

**THE PARENT MAGMA OF UREILITE HUGHES 009 (RE-)INFERRED FROM MELT INCLUSIONS IN OLIVINE: IMPLICATIONS FOR PETROGENESIS OF AUGITE-BEARING UREILITES.** C.A. Goodrich<sup>1</sup> and A.M. Fioretti<sup>2</sup>, <sup>1</sup>Dept. of Physical Sciences, Kingsborough Community College, 2001 Oriental Blvd., Brooklyn, NY 11235 USA (cgoodrich@kingsborough.edu), <sup>2</sup>CNR, Istituto di Geoscienze e Georisorse sezione di Padova, Corso Garibaldi 37, I-35127 Padova, Italy.

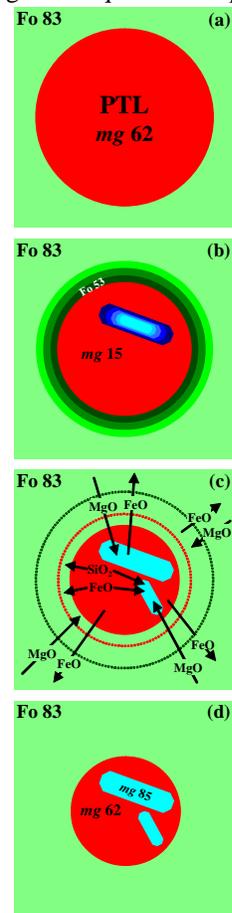
**Introduction:** Melt inclusions in olivine (ol) in Hughes 009 (Hughes) and its near-twin FRO 90054/93008 (FRO) were used to infer the composition of the parent magma of these olivine-augite-orthopyroxene ureilites [1,2]. The occurrence of melt inclusions also in augite (aug) and orthopyroxene (opx) in FRO [3] allowed [4] to evaluate the evolution of this melt during crystallization (ol→aug→opx). Results showed that closed system crystallization of the primary trapped liquid (PTL) in olivine (olPTL) would not lead to either the PTL in aug (augPTL) or the PTL in opx (opxPTL) and was not consistent with formation of an ol-aug-opx cumulate. Admixture of a magnesian, opx-saturated magma was proposed [4]. We have since obtained additional data for Hughes and, more significantly, realized a methodological error in the reconstruction of olPTL [1]. Here, we revise that composition and reconsider the petrogenesis of these (and other) augite-bearing ureilites.

**New Observations:** Glasses in inclusions in olivine in Hughes showed EMPA totals of 96-98% [1], leading to speculation that volatiles (e.g. H<sub>2</sub>O, which could explain the apparently anomalous crystallization sequence), might be present. Subsequently, however, we found that although P was not evident in EDS spectra of the glasses (leading us to omit it from analyses), it was present in significant amounts. New analyses show ~1-3% P<sub>2</sub>O<sub>5</sub>, with satisfactory totals (and otherwise differ little from those of [1]). We also discovered that Hughes has melt inclusions in aug and opx that are petrographically and compositionally similar to those in FRO (though much less abundant), thus eliminating any concern over relying on Hughes for olPTL and on FRO for augPTL and opxPTL.

**Reconstruction of olPTL:** The principal post-entrapment modifications that can affect melt inclusions in olivine, and which must be reversed in reconstructing the PTL, are: 1) fractional crystallization of olivine on inclusion walls; 2) crystallization of daughter minerals; 3) reequilibration (of Fe/Mg) with the host (Fig. 1).

The inclusions in olivine in Hughes present a rare case in which the effects of crystallization of daughter minerals can be reversed with a high degree of certainty. Their glasses show compositional trends (for almost all major/minor elements except Fe and

Mg) that can be demonstrated to result principally from various degrees of crystallization of the only major daughter phase (high-Ca pyroxene), and a small extrapolation from the composition of the least aluminous glass (LAG) yields the composition of the melt before any pyroxene crystallized (ur-LAG). However, in the phase system Ol-Qtz-Wo (Fig. 2), the glasses show a trend that is significantly offset relative to that expected from crystallization of the pyroxene. This offset was interpreted [1] to be due to "Fe-loss" during reequilibration of the inclusions with their hosts [5], and was "reversed" by addition of ~10% FeO to the ur-LAG. Reverse fractional crystallization [6] was then used to reintegrate the wall olivine. However, the addition of 10% FeO was an error, due to misunderstanding the reequilibration process.



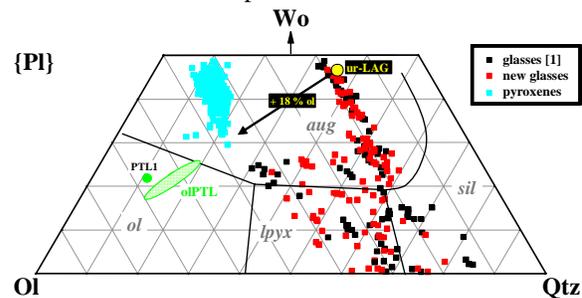
**Fig. 1.** Principle stages of post-entrapment modification of melt inclusions in olivine in Hughes 009.

Inclusions in Hughes show clear evidence of Fe/Mg reequilibration: wall olivine is homogeneous and identical to the host (Fo 87.3); pyroxenes are homogeneous and nearly identical to the primary augite (*mg* 89.2); and glasses are nearly homogeneous *mg* ~62 [1]. The process of Fe/Mg reequilibration of olivine-hosted melt inclusions has been examined in detail [5]. Fractionally crystallized wall olivine rapidly reequilibrates through loss of FeO and gain of MgO (Fig. 1c). The residual melt similarly reequilibrates (since diffusion in melt is even faster than in ol) and maintains *mg* in equilibrium with the host. However, the flux of MgO into the liquid leads to additional ("excess") crystallization of olivine (i.e. the liquid becomes supersaturated with olivine), which leaves it severely depleted in both FeO and MgO (reequilibration of mafic daughter phases should have a similar effect) (Fig. 1c,d). This process was referred to as "Fe-loss" [5], an unfortunate term (because FeO is not lost without comparable MgO gain) that led to our misinterpretation. The error is rectified by recognizing that the offset of the glass trend (Fig. 2) can be eliminated by adding ~18% olivine - i.e. the offset is indeed, due to reequilibration, but this involves loss of FeO, gain of MgO, and crystallization of "excess" olivine, rather than just loss of FeO (note that the "excess" olivine must have crystallized simultaneously with some pyroxene, as inferred by [1]). However, the effect of adding olivine to the ur-LAG is independent of Fe/Mg, and so we cannot necessarily restore the liquid to the state it was in (in terms of Fe/Mg) immediately after fractional crystallization of wall olivine. This implies that the total amount of olivine cannot be calculated, but must be based on some assumption. Olivine-augite cosaturation provides a minimum constraint, and the estimate of ≤50% from olivine "halos" [1] provides a maximum (Fig. 2). The PTL is then obtained by exchanging Mg/Fe until equilibrium with olivine of the assumed primary composition (at the time of melt entrapment) is reached. Typically, this would be the present host composition. In this case, however, there is evidence (*mg* of the glasses and the composition of olivine in equilibrium with the primary pyroxenes at their Ca-equilibration T of 1250°C: [1]) that the primary composition was Fo 83 (Fig. 1d), rather than the present Fo 87.

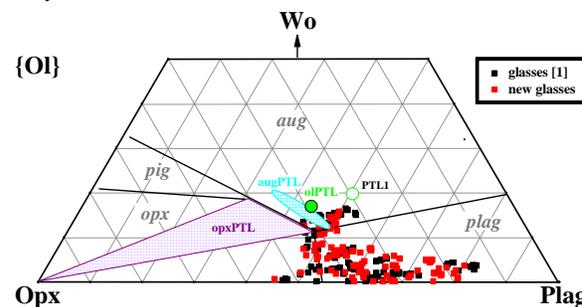
**Discussion:** The new olPTL is shown in Fig. 3 in the system Opx-Plag-Wo, along with augPTL and opxPTL [4]. The most significant change compared to PTL1 (best olPTL of [1]) is higher Si/Al. PTL1 has the crystallization sequence ol→aug→plagioclase, and cannot evolve to augPTL or opxPTL. In contrast, the new olPTL is nearly coincident with augPTL in Fig. 3

(and can differ from it only by olivine crystallization). Neither, however, will evolve to opxPTL, and thus the magma mixing model [1,4] might still be viable. Alternatively, the observation that all pyroxenes in Hughes are in Fe/Mg equilibrium with Fo 87, rather than the Fo 83 that appears to have been the primary composition, suggests that reduction (rather than subsolidus reequilibration [1]) occurred after crystallization of olivine and some augite, since reduction would drive the melt directly toward Opx (Fig. 3). A test calculation with MAGPOX showed that evolving new olPTL to augite saturation and then reducing it to Fo 87 does, indeed, move it into the range of opxPTL. This interpretation is consistent with the model that augite-bearing ureilites are cumulates from magmas that ascended from depth (within the field of augite stability) and were reduced during ascent [7,8].

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**Fig. 2.** Ol-Qtz-Wo system (projected from plag), showing reconstruction of olPTL. The ur-LAG is based on new glass analyses and differs little from ur-LAG1 of [1].



**Fig. 3.** Opx-Plag-Wo system (projected from ol), showing new olPTL, compared to augPTL and opxPTL from [4].

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