FORMATION AND EVOLUTION OF THE UREILITE PARENT BODY AND ITS OFFSPRING.

[1]C.A. Goodrich, [1]A. N. Krot, [1]E.R.D. Scott, [1]G.J. Taylor, [2]A.M. Fioretti and [1]K. Keil. [1]HIGP/SOEST, Univ. of Hawaii at Manoa, Honolulu HI 96822 USA. [2]CNR, Corso Garibaldi 37, I-35137 Padova, Italy. (cyrena@higp.hawaii.edu).

Introduction: We summarize the major constraints on the formation, differentiation, and breakup/reassembly of the ureilite parent body (UPB), incorporating new evidence since the most recent reviews [1,2]. We then outline a model which broadly satisfies these constraints and suggests directions for future work.

Constraints:

(1) Olivine-pigeonite (ol-pig) assemblages constitute ~90% of the >110 ureilites. Their bulk Mn/Mg ratios (or those of their olivine) are chondritic and essentially constant [3,4] over a large range of bulk Fe contents (olivine mg# ~76-95). This suggests that they are residues from <30% single-stage melting of chondritic materials and implies that degree of melting could not have varied greatly among them [3].

(2) Their equilibrium magmas, calculated from pigeonite compositions [4] and determined experimentally [5], have various, superchondritic Ca/Al ratios that are not correlated with mg#. In a single-stage residue model, their precursor materials must have had superchondritic Ca/Al ratios and heterogeneous Ca,Al contents [6].

(3) The high primary C contents of ureilites (up to ~5 vol.%) suggest that C-redox reactions ("smelting"), which are pressure-dependent, must have been the dominant control on fO_2, and therefore mg#, on the UPB. This leads to estimates of the pressure range over which ureilites formed: ~10-25 bars for the most magnesian and 70-100 for the most ferroan [4,7-10]. The correlation between mg# and pyx/ol ratio predicted for smelting has been observed [5].

(4) Bulk oxygen isotopic compositions of ureilites define a line of slope 0.99 on the standard oxygen isotope plot (nearly coincident with the Allende CAI line of [11]), and show a positive correlation of $-\Delta^{17}O$ (–0.23‰ to –2.45‰) with mg# [12]. If the the range of ureilite mg#s results from a depth distribution, then there must have been a primary (pre-igneous) stratification of oxygen-isotopic composition ($-\Delta^{17}O$ decreasing with depth) on the UPB [8].

(5) Materials which could produce the ol-pig ureilites as residues contain ~6-15 wt.% FeO [6], indicating "loss" of ~15-24 wt.% FeO relative to CI/CM/CO/CV. However, ureilites contain only a few % metal, which implies either that metal was fractionated in their precursor material prior to accretion, or that most of the metal formed by reduction on the UPB was not retained in the ol-pig residues. Trace siderophile elements (~0.1-1×CI) show patterns suggesting fractionation of liquid metal from solid metal [4,13,14], more consistent with the latter.

(6) Basaltic meteorites complementary to ol-pig ureilites are unknown. Polymict ureilites (regolith breccias) consist mainly of clasts similar to monomict ureilites and contain only 1-2% feldspathic material.

(7) Olivine-augite-orthopyroxene ureilites (~10% of all ureilites) are cumulates, and mixing of Ca-rich and Ca-poor melts was involved in their formation [15-17]. The melts were strongly LREE-depleted [18], which implies that these ureilites are not cumulates from early magmas complementary to ol-pig ureilites (i.e. part of a basaltic crust). Textural evidence [19] suggests that they formed in close proximity to ol-pig ureilites. They show as large a range in Fo and $\Delta^{17}O$ as ol-pig ureilites. Therefore, they do not represent a single pod of melting, but rather formed individually over the same range of depths as ol-pig ureilites.

(8) All monomict ureilites experienced rapid cooling (on the order of 10°/hr through the T range ~1100-650°C) accompanied by a sudden drop in pressure, during which reduction rims formed on olivine and pyroxenes [1,2,15]. This common P-T history strongly suggests that they are derived from a single parent body.

(9) Clasts of monomict ureilite-like material in polymict ureilites span the full range of mg#s seen in monomict ureilites, and have reduction rims indicating the same P-T history.

(10) One ureilite (FRO 93008) previously thought to be monomict was found to contain a brecciated contact between an ol-aug-opx lithology of Fo 87 and an ol-pig lithology of Fo 79 [20,21]. This suggests that ureilites could be breccias on a much larger scale than that seen in the polymict regolith breccias.

Model:

(1) Ureilite precursor materials had chondritic Mn/Mg and total Fe content similar to bulk CI/CM/CO/CV, but superchondritic (≥ 2×CI) Ca/Al and heterogeneous Ca,Al contents. Significant fractionation of Ca from Al during condensation and accretion appears highly unlikely [6]. However, Ca may have been mobilized and concentrated during pre-igneous, parent-body aqueous alteration and dehydration, as evidenced in dark inclusions in CV chondrites that have Ca/Al up to 4.2×CI [22-27]. The evidence that dark inclusions are lithic fragments derived from preexisting planetesimals suggests the possibility that Ca-enriched material could be concentrated. The range of O-isotopic compositions of

ureilites, which is nearly identical to that of dark inclusions in Allende [28], is consistent with this suggestion. Furthermore, dark inclusions show a correlation of $\Delta^{17}O$ with degree of alteration [23,25], which may result from O-exchange between rock and aqueous fluid [23,29]. A stratification in $\Delta^{17}O$ on the UPB may have been established by radial flow of fluid [29] during alteration and dehydration/heating.

(2) The minimum size of the UPB was ~100 km in radius. Partial melting occurred over a range of depths (e.g. 3–14 km if the body was 250 km in radius or 7-30 km if the body was 125 km in radius), leaving ol-pig residues. Degree of melting was nearly constant, implying that there was no large T gradient over this range. The basaltic melts produced had high buoyancy due to high contents of exsolved CO_2 gas, and migrated upward in the form of veins and dikes rather than forming magma ponds [30]. Therefore, melting must have approximated a fractional (or incremental batch) process, and degree of melting may be less than estimates (15-30% [1,2,6]) based on equilibrium melting. O-isotopes were not equilibrated among residues at different depths because large bodies of melt were not involved [31]. Mg#s of ol-pig residues were determined by depth. Pigeonite compositions were determined by Ca,Al contents of precursor materials, which were not correlated with depth.

(3) The metal produced by reduction was C,S-rich and therefore largely molten. Most of it migrated out of the ol-pig residues and has not been sampled. Although this model predicts a correlation between mg# (amount of metal produced) and siderophile element abundance that is not seen [13], the existing data [4,13,14] for only 8 ol-pig ureilites are probably inadequate to evaluate this.

(4) Ol-aug-opx ureilites may have formed from late (highly refractory) melts complementary to ol-pig ureilites in rare pockets where melts ponded and crystal fractionation and magma-mixing were possible.

(5) Upon eruption, the basalts were lost from the UPB by explosive volcanism [9,31,32] due to high CO_2 contents, leaving an ol-pig mantle exposed.

(6) A family-forming impact [as modelled by 33] excavated ol-pig residues from at least the depth range corresponding to known ureilites. The high proportion of ureilites that are shocked [1,2], and their distinctive, common thermal history, suggest that we are sampling an unrepresentatively high proportion of shocked material derived from near the impact point. This material may have reassembled from ~meter-sized (upper limit from cooling rate) ejecta to form a secondary body, within a few days of the impact. We suggest that ureilites are derived from this offspring. FRO 93008 may sample the reassembly contact between two fragments that originated at very different depths in the parent body, while polymict ureilites represent a regolith developed on the new body. We lack sufficient constraints (size of parent, specific energy of impact) to determine whether the ureilite family resembled more closely that of Vesta (mass of the largest remnant, M_{lr}, large relative to original mass, M_{pb}) or that of Koronis (M_{lr}/M_{pb} very low). In either case, its size distribution may have changed considerably since formation.

Testing the Model: To evaluate this model we are pursuing: 1) Reexamination of dark inclusions to determine whether Ca-enrichment occurred prior to incorporation into their host meteorites; 2) Modelling of basalt migration and explosive eruption for the estimated size range and C contents of the UPB; 3) O-isotopic and petrologic studies to determine whether feldspathic clasts (and unusual mafic clasts) in polymict ureilites are indigenous and represent basaltic complements to ol-pig ureilites [34]; 4) ^{53}Mn-^{53}Cr dating of such clasts to determine the timing of differentiation; 5) Quantitative characterization (composition, shock state, reduction and grain size distributions) of all material in polymict ureilites, to elucidate the breakup/reassembly of the UPB; 5) Measurement of siderophile element abundances in ol-pig ureilites, to constrain the fate of metal on the UPB.

References: [1] Goodrich C.A. (1992) *Meteoritics* **7**, 327. [2] Mittlefehldt D.W. et al. (1998) *In* Planetary Materials, RIM **36**. [3] Goodrich C.A. & Delaney J. S. (2000) *GCA* **64**, 149. [4] Goodrich C.A. et al. (1987) *GCA* **51**, 2255. [5] Singletary S. et al. (2001) *LPS* **32**, #2000 and pers. comm. [6] Goodrich C.A. (1999) *MAPS* **34**, 109. [7] Berkley J.L. & Jones J.H. (1982) *Proc. LPSC **13th**, JGR* **87,** A353. [8] Walker D. & Grove T. (1993) *Meteoritics* **28**, 629. [9] Warren P.H. & Kallemeyn G.W. (1992) *Icarus* **100**, 110. [10] Sinha S.K. et al. (1997) *GCA* **61**, 4235. [11] Clayton R.N. (1993) *Annu. Rev. Earth Planet. Sci.* **21**, 115. [12] Clayton R.N. & Mayeda T.K. (1996) *GCA* **60**, 1999. 13] Goodrich C.A. et al. (1987) *Meteoritics* **22**, 392. [14] Janssens M.J. et al (1987) *GCA* **51**, 2275. [15] Goodrich C.A. et al (2001) *GCA* **65**, 621. [16] Goodrich C.A. (2001) *LPS* **32**, #1300. [17] Goodrich C.A. (2001) *MAPS* **36**, A67. [18] Goodrich C.A. et al. (2000) *LPS* **31**, #1192. [19] Berkley J.L. & Goodrich C.A. (2001) *MAPS* **36**, A18. [20] Fioretti A.M. & Goodrich C.A. (2001) *MAPS* **36**, A58. [21] Smith C.L. et al. (2000) *MAPS* **35**, A150. [22] Krot A.N. et al. (1995) *Meteoritics* **30**, 748. [23] Krot A.N. et al (1997) *MAPS* **32**, 31. [24] Krot A.N. et al (1998) *MAPS* **33**, 1065. [25] Johnson C.A. et al. (1990) *GCA* **54**, 819. [26] Bischoff A. et al. (1988) *LPSC* **19**, 88. [27] Fruland R.M. et al. (1978) *Proc. LPSC **9th***, 1305. [28] Clayton R.N. & Mayeda T.K. (1999) *GCA* **63**, 2089. [29] Young E.D. et al. (1999) *Science* **286**, 1331. [30] Wilson L. & Keil K. (1996) *EPSL* **140**, 191. [31] Scott E.R.D. et al. (1993) *Geophys. Res. Lett.* **20**, 415. [32] Wilson L. & Keil K. (1991) *EPSL* **104**, 505. [33] Michel P. et al. (2001) *Science* **294**, 1696. [34] Goodrich C.A. & Keil K. (2002) *LPSC* **33**.