites are inadequate to determine whether the expected correlation between metal loss (siderophile element abundance) and mg (degree of reduction) exists (see summary of data in Mittlefehldt et al., 1998).
3. Polymict ureilites

Of the 14 known polymict ureilites (Table 1), eight (North Haig, Nilpena, DaG 164, DaG 165, DaG 319, DaG 665, EET 83309 and EET 87720) are well-studied (the other six are recent finds for which only initial descriptions are available). These samples consist of lithic and mineral fragments that represent a variety of lithologies (Fig. 7), and thus can be classified as fragmental breccias. Solar-wind implanted gases are present in Nilpena, EET 83309 and EET 87720, indicating that they are regolith breccias, but appear to be heterogeneously distributed (Ott et al., 1990, 1993; Rai et al., 2003). Thus, the absence of solar gases in other samples does not necessarily imply a grossly different origin. All polymict ureilites are petrographically similar, and most likely formed in the same environment. They represent a regolith formed on or near the surface of either the original UPB (Warren and Kalleneyn, 1989) or one of its offspring bodies (Goodrich et al., 2002a).

Although some of the 14 have been thought to be paired (Prinz et al., 1986; Warren and Kalleneyn, 1989; Grossman, 1997, 1998), in general pairing is difficult to determine because of the inherent heterogeneity of each sample. It is likely that the regolith they represent was heterogeneous on the scale of small samples (and especially thin sections). Although most of the major clast types that have been

Table 1. Polymict ureilites

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References: (1) Berkley et al. (1980); (2) Keil et al. (1982); (3) Prinz et al. (1986); (4) Jaques and Fitzgerald (1982); (5) Brearley and Prinz (1992); (6) Prinz et al. (1987); (7) Warren and Kalleneyn (1989); (8) Cohen et al. (2004); (9) Schwarz and Mason (1989); (10) Warren and Kalleneyn (1991); (11) Guan and Crozaz (2001); (12) Grossman (1997); (13) Goodrich and Keil (2002); (14) Goodrich et al. (2002b); (15) Grossman (1998); (16) Ikeda et al. (2000); (17) Ikeda and Prinz (2001); (18) Kita et al. (2003a); (19) Ikeda et al. (2003); (20) Grossman and Zipfel (2001); (21) McBride and Mason (1998); (22) Russell et al. (2003); (23) Russell et al. (2004).

aNot studied, beyond initial description.
described occur in all of them, each individual appears to contain unique clasts. Furthermore, cosmic ray exposure ages for at least five of them are distinct, indicating that they were ejected by separate events from their source body (Rai et al., 2003).

Fig. 7. Combined three-element X-ray map of thin section of polymict ureilite DaG 165 (see also cover image). Red = Al, Green = Mg, Blue = Ca. Most of the material consists of olivine and pigeonite grains, having compositions similar to those in olivine–pigeonite monomict ureilites. Clast 31 is an unusually large fragment of a clast resembling the augite-bearing monomict ureilites. Feldspathic materials (red) are sparse. Clast 9 (see also Fig. 8a) is one of the largest and most representative clasts from the albite lithology. Clast 4 is a clastic breccia. Clast 1 is an unusual grain of olivine that contains numerous, submicron-sized exsolutions of chromite + pyroxene (see also Fig. 10a). Dark clasts are rare. Oliv-olivine; opx-orthopyroxene; pig-pigeonite; aug-augite.
The most extensive survey of the types of materials found in polymict ureilites is that of Ikeda et al. (2000), who developed a petrographic classification scheme consisting of 7 major groups, with 24 types of lithic clasts and 22 types of mineral clasts, for DaG 319. Cohen et al. (2004) provide an extensive survey of feldspathic materials in DaG 319, DaG 165, DaG 164, DaG 665 and EET 83309. These two works encompass the major types of materials previously observed in North Haig, Nilpena and EET 83309 (Jaques and Fitzgerald, 1982; Prinz et al., 1986, 1987, 1988). In this review, we propose a genetic, rather than purely descriptive, classification scheme (Table 2).

### Table 2. Genetic Classification of lithic and mineral clasts in polymict ureilites

<table>
<thead>
<tr>
<th>Genetic Classification</th>
<th>Lithic Clasts</th>
<th>Mineral Clasts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Monomict ureilite-like</td>
<td>1. Olivine–pigeonite (mantle residues)</td>
<td>1. Ferroan anorthitic (angritic)</td>
</tr>
<tr>
<td></td>
<td>2. Olivine–orthopyroxene (mantle residues)</td>
<td>2. Chondrules and chondrite fragments (ordinary chondrite- and R chondrite-like)</td>
</tr>
<tr>
<td></td>
<td>3. Augite-bearing (mantle cumulates or paracumulates)</td>
<td>3. Dark clasts (carbonaceous chondrite-like)</td>
</tr>
<tr>
<td>1. Indigenous</td>
<td>1. Feldspathic (“basalts”)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A. Pristine</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a. Albitic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. Labradoritic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. Augite-bearing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d. Magnesian anorthitic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B. Non-Pristine (shock-melted, -mixed, -reduced)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a. Fine-grained</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. Glassy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. With relict grains</td>
<td></td>
</tr>
<tr>
<td>2. Mafic</td>
<td>2. Sulfide-rich (metallic portions)</td>
<td></td>
</tr>
<tr>
<td>A. Ferroan or oxidized (deep mantle residues? cumulates?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Highly-magnesian (shock-reduced)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The most extensive survey of the types of materials found in polymict ureilites is that of Ikeda et al. (2000), who developed a petrographic classification scheme consisting of 7 major groups, with 24 types of lithic clasts and 22 types of mineral clasts, for DaG 319. Cohen et al. (2004) provide an extensive survey of feldspathic materials in DaG 319, DaG 165, DaG 164, DaG 665 and EET 83309. These two works encompass the major types of materials previously observed in North Haig, Nilpena and EET 83309 (Jaques and Fitzgerald, 1982; Prinz et al., 1986, 1987, 1988). In this review, we propose a genetic, rather than purely descriptive, classification scheme (Table 2).

### 3.1. Monomict ureilite-like material in polymict ureilites

More than ~97% of the material in polymict ureilites consists of lithic clasts that are compositionally and texturally indistinguishable from monomict ureilites, or...
mineral clasts that could have been derived from them. Oxygen isotopic compositions of bulk polymict ureilites are within the range of those in monomict ureilites (Fig. 5a), also indicating a dominance of monomict ureilite-like materials. These materials show the same range of compositional and textural diversity as the monomict ureilites. Olivine–pigeonite assemblages (A1 clast type of Ikeda et al. (2000)) dominate among the lithic clasts, and pigeonite appears to be the dominant pyroxene among mineral clasts, reflecting the preponderance of olivine–pigeonite assemblages among monomict ureilites. Only one lithic clast resembling the olivine–orthopyroxene monomict ureilite has been identified (Goodrich and Keil, 2002), but isolated orthopyroxene clasts that could have been derived from them (mg 86–92, Wo ~4.5) are common (Ikeda et al., 2000).

Lithic clasts similar to the augite-bearing monomict ureilites have been identified in DaG 319 (Ikeda et al., 2000; Ikeda and Prinz, 2001) and DaG 165 (Goodrich and Keil, 2002), but are much less common than olivine–pigeonite assemblages, reflecting the relatively low proportion of augite-bearing monomict ureilites. Ikeda and Prinz (2001) describe one poikilitic orthopyroxene–olivine–augite clast and two isolated olivine clasts, all of which contain melt inclusions (in olivine and augite) and are compositionally (mg 87–88 olivine) and texturally similar to the augite-bearing monomict ureilites Hughes 009 (Goodrich et al., 2001) and FRO 90054 (Fioretti and Goodrich, 2000; Goodrich and Fioretti, 2000). A similar lithic clast has been observed in another section of DaG 319 as well (unpublished data of the first author). Goodrich and Keil (2002) describe a melt-inclusion bearing olivine clast (Fo 76) which resembles the augite-bearing ureilite HH 064 (Weber et al., 2003), and a large (~7 x 14 mm²) olivine–augite–orthopyroxene–pigeonite clast (Fo 79) which resembles the augite-bearing ureilite META78008 (Berkley and Goodrich, 2001) and has complex poikilitic relationships (Fig. 7). Olivine compositions in all of these clasts have high Mn/Mg ratios relative to the Fe–Mn–Mg trend of olivine–pigeonite and olivine–orthopyroxene ureilites, demonstrating their affinity to the augite-bearing monomict ureilites (Fig. 1b).

Monomict ureilite-like olivine and pyroxene clasts in polymict ureilites have REE abundances and patterns (Figs. 4c and e) similar to their counterparts in monomict ureilites (Guan and Crozaz, 2001). The data from polymict ureilites do show greater variations, particularly for augites and orthopyroxenes, than those from monomict ureilites; this may partly be due to the larger dataset for polymict ureilite grains, but could also reflect a variety of origins for augite and orthopyroxene grains (for example, crystallization from melts produced by different degrees of melting and/or at various stages of differentiation).

Kita et al. (2003a) measured oxygen isotopic compositions of six clasts that are petrographically similar to olivine–pigeonite ureilites, and one melt-inclusion bearing clast in DaG 319 that is similar to the augite-bearing ureilites, and found that they are consistent with those of monomict ureilites (Fig. 5a) and show the same correlation between mg# and Δ¹⁷O (Fig. 5d). Guan and Leshin (2001) obtained a similar result for monomict ureilite-like olivines in EET 83309.

Although this has not been strictly quantified, the monomict ureilite-like material in polymict ureilites appears to show the same bias toward material of low mg
(peaking at $\sim$79) that is seen among the monomict ureilites. For example, all of the olivines designated by Ikeda et al. (2000) as monomict ureilite-like (see Table 2a of these authors) have Fo 76–79, and those studied by Kita et al. (2003a) range only from Fo 76 to 83. Our own observations confirm this bias as well. In addition, bulk oxygen isotopic compositions ($\Delta^{17}O$) of polymict ureilites are restricted to the range shown by monomict ureilites of mg$\sim$76–84 (Fig. 5d), suggesting that they contain mostly low-mg material.

Clast sizes of monomict ureilite-like material vary widely, from cm-sized lithic clasts to submicron-sized mineral clasts. Most clasts are angular and/or irregularly shaped, indicating that they are broken fragments of larger rocks. The shock states of monomict ureilite-like lithic clasts also vary widely (even on the scale of a thin section), reflecting the same range of features seen among monomict ureilites (Goodrich, 1992; Mittlefehldt et al., 1998). Carbon is ubiquitous in polymict ureilites, both in the monomict ureilite-like clasts and finely dispersed in the clastic matrix, and occurs in the same variety of forms (crystalline graphite, diamond, poorly crystalline forms) as in monomict ureilites.

### 3.2. Non-monomict ureilite-like material in polymict ureilites

The remaining 2–3% of material (lithic and mineral clasts) in polymict ureilites is highly diverse, and can be divided (Table 2) into: (1) materials that could be indigenous to the UPB but which are not represented among monomict ureilites; (2) materials that are not indigenous to the UPB and were contributed to the regolith by impactors.

Criteria commonly used to distinguish indigenous from non-indigenous clasts in lunar or HED breccias may not be applicable to ureilites. For example, high abundances of siderophile elements are commonly used to recognize impactor material in lunar breccias; however, since monomict ureilites have near-chondritic abundances of trace siderophile elements, this is not a distinguishing feature. In the case of polymict ureilites, the strongest criterion for determining that a clast is indigenous is that its oxygen isotopes be consistent with those of monomict ureilites (Fig. 5). Although oxygen isotopes have been measured for only a limited number of clasts in polymict ureilites (Clayton and Mayeda, 1988; Guan and Leshin, 2001; Kita et al., 2003a), the conclusions of those measurements can be extended to many other clasts, based on petrologic similarities. Oxygen isotopic compositions distinct from those of ureilites can be considered proof of foreign origin (particularly if both their oxygen isotopic compositions and petrologic characteristics match those of other known meteorite types); however, oxygen isotopic compositions consistent with those of monomict ureilites are not necessarily proof of indigenousness (e.g. dark clasts described below). A second criterion is that a plausible petrologic relationship to monomict ureilites exists.

It is difficult to estimate relative proportions of the various non-monomict ureilite-like clast types, because all exist in low abundance and are heterogeneously distributed, but indigenous materials appear to be much more common than non-indigenous materials.
3.2.1. Indigenous materials

Indigenous clasts can be subdivided (Table 2) into (1) feldspathic (containing plagioclase or glass of plagioclase composition), (2) mafic, (3) metal-rich or (4) sulfide-rich types. Feldspathic clasts have attracted considerable attention because they may represent the “missing” basaltic melts complementary to monomict ureilite residues (note that Ikeda et al. (2000) use the term “felsic” rather than “feldspathic”). Mafic clasts may represent either cumulates related to these melts, or monomict ureilite-like residues derived from a greater range of depths than monomict ureilites themselves. Metal- or sulfide-rich clasts may represent metallic liquids separated during partial melting and/or reduction on the UPB.

3.2.1.1. Feldspathic clasts. One of the striking features of feldspathic clasts in polymict ureilites is that plagioclase compositions span essentially the entire range from An 0 to 100 (Prinz et al., 1986, 1987; Ikeda et al., 2000; Goodrich and Keil, 2002; Cohen et al., 2004). Several distinct feldspathic clast populations have been recognized. Two of these (ferroan anorthitic clasts, and chondrule/chondrite fragments) are non-indigenous, and are discussed below. Indigenous feldspathic clasts are divided by Cohen et al. (2004) and Goodrich and Keil (2002) into those that are pristine (retaining primary petrologic characteristics) and those that are not pristine (shock-melted and/or mixed with other indigenous lithologies and/or impactors). Only pristine clasts can provide direct information about basaltic magma generation, migration, and crystallization on the UPB.

Determining whether a feldspathic clast in a polymict ureilite is pristine is, again, more difficult than it is for lunar and HED breccias, because of the absence of ureilitic basalts for direct comparison. Textural criteria such as fine grain size (quench textures), commonly used to recognize impact-melted clasts, may not be applicable to ureilitic breccias, since primary basaltic magmas on the UPB are thought to have erupted explosively (Warren and Kalleymeyn, 1992; Scott et al.,

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Fig. 8. Back-scattered electron images (BEI) of pristine feldspathic clasts in polymict ureilites. (a–g)=clasts from the albitic lithology (Cohen et al., 2004), most of which are unrepresentative samples of the complete phase assemblage and range of textural features inferred for this lithology. (a) Portion of DaG 165 clast 9 (outlined in white), showing phenocrysts of albitic plagioclase (plag), with intersertal-textured areas of finer plagioclase laths, skeletal pyroxenes, phosphates, ilmenite and Ti, P-rich mesostasis. Large white grain is ilmenite (ilm). Rounded grains are phosphates (ph). (b) DaG 165 clast 19. Fragment of glassy mesostasis (gl) containing needles of ilmenite and skeletal/dendritic silica (sil), with two larger, subhedral pyroxene (px) crystals. Pits are SIMS analysis spots, from the $^{53}\text{Mn} - ^{53}\text{Cr}$ dating of Goodrich et al. (2002b). (c) EET 83309 clast D12, texturally and compositionally similar to the intersertal-textured areas of clast in (a). (d) DaG 665 clast E22. Fragment of albitic plagioclase and large, ferroan pyroxene crystal. (e) DaG 164 clast C1. Albite plagioclase with grains of phosphate. (f) DaG 665 clast E47. Fragment of albitic plagioclase, containing large ferroan pyroxene, and skeletal phosphates. (g) EET 83309 clast D17. Single grain of albitic plagioclase. (h) DaG 164 clast C16, belonging to the olivine–augite lithology of Cohen et al. (2004), with olivine crystals in a groundmass of plagioclase laths and finer-grained augite.
Fig. 8. (Continued)
1993) and would therefore be quench-textured as well. Cohen et al. (2004) suggest that a strong criterion for pristinity of a population of clasts is that it show normal igneous fractionation trends rather than the carbon redox control seen in monomict ureilites (Fig. 1a), since carbon is ubiquitous in polymict ureilites (the regolith of the UPB or its offspring) and therefore all impact melts are likely to have been generated under conditions of carbon redox control. Based on this criterion, they identified four pristine feldspathic lithologies: (1) albitic, (2) labradoritic, (3) olivine–augite, and (4) magnesian anorthite-rich.

**Albitic lithology:** The albitic lithology was recognized by Cohen et al. (2004) to be the most abundant population of feldspathic clasts (both lithic and mineral). Group 3 (“oxidized”) feldspathic clasts of Prinz et al. (1988) appear to be derived from this lithology, as do most type C1 clasts (“porphyritic igneous rocks”) in DaG 319 described by Ikeda et al. (2000) and Ikeda and Prinz (2001). It is characterized by a phase assemblage of albitic plagioclase (Ab$_{75-99}$, commonly as phenocrysts as well as smaller laths in the groundmass), FeO-rich pyroxene (mg$_{70-25}$, with normal zonation), phosphates (Cl-apatite and whitlockite), ilmenite, silica, and FeO–, MnO–, K$_2$O–, P$_2$O$_5$– and TiO$_2$–rich glass (Fig. 8). Only a few of the clasts identified as belonging to this lithology show the complete phase assemblage and range of textural variations inferred for it (e.g. Fig. 8a). Most appear to be unrepresentative samples of the complete assemblage, or isolated plagioclase mineral clasts having compositions similar to those of plagioclase in the lithic clasts (Figs. 8b–g). Nevertheless, the similar mineralogies and textures of these clasts suggest that they represent a common igneous lithology. This is supported by mineral compositional trends among the clasts, which include a normal igneous fractionation trend of near-constant Fe/Mn ratio over a large range of Fe/Mg ratios extending to much higher values than seen in the olivine–pigeonite ureilites (Fig. 1c), and a correlation between anorthite (An) content of plagioclase and Fe/Mg ratios of coexisting pyroxene (see Fig. 6 of Cohen et al. (2004)).

Cohen et al. (2004) inferred a crystallization sequence for the albitic lithology of plagioclase → plagioclase + intermediate and high-Ca pyroxenes → ilmenite + silica + phosphate. This sequence, as well as the observed Fe–Mn–Mg and An vs. Fe/Mg trends, can be modelled by extensive fractional crystallization of ~5–7% melts (the first melt fraction that would be expected to migrate from its source regions) of precursor materials from which the most magnesian olivine–pigeonite ureilites were produced as residues. The lack of carbon redox control during crystallization of these melts may be due to the fact that in such source regions (the shallowest, and therefore most reduced), most of the original carbon budget of ureilite precursor materials would already have been consumed. This may also explain why the albitic feldspathic clasts are the most abundant, since carbon-free melts would not have erupted explosively and therefore are the most likely to have been preserved.

Kita et al. (2003a) measured oxygen isotopic compositions of several porphyritic feldspathic (felsic) clasts in DaG 319 containing albitic plagioclase, and found that they are consistent with the monomict ureilite oxygen array (Fig. 5b). They show no correlation of $\Delta^{17}$O with plagioclase composition. It is unclear how to evaluate
whether such clasts show a correlation of $\Delta^{17}$O with $mg\#$, since their pyroxenes are strongly zoned.

**Labradoritic lithology:** The labradoritic lithology of Cohen et al. (2004), which is less common and was found as lithic clasts only in DaG 665 and EET 83309 (although plagioclase mineral clasts of An 40–50 are found in all polymict ureilites), is characterized by labradoritic plagioclase ($An_{40–60}$) in association with pyroxene, Si-rich glass, and in at least one case, ulvöspinel. Pyroxene grains are ferroan, and are normally zoned ($mg\sim50–30$) or show signs of resorption and rimming. Plagioclase occurs principally as masses of laths, interstitial to the pyroxenes. The mesostasis in these clasts is extremely silica-rich, but less enriched in incompatible elements than the mesostasis in the albitic clasts. Mineral compositions and compositional trends in the labradoritic clasts suggest that they also represent a fractionated igneous lithology, but one that is different from the albitic lithology. Pyroxenes show a trend of near-constant Fe/Mn ratio (Fig. 1c), over a range of Fe/Mg values similar to those in the albitic clasts but at higher Fe/Mn. They also show a correlation between An content of plagioclase and Fe/Mg ratios of coexisting pyroxenes (see Fig. 6 of Cohen et al. (2004)).

The Fe/Mn–Fe/Mg fractionation trend and An vs. Fe/Mg trend of the labradoritic clasts can be modelled by fractional crystallization of melts complementary to more ferroan olivine–pigeonite ureilites than those used to model the albitic lithology, and derived from deeper in the UPB (Cohen et al., 2004). Ikeda and Prinz (2001) discovered a large, melt inclusion-bearing plagioclase mineral clast of An 40–50, in DaG 319. Based on the compositions of the inclusions, they inferred that it is derived from a melt that crystallized along the plagioclase-pyroxene cotectic, and thus it may be similar to the labradoritic lithology of Cohen et al. (2004).

Kita et al. (2003a) measured the oxygen isotopic composition of one clast of labradoritic (An 47) plagioclase in DaG 319, and found that it is consistent with the monomict ureilite oxygen array (Fig. 5b).

**Olivine–augite lithology:** The third pristine feldspathic lithology identified by Cohen et al. (2004) comprises five clasts in which olivine and augite are the only mafic minerals (Fig. 8h). In four clasts, olivine occurs as euhedral, normally zoned crystals ($Fo\sim90–54$) in a groundmass of labradoritic ($An_{39–54}$) plagioclase. Augite occurs either as well-developed crystals or feathery/skeletal masses, and is also normally zoned ($mg\sim90–77$). Olivines show trends of near-constant Fe/Mn ratio (Fig. 1d), indicating that these clasts represent fractionally crystallized melt(s). As discussed above (with reference to the origin of the augite-bearing monomict ureilites), melts saturated with olivine + augite could only have formed at depths greater than those at which the olivine–pigeonite ureilites formed on the UPB (Fig. 3). Crystallization of such melts at depths near those at which they were generated would have resulted in olivine and augite with more ferroan compositions than those of the olivine–pigeonite ureilites, as well as coarse-grained, equilibrated textures. However, ascent to shallower depths (lower pressures) would have resulted in reduction. Model calculations (Cohen et al., 2004) indicate that $\sim10–15\%$ partial melts (near or slightly beyond the point of plagioclase disappearance), generated
from bulk UPB precursor materials with mg~65, could be reduced to mg~90 without leaving the augite stability field (Fig. 3), and could crystallize to assemblages mineralogically and compositionally similar to those seen in the olivine–augite clasts (although this is not a unique solution). Normal zonation and constant Fe/Mn ratios of olivine and augite in these clasts requires that carbon was absent during their crystallization, which can be explained if most of the carbon was consumed by reduction during ascent and the clasts represent the latter stages of crystallization. Crystallization at or near the surface could also account for their unequilibrated textures (Fig. 8h).

One additional olivine–augite clast (Cohen et al., 2004) has a poikilitic texture in which albitic pyroxene (An9) encloses blebs of ferroan olivine (Fo59–64) and augite (Wo44En43Fs13). The ferroan compositions of its olivine and augite, and its relatively coarse-grained texture, suggest crystallization as a cumulate from a melt generated at depth. The Fe/Mn–Fe/Mg compositions of its olivine are distinct from those of the other olivine–augite clasts (Fig. 1d), and are consistent with such an origin: they plot near the monomict ureilite trend (but still at significantly higher Mn/Mg ratios), as expected for cumulus minerals (Goodrich and Delaney, 2000). However, its plagioclase is much more albitic than model calculations predict (and than plagioclase in the other olivine–augite clasts), unless it crystallized from a much later, more fractionated melt than the mafic minerals.

Magnesian anorthite-rich plagioclase clasts: A fourth, rare type of feldspathic clast that appears to be both indigenous and pristine, is characterized by very anorthite-rich plagioclase. Prinz et al. (1986, 1987) noted the unusual occurrence of anorthite-rich plagioclase in polymict ureilites. Petrologic and oxygen isotopic studies have now shown that there are two distinct populations of such plagioclase — one associated with magnesian mafic minerals, which is indigenous, and one associated with ferroan mafic minerals, which is non-indigenous (described below).

The magnesian anorthite-rich lithology, as represented by one coarse-grained lithic clast in DaG 319 (C4-1 troctolite type of Ikeda et al., 2000), consists of plagioclase of An87 and olivine of Fo93. Kita et al. (2003a) showed that this clast has an oxygen isotopic composition similar to compositions of magnesian monomict ureilites (Figs. 5b and d), and thus appears to be indigenous. Anorthite-rich (An75–99) plagioclase mineral clasts also occur in EET 83309, DaG 164/165, DaG 319, and DaG 665 (Prinz et al., 1987; Ikeda et al., 2000; Goodrich and Keil, 2002; Cohen et al., 2004), but whether these are derived from the magnesian (indigenous) or ferroan (non-indigenous) population is not known, because no surrounding mafic minerals can be positively associated with them.

Cohen et al. (2004) discussed a mechanism for generation of such anorthite-rich plagioclase on the UPB. They showed that repeated extraction of partial melts (incremental batch melting) from precursor materials such as those (with Ca/Al = 2 × Cl) required to produce olivine–pigeonite monomict ureilites as residues can lead to melts that crystallize plagioclase with anorthite contents > 90 (feldspathic lithologies with labradoritic plagioclase can be produced from the same materials at lower degrees of melting). This result is consistent with conclusions based on rare earth and other trace element modeling (Guan and Crozaz, 2001; Kita et al., 2003a)
that the high-Ca and low-Ca plagioclase in polymict ureilites cannot be derived from common magmas.

Other possibly pristine feldspathic clasts: Cohen et al. (2004) also identified many lithic clasts containing plagioclase with a range of An content (similar to the albitic and labradoritic lithologies), and pyroxene and/or olivine with compositions that differ from those of olivine–pigeonite ureilites in being more calcic and more ferroan, but which nevertheless lie on the monomict ureilite Fe/Mg–Fe/Mn trend (Fig. 1). Because igneous fractionation trends cannot be seen in these clasts, it is not possible to determine whether they have a common source. Nevertheless, they could represent early products of ureilite melts, which crystallized before carbon was completely consumed.

Ureilite chronology from pristine feldspathic clasts in polymict ureilites: The presence in polymict ureilites of Mn- and Al-rich phases not found in monomict ureilites has permitted determination of precise age data using the $^{53}\text{Mn}–^{53}\text{Cr}$ and $^{26}\text{Al}–^{26}\text{Mg}$ short-lived radionuclide systems. Two highly fractionated feldspathic clasts belonging to the albitic population (including clast 19 from DaG 165 shown in Figs. 7 and 8b) have a well-defined $^{53}\text{Mn}–^{53}\text{Cr}$ age (from their FeO- and MnO-rich glass phase) of $4.5 \pm 0.4$ Ma prior to the angrites, yielding a calculated absolute age of 4.562 Ga (Goodrich et al., 2002b and unpublished data of the same authors). This age is similar to that of the oldest eucrites, and thus demonstrates that melting on the UPB began very early in the history of the solar system. A Pb–Pb age ($4.559 \pm 0.028$ Ga) consistent with this was obtained from apatite in two albitic clasts from DaG 319 (Kita et al., 2002). In addition, $^{26}\text{Al}–^{26}\text{Mg}$ measurements of a diverse suite of plagioclase-bearing clasts (An contents ranging from 2 to 96) in DaG 319 show excesses of $^{26}\text{Mg}$ and an initial $^{26}\text{Al}/^{27}\text{Al}$ value corresponding to $\sim 5$ Ma after formation of CAIs (Kita et al., 2003b), thus suggesting that $^{26}\text{Al}$ was the heat source for partial melting on the UPB (although previous searches for excess $^{26}\text{Mg}$ in plagioclase in polymict ureilites were negative (Davis et al., 1988; Guan and Grozaz, 2001)).

Non-pristine feldspathic clasts: A variety of feldspathic clasts that appear to have been shock-melted, and possibly mixed with other lithologies, have been observed. Clasts consisting of glass with sprays of radiating plagioclase microlites (giving them a chondrule-like appearance) occur in North Haig, Nilpena, EET 83309, DaG 319, and DaG 165 (Prinz et al., 1986, 1988; Goodrich and Keil, 2002; unpublished data of the first author). They have bulk compositions equivalent to non-stoichiometric plagioclase (showing a wide range of An contents from clast-to-clast) with a small, highly magnesian mafic component. They appear to be shock-melted plagioclase grains with various amounts of admixed mafic material.

Fig. 9. Non-pristine (shock melted and/or mixed) feldspathic clasts in polymict ureilites. (a) Pilotaxitic clast in DaG 665. (b) Fine-grained clast in DaG 165, with skeletal/feathery mafic minerals in crystalline plagioclase. (c) Similar clast in DaG 319. (d) DaG 319 clast B23 (Cohen et al., 2004). Pyroxene grains consisting of relict cores of monomict ureilite pigeonite composition, with overgrowths of ferroan augite. All images are BEI.
Ikeda et al. (2000) describe pilotaxitic clasts (type C2), consisting of masses of irregularly interwoven, small (10–20 × 2–10 μm) plagioclase laths and minor interstitial pyroxene and silica-rich mesostasis (Fig. 9a). Although the composition of plagioclase (An 40–55) in these clasts is similar to that of the labradoritic lithology of Cohen et al. (2004), the pyroxene is much more magnesian (mg > 90). Another magnesian (almost FeO-free) clast type (C3-1 type of Ikeda et al. (2000)) is largely glassy, with quench needles of enstatite and diopside, and has a more albitic (An 8) normative plagioclase composition. The textures and highly magnesian compositions of these clasts suggest that they are impact-melted.

Another variety of extremely fine-grained clast (Cohen et al., 2004) consists of skeletal to feathery mafic minerals in crystalline plagioclase (Figs. 9b and c). Plagioclase compositions are homogeneous within each of these clasts, but vary widely among clasts from An 33 to 80. Normative pyroxene compositions show typical ureilitic Fe–Mn–Mg carbon redox control. Their textures, wide range of plagioclase compositions, and reduced pyroxenes suggest that they too are impact melts. The crystalline state of the plagioclase suggests that they have been annealed.

Cohen et al. (2004) and Goodrich and Keil (2002) describe several feldspathic clasts in which pyroxene grains have monomict ureilite-like pigeonite cores, with sharp boundaries to augite rims (Fig. 9d). The cores appear to be relict crystals that were incorporated into a feldspathic melt, probably by impact mixing. Prinz et al. (1988) describe relict grains of ureilitic olivine and pigeonite in some highly reduced melt clasts in North Haig and Nilpena.

Two clasts described by Cohen et al. (2004) consist of abundant euhedral, normally zoned olivine crystals in a glassy groundmass of albitic, non-stoichiometric plagioclase composition with fine crystallites. A few larger olivine grains are irregularly shaped and may be relict. Olivine core compositions (Fo 88–80) follow the monomict ureilite Fe–Mn–Mg trend of carbon redox control; normally zoned rims are generally too small to analyze. One clast in EET 83309 (Guan and Crozaz, 2001; see their Fig. 2) appears to be similar to these, and has an oxygen isotopic composition consistent with the monomict ureilite oxygen isotopic array (Guan and Leshin, 2001). The texture of these clasts suggests that they are impact melts, although their protolith(s) are uncertain (an olivine–augite lithology?).

In addition, some feldspathic clasts are clastic breccias, containing a variety of angular grains of various types in a glassy feldspathic groundmass (Fig. 7, clast 4), indicating multiple episodes of brecciation.

**Feldspathic clasts of uncertain origin:** One clast (x16A) described by Ikeda et al. (2000) is of uncertain origin. It consists of normally zoned olivine (mg 80–60) and low-Ca pyroxene phenocrysts in a ferroan, CaO- and Al₂O₃-rich groundmass, with a moderate SiO₂ content (~62%). Two analyses of olivine show disparate Fe/Mn ratios (Fig. 1d), which are difficult to explain.

**Rare earth elements in feldspathic clasts:** REE abundances of bulk polymict ureilites are elevated, relative to monomict ureilites, with LREE enrichments (Fig. 4d). These patterns can be partly explained by the presence of feldspathic material, although the LREE-enrichment may, to a large extent, be due to the ureilitic LREE-enriched component, which has been identified in the C-rich matrix.
of polymict ureilites (Guan and Crozaz, 2001). In situ (SIMS) measurements of plagioclase grains in polymict ureilites (Davis and Prinz, 1989; Guan and Crozaz, 2001) show typical plagioclase REE patterns, with large positive Eu anomalies (Fig. 4f). There is no correlation of REE abundance with An content, indicating that these grains could not have been derived by igneous fractionation of a common magma (Guan and Crozaz, 2001). Bulk REE patterns measured by SIMS for two feldspathic clasts that appear to be olivine-rich impact melts and for one melt inclusion in a plagioclase grain in EET83309 (Fig. 4f) show essentially flat patterns, at ~4–5 × CI (Guan and Crozaz, 2001). Two other feldspathic clasts, whose affinity is not clear, show slightly fractionated patterns (Fig. 4f). An essentially flat REE pattern at ~10 × CI was inferred (from measurements of their constituent minerals) for feldspathic clasts belonging to the albite lithology in North Haig and Nilpena (Davis and Prinz, 1989).

3.2.1.2. Mafic clasts. Mafic clasts (olivine and/or pyroxene) that are more magnesian (mg > ~92), and thus record more reduced conditions than seen in monomict ureilites (except during the formation of late reduction rims), are common in polymict ureilites. Mafic clasts that are more ferroan (mg < 75), and thus more oxidized, are rare.

Highly magnesian Mafic clasts: Lithic and mineral clasts consisting of highly magnesian olivine (Fo 90–99, usually with strong reverse zoning) and/or pyroxene (enstatite) are common in DaG 319 (Ikeda et al., 2000), DaG 165 (unpublished data of the first author), North Haig and Nilpena (Prinz et al., 1986, 1988) and EET 83309 (Prinz et al., 1987). Ikeda et al. (2000) distinguish four types of highly reduced lithic clasts. Coarse-grained, magnesian clasts (type A3) consist mainly of olivine, with minor orthopyroxene and diopside, and sometimes have highly mosaiced textures (suggesting shock recrystallization). Fine-grained, magnesian olivine–pyroxene clasts (type B1) consist mainly of olivine, with some pyroxene-rich areas of orthopyroxene, pigeonite, and augite. They often have textures (aggregates of small olivine or pyroxene grains that seem to correspond to original larger grains) suggesting shock-recrystallization. Fine-grained, magnesian pyroxene-rich clasts (type B2), consist mainly of aggregates of orthopyroxene, pigeonite, and augite having textures that suggest replacement of pigeonite by orthopyroxene, augite and SiO₂-rich glass (this replacement is commonly seen in shocked areas of monomict ureilites: Berkley et al., 1980, Ikeda, 1999). These clasts resemble the pyroxene-rich areas of type B1 clasts. Some that consist mainly of enstatite contain daubreelite. Both B1 and B2 type clasts may contain rare grains of plagioclase (An₂₉ has been observed in B1 and An₈₅ in B2), in addition to interstitial SiO₂-rich, feldspathic glass. Granular clasts of highly magnesian olivine, pyroxenes and minor plagioclase described by Prinz et al. (1988) are similar to B1 and B2 clast types of Ikeda et al. (2000). Fine-grained forsteritic (Fo > 95) olivine clasts (type B3) consist of aggregates of forsterite riddled with tiny metal grains (similar to reduction rims on olivine in monomict ureilites) and contain only very minor pyroxene (augite). In addition, Ikeda et al. (2000) recognized highly reduced mafic mineral clasts (types G1-3, G2-1, G2-2, G2-4) having compositions similar to the olivine and pyroxenes in the reduced mafic lithic clasts.
Although some of these highly reduced mafic clasts may be derived from pristine ureilitic residues that formed at very shallow depths, most of them were probably smelted in the regolith (a low-pressure environment with abundant carbon) or during catastrophic breakup of the UPB, and have been shocked and remelted to various degrees.

**Ferroan or oxidized Mafic clasts:** Goodrich and Keil (2002) describe one large (~5 × 4 mm), extremely unusual clast in DaG 165 (designated clast 1), which consists of several crystals of olivine of Fo~78 (Fig. 6). These crystals contain an extremely high abundance of crystallographically oriented, micron to submicron-sized two-phase inclusions of chromian magnetite and calcic pyroxene (Fig. 10a), of a type known to form by exsolution due to oxidation (Mosley, 1984). The inferred Cr₂O₃, CaO and MnO contents of the olivine before exsolution (which resulted in loss of Cr and Mn to chromite, and of Ca to pyroxene) are consistent with those of olivine in monomict ureilites (Fig. 1d). Exsolutions of this type would be expected in ureilitic olivine if it experienced late oxidation with sufficiently slow cooling. However, when this could have occurred, given the rapid cooling history and late reduction seen in monomict ureilites, is unclear. Of course, the oxygen isotopic composition of this clast has not been measured, and so it is not certain that it is indigenous.

No mafic lithic clasts more ferroan than monomict ureilites have been observed in polymict ureilites. Among isolated mineral clasts, rare ferroan olivines and pyroxenes do occur (Ikeda et al., 2000), though most of these appear to be derived from non-indigenous materials (such as chondrule and chondrite fragments – see below). One large (~1.2 mm), unshocked grain of pigeonite of mg 55–56 was observed in DaG 165 (Goodrich and Keil, 2002). Its Fe–Mn–Mg composition (Clast 14, Fig. 1c) indicates that it may be related to the labradoritic feldspathic lithology of Cohen et al. (2004).

### 3.2.1.3. Sulfide-rich clasts.

Sulfides occur as isolated mineral clasts in all polymict ureilites, and are mostly troilite, the major sulfide found in monomict ureilites. Pentlandite grains are extremely rare, and may be derived from equilibrated chondrite fragments (Ikeda et al., 2000).

Rare sulfide-rich lithic clasts in DaG 319 are described by Ikeda et al. (2000, 2003). They consist of anhedral grains of olivine, sometimes enclosed in massive sulfide (troilite), with a fine-grained, porous silicate matrix containing disseminated sulfide. Larger olivine grains are normally zoned, from Fo 80–90 to Fo 50–70, and have lower CaO and Cr₂O₃ contents than olivine in monomict ureilites. The matrix

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**Fig. 10.** (a) Olivine clast 1 in DaG 165 (see Fig. 7), containing abundant exsolutions of chromite + pyroxene. (b) Dark clast in DaG 165 (see Fig. 7), outlined in black, consisting of phyllosilicate-rich matrix with abundant magnetite and sulfide. White boxes show locations of images in (c) and (d). (c) Detail from (b), showing framboidal magnetite. (d) Detail from (b), showing isolated fragments that appear to be dominantly phyllosilicates but have a different composition from the matrix. All images are BEI.
consists largely of ferroan olivine. It resembles the matrix of Allende, and has a CI-like bulk composition (Ikeda et al., 2000, 2003). Oxygen isotopic compositions of olivine in two sulfide-rich clasts (Ikeda et al., 2003) lie on the CCAM line (Fig. 5c), suggesting a genetic relationship to ureilites. Ikeda et al. (2003) suggest that the matrix of these clasts may represent ureilite precursor material that escaped igneous processing on the UPB and was later sulfurized (presumably by an Fe–S metallic melt). However, the high temperature differentiation history of the UPB suggests that precursor materials are unlikely to have been preserved. We interpret the matrix of these clasts to represent non-indigenous carbonaceous chondrite-like material derived from impactors (see discussion of dark clasts below), which was invaded by indigenous metal–sulfide melt in the regolith.

3.2.1.4. Metal-rich clasts. Fine-grained metal-rich clasts in DaG 319 (Ikeda et al., 2000, 2003) consist mainly of enstatite and metal, with variable amounts of a silica phase, plagioclase, sulfide and rarely olivine. A few large enstatite grains contain aggregates of submicrometer-sized metal and silica, probably formed by in situ reduction. One clast contains a few grains of olivine of Fo 79–83, enclosed in sulfide, which appear to be relict. The metal is kamacite (with 2–4% Si), and the sulfide is troilite, with 0.4–7.0% Cr, similar to compositions of metal and sulfide in monomict ureilites. Enstatite in one metal-rich clast has an oxygen isotopic composition that lies on the CCAM line (Fig. 5c), near the composition of Allende matrix. Ikeda et al. (2003) suggested that the silicate portions of these clasts, like those of the sulfide-rich clasts, represent ureilite precursor materials that escaped igneous processing. Again, however, it seems unlikely that precursor materials would have been preserved on the UPB. The highly reduced mineralogy of these clasts, and their brecciated appearance (see Ikeda et al., 2003, Fig. 1f) suggests that they represent highly shocked and reduced ureilitic material that was invaded by indigenous metallic melt. Similar materials occur in brecciated shock veins in the monomict ureilite Hughes 009 (Goodrich et al., 2001).

3.2.2. Non-indigenous clasts

3.2.2.1. Ferroan anorthite-rich plagioclase clasts. Rare, ferroan anorthitic clasts resembling the angrite meteorites (particularly Angra Dos Reis, or ADOR) were described from Nilpena and North Haig (Jaques and Fitzgerald, 1982; Prinz et al., 1986, 1987). The Nilpena clast (Jaques and Fitzgerald, 1982) consists of anorthite-rich (An$_{98}$) plagioclase laths, ferroan (mg 39) Ca–Al-rich clinopyroxene (Wo 50, with 6% Al$_2$O$_3$ and 1% TiO$_2$), and ferroan (Fo 49–53) olivine. The North Haig clast (Prinz et al., 1986) consists of 20% plagioclase (An$_{98}$), 70% ferroan (mg 42) Ca–Al–Ti-rich (fassaitic) clinopyroxene (Wo 50, with 6–8% Al$_2$O$_3$ and 2% TiO$_2$), and 10% ferroan (Fo 47–60, normally zoned) olivine with high CaO (1.3–1.7%). One small clast observed in DaG 319 (C4-2 gabbroic type of Ikeda et al., 2000) consists of An$_{90}$ plagioclase and ferroan (mg 68) Ca–Al-rich clinopyroxene (Wo 49, with 5% Al$_2$O$_3$ and 0.7% TiO$_2$), and probably represents the same lithology. Some of the most anorthite-rich plagioclase mineral clasts found in EET 83309, DaG 164/165, DaG 319, and DaG 665 (Prinz et al., 1987; Ikeda et al., 2000; Goodrich and Keil,
2002; Cohen et al., 2004) may also be derived from it. Davis et al. (1988) found that REE in fassaitic pyroxene in one ADOR-like clast in North Haig are similar to those of fassaite in ADOR.

Although petrogenetic links between ADOR-like lithologies and monomict ureilites have been considered (Prinz et al., 1986; Guan and Crozaz, 2001), Kita et al. (2003a) showed that the oxygen isotopic composition of one ferroan anorthite-rich clast in DaG 319 is similar to that of ADOR (Fig. 5a), indicating that it is of foreign origin.

3.2.2.2. Chondrules and chondrite fragments. Jaques and Fitzgerald (1982) described an olivine–clinobronzite clast in Nilpena that appeared to be an unequilibrated H-group chondrule. Prinz et al. (1986, 1987) noted that some orthopyroxene mineral fragments in North Haig and Nilpena and rare olivine mineral fragments in EET 83309 are of ordinary chondritic composition, and Prinz et al. (1988) recognized barred olivine, radial pyroxene, and cryptocrystalline chondrules. Ikeda et al. (2000, 2003) identified barred olivine (type F1-1), porphyritic olivine (type F1-2), porphyritic olivine–pyroxene (type F1-3), and radial pyroxene (type F1-5) chondrules and chondrule fragments, as well as equilibrated chondrite fragments (type F2) in DaG 319. The chondrules and chondrule fragments contain clear or devitrified glass, and have textures and mineral compositions similar to those of chondrules in type 3 ordinary chondrites. Olivines are magnesian (Fo~73–98) and normally zoned, and have low Ca and Cr contents (distinct from the high Ca and Cr contents of olivine in monomict ureilites). Equilibrated chondrite fragments have homogeneous olivine, with lesser amounts of pyroxenes, plagioclase, sulfide and chromite, and are similar in mineralogy and mineral compositions to R group chondrites. Olivine is ferroan (Fo 59–68), and plagioclase (An6–11Or5–8) is albitic with a significant orthoclase component (the orthoclase component distinguishes it from albitic plagioclase in indigenous feldspathic clasts in polymict ureilites). Kita et al. (2003a) found that the oxygen isotopic compositions of chondrules and chondrite fragments in DaG 319 are similar to those of ordinary chondrites (Fig. 5a), confirming that they are of foreign origin.

3.2.2.3. Dark clasts. Dark clasts resembling carbonaceous chondrite matrix material were first observed as components of polymict ureilites in North Haig and Nilpena (Prinz et al., 1987; Brearley and Prinz, 1992). Petrographic studies showed that they consist largely of fine-grained phyllosilicate matrices, with larger grains of magnetite, sulfide (pentlandite), Fe–Mn–Mg carbonate, Mn-bearing ilmenite, and chlorapatite (Prinz et al., 1987). Transmission electron microscopy of the matrix material (Brearley and Prinz, 1992) showed that it consists largely of a serpentine group mineral having low Fe contents (fe# ~0.29) and 3–4 wt% Al2O3, with lesser Mg-rich, Fe-bearing smectite-type clay (probably saponite). The mineralogy of these clasts suggests that they have affinities to CI1 chondrite matrix, and differ significantly from CM, CV3 and CO3 matrices. Nevertheless, they are not identical to known CI1 material, and Brearley and Prinz (1992) suggested that they represent a lower degree of alteration. The bulk oxygen isotopic composition of the
dark clast from Nilpena plots near an extension of the Allende mixing line (and therefore of the ureilite oxygen isotopic array as well), on the $^{17}$O-rich side of the terrestrial fractionation line (Fig. 5c), and is unlike that of any known carbonaceous chondrite matrix material (Clayton and Mayeda, 1988).

Similar dark clasts, generally a few hundred microns to several mm in size and angular, are abundant in DaG 319 (Ikeda et al., 2000, 2003). Ikeda et al. (2003) divided them into two subtypes: fayalite-free (D1), which are common, and fayalite-bearing (D2), which are rare. In the fayalite-free dark clasts, phyllosilicates predominate and other phases are minor. Phyllosilicates occur as matrix, isolated fragments or nodules, or as veins that end at the clast boundaries and thus appear to be endogenetic. Their compositions suggest that they consist mostly of serpentine, with some smectite. The $\text{Al}_2\text{O}_3$ contents of the phyllosilicates vary from 0.5 to 6.0 wt%, with the higher-Al compositions generally occurring as veins that crosscut lower-Al compositions. In some cases, pseudomorphic textures of anhydrous minerals show replacement by phyllosilicates. Sulfide (mainly euhedral pyrrhotite), magnetite (occurring as framboids, or aggregates of tiny spherules), phosphate, and rare ilmenite (compositionally distinct from ilmenite in feldspathic clasts in polymict ureilites) occur as fine grains in the matrix. Dolomite or magnesite occur as fragments of large grains, and are rich in MnO, similar to carbonates in CI matrix. Calcite occurs only as veins that crosscut and extend beyond the clasts, and is probably a terrestrial weathering product. In addition, these dark clasts sometimes contain isolated fragments of unaltered magnesian olivine and pyroxene, and rhyolitic glass, which appear to be “exotic.” The textures of these clasts (occurrence of phyllosilicates as nodules, fragments and veins as well as matrix, and occurrence of carbonate and silicate fragments) indicate that they are breccias (similar to many C-chondrite dark clasts), which formed as such before incorporation into their present hosts (ureilite breccias or UPB regolith). The Si-normalized bulk compositions of fayalite-free dark clasts are close to CI, except for depletions in Mn and Na.

Fayalite-bearing dark clasts consist of a silicate-rich matrix, plus abundant opaque minerals (sulfide and magnetite) and large, angular lithic and silicate mineral fragments. The matrix is largely phyllosilicates, but also contains fayalitic ($\text{Fa} > 70$) olivine. It is more porous than matrix of the fayalite-free clasts, and appears to be poorly crystalline. In contrast to the fayalite-free clasts, ferroan phyllosilicates dominate and Mg-phyllosilicates are rare (suggesting a larger smectite component). The lithic fragments (which may be pieces of igneous rocks or chondrule fragments) have phenocrysts of olivine (normally zoned from Fo 85–90 cores to Fo 75–80 rims; rarely with relict cores of Fo 97–100) and/or orthopyroxene. Their groundmasses are partly hydrated and contain fayalitic olivine and magnetite, suggesting that they were altered in situ in their dark clast hosts. Isolated fragments of magnesian olivine also occur. The Si-normalized bulk compositions of fayalite-bearing dark clasts are similar to those of the fayalite-free clasts, but are less depleted in Na. Ikeda et al. (2003) noted that the occurrence of fayalite in these clasts suggest affinities to oxidized CV chondrites such as Kaba, Bali and Mokoia.
Three dark clasts, 350–300 μm in size, have been observed in DaG 165 (Goodrich and Keil, 2002). They have extremely fine-grained matrices (red-brown in transmitted light) consisting largely of phyllosilicates with bulk compositions similar to those of the dark clasts in Nilpena and North Haig (Brearley and Prinz, 1992), and contain abundant grains of Fe, Ni sulfide, framboidal magnetite, and larger magnetite (Figs. 10b and c). They also contain isolated fragments that appear to be dominantly phyllosilicates but have a different composition from the matrix (Fig. 10d). The presence or absence of fayalite in the matrix was not determined.

Brearley and Prinz (1992) and Ikeda et al. (2003) discussed the possibility that dark clasts in polymict ureilites represent a previously unknown type of carbonaceous chondrite material that was parental to ureilites, since the oxygen isotopic composition of the Nilpena clast is near an extension of the Allende oxygen array (Fig. 5c). Although this is an attractive hypothesis, particularly in light of the argument of Goodrich et al. (2002a) that dark clast material similar to that found in CV chondrites (enriched in Ca relative to Al by aqueous alteration and subsequent dehydration) might have been the precursors of ureilites, there are several arguments against it. First, as also discussed by Ikeda et al. (2003), these clasts have clearly experienced intense hydration, which is likely to have shifted their original oxygen isotopic compositions (Young and Russell, 1988); thus, their present near-coincidence with the ureilite array may be purely coincidence. Furthermore, the high temperature history of the UPB makes it extremely unlikely that unaltered precursor materials were preserved. Thus, the dark clasts in polymict ureilites are probably foreign materials derived from impactors (Brearley and Prinz, 1992).

Two other extremely fine-grained clasts in DaG 165 (Goodrich and Keil, 2002) have some similarities to the dark clasts described above, but are of uncertain origin. One (~635 μm in size) appears to consist of an intimate mixture of Ca-sulfate, phyllosilicates, and possibly sulfides. It has a rim (~15 μm thick) of nearly pure Ca-sulfate that may be of terrestrial origin, surrounded by an outer rim (15–60 μm thick) of massive olivine. The other (~1.9 mm) consists of skeletal crystals of olivine or low-Ca pyroxene in a matrix similar to that of the dark clasts. It contains no magnetite or sulfide, but has one lath (~100 μm) of graphite. Further characterization of these clasts is required to determine their affinity and origin.

4. Dimict ureilites

One ureilite, FRO 93008, has been recognized as a dimict breccia (Smith et al., 2000; Fioretti and Goodrich, 2001) that may have a very different origin from the polymict ureilites. Two thin sections of FRO 93008 consist entirely of a melt inclusion-bearing augite–olivine–orthopyroxene lithology of Fo~87 (Fioretti and Goodrich, 2000; Goodrich and Fioretti, 2000), which is identical to FRO 90054 (Fioretti and Molin, 1996) and FRO 90233 (Smith et al., 2000). It is also similar to the melt inclusion-bearing augite–olivine–orthopyroxene ureilite Hughes 009, but shows subtle compositional differences and is not paired with Hughes 009 (Fioretti
and Molin, 1996). However, Smith et al. (2000) reported that a third section of FRO 93008 consists of two distinct lithologies – the augite–olivine–orthopyroxene lithology, and a typical ureilitic olivine–pigeonite lithology of Fo 78–79. Fioretti and Goodrich (2001) examined the contact between these two lithologies, to determine whether it represents a primary igneous contact or a clast–clast relationship.

The contact is parallel to the preferred orientation of minerals in the olivine–pigeonite lithology, and consists of a cataclastic area with diminished grain size (Fig. 11a). The width of the cataclastic belt varies from ~1 mm to almost nothing, where the two lithologies are separated only by a <100 μm-wide strip of highly reduced orthopyroxene (left side of Fig. 11a). Most clasts in the cataclastic belt are angular, but a few are well rounded. Shocked veins and discrete melt pockets occur close to the contact and along a fracture zone roughly orthogonal to the contact. Most of the clasts along the contact have compositions consistent with derivation from one of the adjacent lithologies, although most are reduced relative to the primary minerals (Fig. 11b). A few clasts, however, are exotic. These include olivine of Fo 61 (with lower CaO and Cr₂O₃ contents than olivine in most monomict ureilites), orthopyroxene with Wo ~1, and feldspathic melt clasts (Fig. 11b–d).

The brecciated nature of this contact, and the presence of exotic material, indicates that it is unlikely to be a primary magmatic contact. Moreover, as pointed out by Fioretti and Goodrich (2001), the smelting model for ureilites implies that materials of mg 79 and mg 87 must have formed at very different depths from one another (Fig. 2a). However, if this ureilite is a breccia, then the scale of the brecciation is much larger than that seen in the polymict ureilites, and it may have formed in an environment other than a regolith. Smith et al. (2000) pointed out that all seven (as of the time of their study) ureilites other than FRO 93008 recovered from Frontier Mountain, Antarctica, consist of one of the two primary lithologies present in FRO 93008 (these authors also identified a third lithology, which consists largely of mosaicized olivine of Fo ~81, but we interpret this to be a highly shocked, slightly reduced version of the olivine–pigeonite lithology), and suggest that all FRO ureilites are paired (three ureilites recovered more recently in Frontier Mountain (Russell et al., 2003) may belong to this group as well). This proposal is also supported by the

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**Fig. 11.** BEI of dimict breccia FRO 93008. (a) A portion of the contact between a melt-inclusion bearing olivine (Fo ~87)-augite (mg ~88)-orthopyroxene (mg ~88) lithology (top) and an olivine (Fo ~79)-pigeonite (mg ~81) lithology (bottom). Contact consists of a brecciated zone, narrowing to a thin strip of reduced orthopyroxene to the left. A melt inclusion in mg ~88 orthopyroxene can be seen in the upper right. Large white patch on the right in the brecciated zone is metal. (b) Detail of the area of the contact shown in (a). Most clasts in the brecciated zone have compositions consistent with derivation from one of the two adjacent lithologies (albeit with an overprint of secondary reduction), but exotic fragments, such as the large clast of Fo 61 olivine, are also present. (c) Feldspathic melt clast in contact area. Plagioclase laths (dark), pyroxenes (bright), and glassy mesostasis. (d) Partly glassy feldspathic melt clast in contact area. Glass (upper) is non-stoichiometric plagioclase composition (An ~12–20). Spots are points of analyses.
statistic that the percentage of ureilites (relative to all meteorites) recovered in Frontier Mountain is much higher than it is for Antarctica as a whole (2.35% vs. 0.45%). Goodrich et al. (2002a) suggested that the Frontier Mountain meteoroid may sample a contact between two large (relative to the size of fragments in a regolith) fragments of the UPB (originally formed at very different depths) that were excavated by a catastrophic impact and reassembled, either in an outer shell of the original parent body or in an offspring body.

5. Discussion

5.1. Ureilitic breccias and the petrologic structure of the UPB

It is clear that the major populations of feldspathic clasts in polymict ureilites are indigenous, and represent some component of the “missing basalts” from the UPB. However, these clasts are small and not very abundant, and none of them are true basalts. The majority are isolated plagioclase mineral fragments, and the lithic clasts are mostly unrepresentative samples of the lithologies from which they are thought to be derived. Furthermore, the most abundant, and apparently most completely sampled lithology (the albitic lithology) is not mineralogically or chemically basaltic, but rather highly fractionated.

These observations provide support for the hypothesis that basaltic magmas on the UPB erupted explosively and were largely lost into space (Warren and Kallemeyn, 1992; Scott et al., 1993). If the UPB had ever had an extensive basaltic crust, then we would expect polymict ureilites to contain at least some basaltic clasts of comparable size to the large monomict ureilite-like clasts. The small size of most of the clasts suggests that they may represent material that rained back onto the UPB after being fragmented by explosive volcanism.

It may not be fortuitous that the albitic lithology is the most abundant. This lithology shows an extensive normal fractionation trend, without the carbon redox control that characterizes monomict ureilite materials. Considering the ubiquitous presence of carbon in ureilites (including polymict ureilites), it is surprising that any materials would show normal igneous trends. However, as pointed out by Cohen et al. (2004), this lithology appears to be related to the most magnesian (most reduced) ureilite residues, and therefore derived from those UPB source regions that contained the least carbon (assuming homogeneous carbon contents in ureilite precursor materials). It is also highly fractionated (this is true of the labradoritic lithology as well), representing the latter stages of crystallization when any carbon initially present is likely to have been consumed. This suggests that the only melts that may have been preserved on the UPB are those derived from shallow source regions, and late fractionates of rare magmas that were not lost in early explosive volcanism (Fig. 2a). Of course, a potential pitfall of this argument is that it is only the fractionated lithologies that we are able to recognize as forming coherent groups. Cohen et al. (2004) point out that there are other feldspathic clasts, with mafic
minerals having Fe–Mn–Mg compositions similar to those of monomict ureilites, which may have crystallized before carbon was completely lost from their melts. Further statistical studies may be necessary to determine how abundant such clasts are. Nevertheless, it is clear that feldspathic materials as a whole are a minor component of the regolith represented by polymict ureilites, and thus it is unlikely that the UPB ever had an extensive basaltic crust.

The identification of the olivine–augite lithology of feldspathic clasts provides support for the hypothesis that some melts were derived from deeper on the UPB than the most ferroan olivine–pigeonite residues. Our petrologic model indicates that such melts would have been saturated with olivine and augite (Fig. 3), and that the augite-bearing monomict ureilites represent early cumulates from them. The olivine–augite feldspathic clasts may be complementary to these cumulates (Fig. 2a).

At least two of the populations of feldspathic clasts provide support for the argument that melt extraction on the UPB was a fractional (incremental batch), rather than batch process (as discussed by Kita et al. (2003a) and Cohen et al. (2004)). The albitic lithology, as modeled by Cohen et al. (2004), could only be derived from early (5–7%) melts of their postulated source regions. And the indigenous anorthitic lithologies could only have crystallized from melts produced in very late stages of an incremental batch melting process. Thus, the requirement that melt extraction be fractional, in order to preserve oxygen isotopic anomalies, appears to be met.

The conclusion that melt extraction was a fractional process appears to be contradicted, however, by REE data. Warren and Kallemeyn (1992) argued that the REE patterns of monomict ureilites are consistent only with nearly perfect batch melting, and Guan and Crozaz (2001) calculated that the nearly flat REE patterns of feldspathic clasts in polymict ureilites are similar to those expected for 20–30% batch melts. This apparent contradiction may be resolved, however, if melt extraction, aided by the generation of large quantities of CO/CO2 gas, was so rapid that chemical equilibrium was not achieved. Van Orman et al. (2002) have shown that with increasing degrees of diffusive disequilibrium, the REE composition of a solid produced by fractional melting approaches that of a solid produced by batch melting. Complementary melts would, therefore, also have REE compositions resembling those produced by batch melting. Thus, the REE characteristics of both monomict ureilites and feldspathic materials in polymict ureilites may be consistent with fractional melting.

With regard to other missing lithologies, it is notable that polymict ureilites have not revealed any residual materials derived from deeper on the UPB than the most ferroan olivine–pigeonite ureilites – neither the olivine–augite residues we predict, nor, for that matter, any other type of residue (that might, for example, contradict our model). Olivine–augite feldspathic clasts may represent melts that were generated at greater depths than the olivine–pigeonite ureilites, but even so they are products of crystallization at shallower depths. Thus, both our collection of monomict materials from the UPB, and the regolith represented by polymict ureilites, appear to be restricted in depth of sampling. In the following section we discuss the implications of this observation.
One puzzle is why the only (that is, almost the only) melts that appear to be represented among monomict ureilites were augite-saturated (i.e. derived from deep). Considering the evidence that melt extraction on the UPB was a fractional process, it is likely that these melts were not basaltic (i.e. early and plagioclase-saturated), but rather highly refractory (i.e late, and saturated only with olivine + pyroxene). Late melts would presumably have had lower ascent velocities, due to both the slowing and eventual cessation of melting, and to the scavenging of most of the carbon into earlier melts, and hence would be more likely to stall within the residue pile and form (para)cumulates. This suggests the possibility that more of the olivine–pigeonite or olivine–orthopyroxene ureilites than is apparent from their olivine (Fe–Mn–Mg) compositions are not pure residues. Late melts generated within the low-Ca pyroxene stability fields would crystallize only pyroxene (because they are in reaction relationship with olivine), and could thereby form paracumulates in which the olivine was truly residual but the pyroxene was cumulus.

It is also notable that polymict ureilites do not reveal a large quantity of metal-rich (or metal+sulfide-rich) material, that could account for iron lost during smelting. This suggests the possibility that the low-melting T metallic melts were lost into space due to explosive volcanism (Keil and Wilson, 1993), along with the majority of the basaltic melts. Nevertheless, further studies of trace siderophile elements in olivine+low-Ca pyroxene ureilites (spanning the full range of observed mg#) are needed to determine the degree to which metal is unaccounted for.

5.2. Ureilitic breccias and impact disruption of the UPB

It is well established that the monomict ureilite-like materials in polymict ureilites show the same range of compositions (mg#), petrologic type, and shock state as do monomict ureilites themselves. They also show similar relative proportions of the different petrologic types, as well as the same bias toward materials of mg~79. Therefore, the regolith represented by polymict ureilites appears to be sampling the same grab-bag of material as the recent impacts that have delivered monomict ureilites to earth. As already surmised from monomict ureilites, it is unlikely that ureilites are being delivered to us directly from an intact UPB. The evidence that they all experienced a sudden drop in both temperature and pressure indicates that they were all excavated by a major impact, most likely simultaneously, and yet their young cosmic ray exposure ages imply that it is not this impact that is responsible for their delivery to earth. In addition, the strong bias toward materials of mg~79 indicates that we are sampling a preponderance of materials derived from nearly the deepest source regions, which is highly unlikely if the UPB was still intact. The fact that monomict ureilite-like materials in polymict ureilites show this same bias, strengthens this conclusion. It seems impossible that a regolith formed on the surface of the original UPB could be composed mainly of materials derived from deep regions.

The observation that shock features seen in monomict ureilite-like clasts in polymict ureilites vary widely (in terms of the level of shock they record) on the intimate scale of a thin section, implies that they were acquired before reassembly of
ureilitic materials, and are not due to regolith-forming impacts or to the impacts responsible for recent launch to Earth. This strengthens the inference that they were established principally during the disruptive impact experienced by the UPB, and the high proportion of ureilites that are shocked is another indication that ureilite material was reassembled (see similar argument made by Haack et al. (1996a) for L chondrites). At the same time, the fact that ureilite regolith breccias exist, implies that we are sampling a body large enough to develop a regolith and not just small hunks of debris scattered by the disruptive impact (Fig. 2b). The question, then, is whether that body is the UPB itself, onto which ejecta rained back in some random fashion, or an offspring body that formed from a subsample of the ejecta.

We suggest that the latter is more likely and that ureilites come from one or more daughter asteroids, which formed during a catastrophic impact. If they came from crater ejecta that rained back onto the original body, we would expect them to have been metamorphosed, as a cratering event could not have cooled that body. In addition, we would not expect to see any large peak in the histogram of ureilite mg#s (Fig. 6a). The preponderance of material from deep source regions might be explained, however, if all of that material was ejected along roughly the same trajectory, and was reassembled without reaccreting to the original body (while materials derived from other depths were ejected predominantly in other directions). Based on cooling rates determined for ureilites (3–20 °C/h), the ejecta must have been ~meter-sized, and reassembled in a few days after they cooled from >1250 °C to <800 °C. This thermal history and rather uniform fast cooling seem anomalous, as we would expect ejecta fragments to have a wide range of sizes and to reaccrete before much heat had radiated away (see Haack et al., 1996b). However, the formation of CO/CO₂ gas upon pressure release may have aided fragmentation and, as a result, ejecta may not have travelled on purely ballistic trajectories. Unfortunately, we lack sufficient constraints (size of parent, specific energy of impactor) to determine the size of the reassembled body relative to the UPB, or whether a family of offspring bodies, as modeled by Michel et al. (2002, 2003), was formed (it is not out of the question, for example, that ureilites are currently being derived from several similar offspring bodies).

It is tempting to conclude that the impact that disrupted the UPB did not excavate materials from depths greater than those represented by the most ferroan monomict ureilites. However, if we are currently sampling an offspring body that acquired an unrepresentative sample of the ejected material, this may not be the case; materials derived from deeper on the UPB may have been ejected in other directions. Nevertheless, it is certain that materials were excavated from at least the depths represented by the most ferroan ureilitic residues. Since this depth appears to be roughly the depth at which ureilite precursor materials move from the pigeonite stability field to the augite stability field (Fig. 3), this suggests that the remnant of the original UPB has a surface consisting of olivine+augite, rather than olivine+low-Ca pyroxene, and that it is this signature that should be sought in asteroidal spectral studies.

The recognition that ureilites also include dimict breccias, in which the “clast” size is much larger than it is in polymict ureilites, supports the conclusion that we are
sampling a reassembled body. FRO 93008 (or the FRO ureilite meteoroid) is probably not derived from the regolith of that body, but from deeper in the rubble pile, and represents an “assembly contact” (Fig. 2b) between materials that originally formed at very different depths in the UPB (it is notable that even within this meteoroid, material of mg~79 dominates).

The $^{53}\text{Mn} - ^{53}\text{Cr}$ and $^{26}\text{Al} - ^{26}\text{Mg}$ ages obtained for feldspathic clasts in polymict ureilites date the crystallization of at least some ureilite basalts at $\sim 4.562\text{Ga}$. No comparably precise ages have been obtained for monomict ureilites (see Mittlefehldt et al., 1998 and references therein), but they might be expected to be younger, reflecting a history of high-$T$ equilibration at depth. Goodrich and Lugmair (1995) have argued that a 3.79 Ga Sm–Nd isochron for some ureilites dates the time of introduction of the LREE-enriched component, a metasomatic fluid. One possibility is that this event was coincident with the major impact and breakup of the UPB. However, as discussed above, that impact occurred while mantle materials were still hot ($>1100\text{ }^\circ\text{C}$). It is unlikely that the UPB remained hot until 3.79 Ga, unless it was originally lunar-sized.

Finally, the mix of non-indigenous clasts present in polymict ureilites tells us that the region of the solar system (asteroid belt) in which this body formed also contained ordinary chondritic, carbonaceous chondritic, and angritic bodies.

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