

OXYGEN ISOTOPE AND SIDEROPHILE ELEMENT TESTS OF UREILITE PETROGENESIS MODELS. ¹Cyrena A. Goodrich and ²Lionel Wilson. ¹Planetary Science Institute, 1700 E. Ft. Lowell Dr., Tucson AZ 85719 USA. cgoodrich@psi.edu. ²Lancaster Environment Centre, Lancaster Univ., Lancaster LA1 4YQ UK.

Introduction: Main group ureilites are ultramafic rocks thought to represent the mantle of a partially melted, carbon-rich asteroid [1,2]. Their oxygen isotope and metal/siderophile element characteristics are difficult to reconcile with any petrogenetic model [3-5]. We examine 1) homogeneous equilibrium smelting, 2) heterogeneous equilibrium smelting, 3) disequilibrium smelting and 4) non-smelting models. Equilibrium smelting models [6-11] assume that pressure/depth-dependent carbon redox reactions led to various degrees of smelting ($\text{FeO} + \text{C} \rightarrow \text{Fe}^0 + \text{CO/CO}_2$) on the ureilite parent body (UPB), and are responsible for the large range of ureilite Fo (75–95). The homogeneous version [10,11] assumes chemically homogeneous ureilite precursors. One heterogeneous version posits local variations in CAI abundance [12]. Disequilibrium smelting [12] assumes that reduction by C was not buffered by pressure but was still responsible for the variation in Fo. Non-smelting models [e.g., 13,14] attribute this variation to causes other than smelting.

Oxygen Isotopes: The oxygen isotope compositions of ureilites form a $\delta^{17}\text{O}$ - $\delta^{18}\text{O}$ array nearly coincident with the slope ~ 0.94 CCAM array, and have $\Delta^{17}\text{O}$ values (-2.45 to -0.23‰) correlated with Fo [15]. Two critical questions arise: 1) How was heterogeneity in $\Delta^{17}\text{O}$ preserved during igneous processing? 2) What is the origin of the correlation between $\Delta^{17}\text{O}$ and Fo?

Preservation of Oxygen Isotope Heterogeneity: Ureilites experienced temperatures of 1200-1300°C and extraction of their entire basaltic component [1]. A model [11] of heating and melt extraction on the UPB based on homogeneous equilibrium smelting showed that melt extraction was a rapid, fractional process, with melt transit times (source to surface) of 1-4 months. The distance that oxygen diffuses in olivine in a year at magmatic T is only $\sim 1 \mu\text{m}$ [11]. Thus, pre-existing variation in $\Delta^{17}\text{O}$ would have been preserved in residues, despite 15-30% melting.

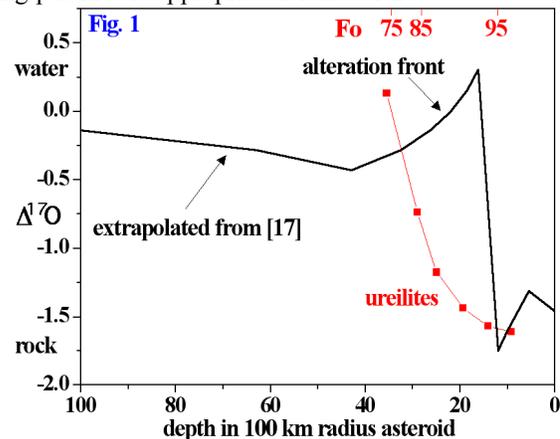
In the heterogeneous equilibrium smelting model of [12], the amount of ^{26}Al varies locally. This causes maximum T and degree of melting to vary, but as long as a few vol. % melting occurs, melt extraction times will not differ from the homogeneous case [11].

Disequilibrium smelting invokes formation of cracks that allow escape of CO gas [12]. Since cracks would facilitate rapid migration of melt, this type of model would also be conducive to preservation of oxygen isotope heterogeneity on the UPB.

For non-smelting models, we re-evaluate the parameters in [11] that depend on smelting – melt buoyancy ($\Delta\rho$) and radius (R). $\Delta\rho$ is $\sim 3000\text{-}3200 \text{ kg m}^{-3}$

if smelting (adding gases to the melt) occurs and $\sim 400 \text{ kg m}^{-3}$ if not, so the latter value applies. Without equilibrium smelting we have no constraint on asteroid size, but if $R = 5\times$ our original estimate of 100 km, total melt transit time, proportional to $(R/\Delta\rho)^{1/2}$, will be 6.2 \times longer [11, eqn. 27]. In the worst case this implies ~ 24 months, still very short compared with the time needed for oxygen isotopic homogenization. Pre-existing heterogeneity in $\Delta^{17}\text{O}$ would be preserved during igneous processing of ureilites in non-smelting models.

Correlation of $\Delta^{17}\text{O}$ with Fo: In the homogeneous equilibrium smelting model, a radial gradient in Fo is established by smelting [2]. This implies a radial gradient in $\Delta^{17}\text{O}$ (Fig. 1), which [7] suggested was accretionary. Goodrich et al. [16] suggested that it was established by water-rock exchange during early heating, as proposed for CC parent bodies [17,18]. To test this hypothesis, we evaluated the model of [17,18] using parameters appropriate for the UPB.



Results show that the timescale of heating on the UPB would have allowed oxygen isotope exchange between rock and radially flowing water, and that the size of the UPB could have been consistent with single pass (rather than convective) flow. However, the radial gradient that results from single pass flow does not match that required for ureilites. In Fig. 1, we re-cast results of [17] as $\Delta^{17}\text{O}$ vs. depth at the end of aqueous alteration, extrapolated (based on T contours) to the size of the UPB. The aqueous alteration model predicts an alteration front in shallow regions, with a maximum ($\Delta^{17}\text{O}$ approaching that of water) just below the cold outer shell. Above this, $\Delta^{17}\text{O}$ values rapidly drop off to those of unaltered rock. In the hypothesis of [16], ureilites should be derived from the alteration front, but the sign of the trend in this region is the opposite of what is required (Fig. 1). The ureilite

trend is similar in sign and slope to the steep transition zone just above the alteration front, but this would require ureilites to be derived from the unheated outer shell, clearly impossible. Thus, aqueous alteration (at least as in [17]) cannot explain the correlation of $\Delta^{17}\text{O}$ and Fo in the homogeneous equilibrium smelting model.

In the heterogeneous equilibrium smelting model of [12], variations in CAI abundance imply variations in oxygen isotope composition. We performed mixing calculations, using bulk Allende and Allende CAI "A" [19] as endmembers, with O-isotopes along the CCAM array [20]. If the bulk has $\delta^{17}\text{O} = 4.25$, $\delta^{18}\text{O} = 9$ (upper end of the ureilite array) and the CAI has $\delta^{17}\text{O} = -42$, $\delta^{18}\text{O} = -40$ [20], addition of ~9% excess CAI would result in the entire ureilite array.

However, for this model to work, increased CAI abundance must also lead to increased smelting. [12] suggested that heterogeneous distribution of ^{26}Al resulted in hotter packages of material rising and smelting more. However, this requires the residue to rise diapirically, and diapirism in small asteroids is extremely unlikely [11]. A second option is that different degrees of smelting occurred at the same depth in packages heated to different T. However, this would imply that Fo and T were not correlated among ureilites, whereas pyroxene thermometry [12,21-23] indicates that they are. A third possibility is accretion with a radial gradient in CAI component. This would provide the gradient in $\Delta^{17}\text{O}$ [7] and obviate diapirism.

In disequilibrium smelting [12], the extent of smelting (hence Fo) is determined by the degree to which gas can escape, i.e., the degree of crack development. It is not clear how degree of crack development could be correlated with $\Delta^{17}\text{O}$.

In a non-smelting model in which heterogeneity in bulk Fe (hence Fo) content was inherited from nebular precursors, correlated heterogeneity in $\Delta^{17}\text{O}$ could have been too. An example of a similar correlation in chondritic materials is the OC. It is not, however, clear whether the scale of this correlation (3 parent bodies?) is analogous to that of ureilites (one parent body?).

Metal and Siderophile Elements: Ureilites have uniformly low metal contents ($\leq 5\%$), and near-chondritic ($\sim 0.1\text{-}1\times\text{CI}$) bulk siderophile element abundances suggesting that the UPB did not undergo core formation [5,8,24-26].

Homogeneous equilibrium smelting predicts a difference of ~11 wt.% metal over the Fo range of ureilites. This is inconsistent with their uniform metal contents. If excess metal was removed, ureilites should show a correlation between siderophile element abundances and Fo. Such a correlation is not observed in bulk [4,5] or metal [27,28] compositions.

Heterogeneity in CAI abundance may explain ureilite siderophiles in equilibrium smelting. Highly siderophile elements (HSE) can be enriched in Allende

CAI up to $\sim 100\times$ relative to the bulk [29]. Addition of ~10% excess CAI (consistent with O-isotopes) could therefore result in bulk HSE enrichment by a factor of ~10. Thus, to first order, if all ureilites lost the majority of their smelting-produced metal, the loss of greater quantities of siderophiles from the most magnesian samples would be exactly compensated by their precursors having had higher abundances to begin with. This would explain the lack of correlation between Fo and siderophile abundances.

Non-smelting models in which extreme heterogeneity in bulk Fe content is inherited from nebular precursors would require that those materials were unlike any known bulk chondrites. Ureilites have lower bulk Fe contents ($\sim 5\text{-}18$ wt.%) than any major chondrite group ($\sim 18\text{-}28\%$). In addition, despite the fact that the $\Delta^{17}\text{O}\text{-FeO}$ trend of OC is similar to that of ureilites, OCs show a negative trend of FeO vs. bulk Fe, while ureilites show a positive one.

Conclusions: An equilibrium smelting model in which ureilite precursors are heterogenous in CAI abundance [12] may explain siderophile elements in ureilites. The possibility that the UPB accreted with a radial gradient in CAI should therefore be investigated. Other models to consider include multiple UPBs, and accretion of differentiated materials.

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