

COMPOSITION OF UREILITE PRECURSOR MATERIALS. C.A. Goodrich, Dept. of Physical Sciences, Kingsborough Community College, 2001 Oriental Blvd., Brooklyn, NY 11235 USA (cgoodrich@kingsborough.edu).

Previous Work: Many models for the petrogenesis of ureilites have assumed CC-like precursor material, as suggested by their O-isotopes (which point toward CV) and high C contents [1]. Although in detail the data do not show a clear link to any specific CC group [1], this remains the most reasonable assumption. Goodrich [2] examined chondritic silicate compositions with respect to their ability to produce ureilites (i.e. their major silicate mineralogy) as residues of batch partial melting. This modelling, based on MAGPOX [3], showed that strictly chondritic compositions (reduced to the range of mg of ureilites) do not produce olivine-pigeonite (ureilite-like) residues; rather, they produce olivine-opx residues. Investigation of key compositional parameters led to the conclusion that ureilite precursor materials had: 1) Ca/Al of $2\text{--}3.5\times CI$; 2) very low alkali contents (similar to CV); 3) various Al/Mg ratios ($\sim 0.75\text{--}1.25\times CI$); 4) Si/Mg ratio similar to that of OC ($\sim 1.15\times CI$), rather than CC.

Recently, some of the conclusions of [2] were challenged by [4], who reported that, in MELTS [5], batch melting of CM at mg 77 (low end of ureilite range) produces an olivine-pigeonite residue. They also suggested that, in general, fractional melting of chondritic materials might result in increased Ca/Al, and thus pigeonite, in residues. In addition, their trace element modelling suggested that feldspathic clasts in polymict ureilites (assumed to represent ureilitic melts) were derived from alkali-undepleted materials.

Reexamination: I reinvestigated batch melting of CM at mg 77 using both MAGPOX and MELTS, in order to examine discrepancies between the programs. The melting sequence I derive from MELTS (Fig. 1a) is in agreement with that of [4] up to $\sim 23\%$ melting – where plagioclase is eliminated and an olivine + low-Ca pyroxene residue is produced. At this point, pigeonite ($Wo \sim 14$) is replaced by opx ($Wo \sim 5$), indicating a configuration of phase boundaries in the Opx-Plag-Wo system such as that shown in Fig. 1b. In contrast, [4] report no change in pyroxene identity. Nevertheless, the abundances of low-Ca pyroxene obtained here agree with those reported by [4].

The melting sequence derived from the analogous calculation in MAGPOX (Fig. 2a) appears at first glance to be dramatically different: the initial ratio of augite to low-Ca pyroxene is higher than it is in MELTS (thus plagioclase is eliminated before augite), and the low-Ca pyroxene is always opx. However, at least with respect to the latter, the configuration of phase boundaries corresponding to this melting sequence (Fig. 2b) differs only slightly from that

inferred from MELTS (Fig. 1b) – in that the opx-pig boundary is located at slightly higher Wo . This comparison, then, reveals a discrepancy between the programs with respect to the mg dependence of the opx-pig boundary. The discrepancy is not, however, extreme, and the calculations fundamentally support the conclusion of [2] that strictly chondritic precursor compositions will not produce ureilite-like residues, since the case most likely to do so (lowest mg of the ureilite range) does not, in either program.

As discussed by [4], it is likely that melt extraction on the ureilite parent body (UPB) was fractional [6-9]. Fractional melting cannot be modelled to any high degree of accuracy using either MAGPOX or MELTS, because both programs fail to correctly calculate compositions of very low-degree melts. However, a qualitative examination of the Opx-Plag-Wo system (Fig. 2b) indicates that fractional melting of chondritic compositions is unlikely to lead to ureilite-like residues. The earliest melts must plot at the aug-lpyx-plag-(ol) cosaturation point ("peritectic"), and will remain there until one phase (plagioclase or augite, for compositions relevant to ureilites) is exhausted. The location of this point varies slightly with mg and alkalis, but in all cases lies close to the locus of chondritic Ca/Al. If both the bulk and the melt have the same Ca/Al ratio, fractionation cannot alter it in the residue. However, there is slight variation in Ca/Al among the chondrite groups, as well as variation in the location of the peritectic. For CM at mg 77 (Fig. 2b) the peritectic is at slightly lower Ca/Al and slightly higher Plag than the bulk (nearly directly right of it), in the region of opx stability; fractionation of early melts will therefore move the residues along a path of nearly constant Wo (directly left), which does indeed pass through successively higher Ca/Al. This does not, however, necessarily imply that they will produce olivine-pigeonite residues. In fact, the likelihood of this is low, as their path is nearly parallel to the opx-pig boundary.

This is, in fact, demonstrated by the fractional melting simulation that [4] performed for this composition using MELTS (with 5% melt increments). The compositions of their residues increase in Ca/Al by a factor of >3 by 25% melting (Fig. 2b); yet only the final residue reaches the pigeonite field and it contains only $\sim 4\%$ pigeonite, far too little to match an olivine-pigeonite ureilite of $mg \sim 77$ (should be $\sim 25\text{--}30\%$ [10]).

This analysis supports the conclusion [2] that starting compositions with superchondritic Ca/Al ratios are required to produce ureilite-like residues, and

furthermore indicates that this is the case even if melt extraction was fractional. The required Ca/Al ratios have been reevaluated, however, and are not as high as reported by [2]. Higher values are needed to produce pigeonite-bearing residues at higher *mg*. Goodrich [2] was constrained to match the most magnesian ureilite (*mg* 94). However, it is now recognized that all ureilites of *mg* >~87 are either olivine-opx residues or augite-bearing cumulates [7]. Thus, the highest Ca/Al ratio now required is only $\sim 2.5 \times CI$.

The requirement of [2] for a range of non-chondritic Al/Mg ratios in ureilite precursor materials arose from the fact that the ureilite data available at the time showed no correlation between pyroxene/olivine ratio and *mg* (such a correlation would be a consequence of smelting). Hence, at a given *mg*, some variation had to be introduced to move the composition to various locations in the pigeonite field (i.e. various distances from Opx and thus various pyroxene/olivine ratios). This requirement can now be eliminated, as the new data of [10] do show the expected correlation. Using a single composition with Ca/Al = $2.5 \times CI$ and Al/Mg = CI, a reasonable match to the ureilite data can be obtained over the full range of *mg*.

The OC-like Si/Mg ratio required by [2] is unsatisfactory from a theoretical point of view. This higher value (relative to CC) was used to move all compositions (i.e. at all *mg*) toward Opx and thus increase their pyroxene/olivine ratios to match those of ureilites. However, the present investigation shows that the necessity for this is uncertain. For example, the composition with Ca/Al = $2.5 \times CI$ at *mg* 76 produces (when augite is exhausted) an olivine-

pigeonite residue with ~ 26 vol.% pigeonite in MAGPOX but $\sim 45\%$ in MELTS (as noted above, MELTS calculates a higher ratio of low-Ca pyroxene to augite). At present, I am working with John Longhi to understand the source of this discrepancy and improve the applicability of MAGPOX to ureilites. It is likely that the requirement for a non-CC-like Si/Mg ratio [2] can be discarded.

The requirement of [2] for low alkali contents arose from the fact that alkalis enhance the stability of opx relative to pigeonite [3]. I have performed a number of tests with increased alkali contents, but found no solutions that satisfy the constraints of the ureilite data (without undesirably altering other parameters). Thus, it remains to reconcile this modelling with the trace element results of [4].

In summary, new modelling indicates that ureilite precursor material had Ca/Al of $\sim 2.5 \times CI$ but was otherwise CV-like (neglecting, for the present, Si/Mg). For purposes of modelling smelting [8,9], we assign it a bulk Fe content similar to that of Allende. If superchondritic Ca/Al ratios resulted from pre-igneous aqueous alteration on the UPB [11], then the UPB likely accreted with an Fe-rich CV-like composition.

References: [1] Mittlefehldt D.W. et al. (1998) In *Planetary Materials*, RIM 36. [2] Goodrich C. A. (1999) *MAPS* 34, 109. [3] Longhi J. (1991) *Am. Min.* 76, 785. [4] Kita N.T. et al. (2004) *GCA* 68, 4213. [5] Ghiorso M.S. and Sack R.O. (1995) *CMP* 119, 197. [6] Cohen B.A. et al. (2004) *GCA* 68, 4249. [7] Goodrich C.A. et al. (2004) *Chemie de Erde* 64, 283. [8] Wilson L. et al., this vol. [9] Goodrich C.A. et al., this vol. [10] Singletary S.J. and Grove T.L. (2003) *MAPS* 38, 95. [11] Goodrich C.A. et al. (2002) *LPSC* 33, #1379.

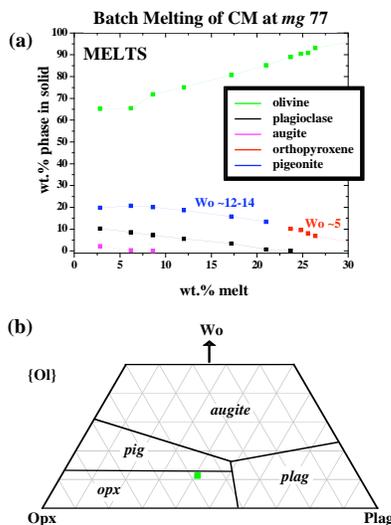


Fig. 1. (a) Batch melting sequence, from MELTS, for CM at *mg* 77. (b) Corresponding phase relations in Opx-Plag-Wo. Green square = bulk.

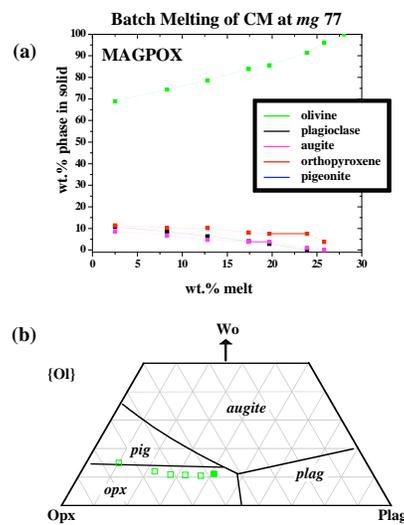


Fig. 2. (a) Batch melting sequence, from MAGPOX, for CM at *mg* 77. (b) Corresponding phase relations in Opx-Plag-Wo. Solid green square = bulk. Open green squares = residues of fractional melting from [4].