THERMAL HISTORY AND PHYSICS OF MELT EXTRACTION ON THE UREILITE PARENT BODY.
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Introduction: Ureilites are fragments of the mantle of a small (~100 km radius) asteroid that underwent ~30% partial melting at depths corresponding to pressures in the range 30-125 bars [1,2]. The preservation of oxygen isotopic heterogeneity on the ureilite parent body (UPB), despite high-T igneous processing [1], suggests that melts were extracted very rapidly. To determine if this was possible we modelled the thermal history of the UPB, and the melt extraction process.

Assumptions: The bulk composition of the silicate part of the UPB is assumed similar to that of CV chondrites [3]. This, plus the accretion time, determined the initial amount of ^{26}Al. The other factors determining the thermal history are the accretion temperature and initial ice content, if any. The inferred amount of partial melting requires the UPB to have accreted soon after CAI time, and uncertainties in amounts of radioactives present other than ^{26}Al have minimal influence on the time variation of the melt production rate.

Heating process: Starting from a given formation time, accretion temperature, and initial ice content of the UPB, we find the amount of heat released by the decay of all radioactive species present in each of a series of small time steps. The available heat is used to raise the temperature, taking account of any latent heat involved in phase changes. In general seven stages are involved: heating of rock and ice to 273.15 K; melting of ice at 273.15 K while the latent heat of 330 kJ kg^{-1} is supplied; heating of unreacted water and silicate reaction products while hydration occurs between 273.15 K and 300 K; heating of silicates until dehydration begins at 530 K; heating of dehydration products until dehydration ends at 623 K; heating of dehydration products until the onset of silicate melting at 1333 K; heating of unmelted silicates as melting progresses. During hydration (273.15 to 300 K) and dehydration (530 to 623 K), the latent heat of reaction (249 kJ kg^{-1}) is added to and subtracted from, respectively, the heat released by radioactives to find the temperature rise, and it is assumed that latent heat transfer occurs uniformly in the relevant temperature interval. During silicate melting the latent heat (taken as 400 kJ kg^{-1}) is absorbed uniformly across the melting temperature range. Converting available heat into temperature rise involves the specific heats at constant volume of the materials (ice, water and/or silicates) present. Both the water vapor released during dehydration and the silicate melt produced during melting would have escaped very efficiently through fractures to the surface due to the large pressures involved in their formation [4, 5] and do not contribute to the thermal budget after their formation. This is particularly important in the case of the melt, since most of the Al in the rock is contained in plagioclase, a mineral which is completely melted. Hence the main heat source is effectively removed from the asteroid interior. The sensitivity of the melting history to the input parameters is shown in Figs. 1 and 2, and Fig. 2 is used to compute the melt production rate as a function of time in Fig. 3: initial rates of nearly 40 m^3/s decline rapidly to less than a few m^3/s.

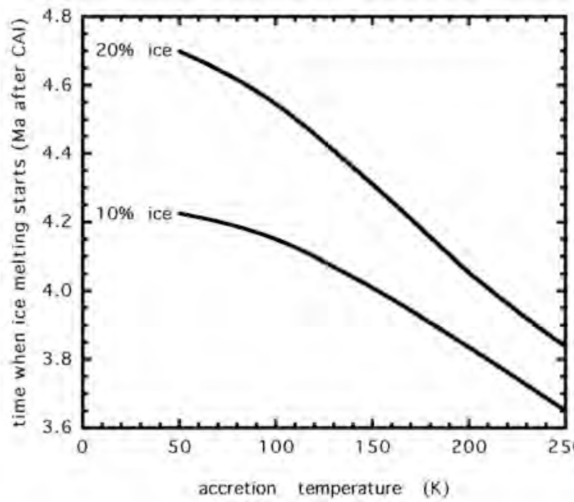

Figure 1. Effect of accretion temperature and ice content on time of start of silicate melting.

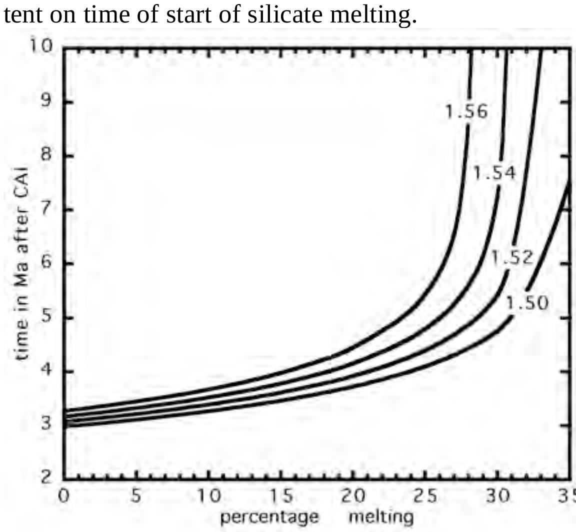

Figure 2. Degree of melting at P = 65 bars as a function of time for 4 asteroid formation times (labels = Ma after CAI). Relationship between temperature and degree of melting obtained from [13].

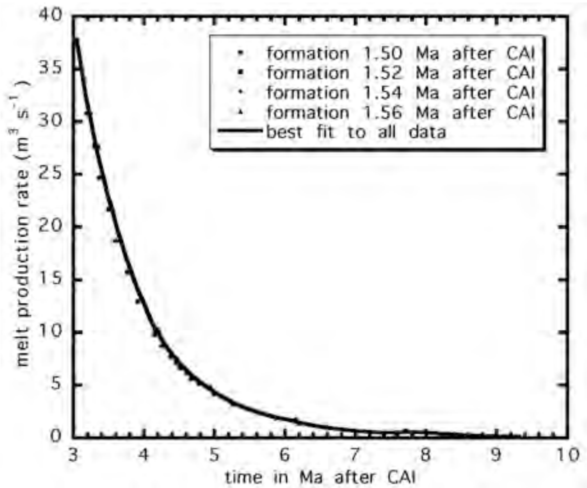

Figure 3. Typical variation with time of melt production rate, showing insensitivity to exact formation time.

Although no precise age dates have been obtained for monomict ureilites, ages of ~5 Ma after CAI formation have been obtained by ^{26}Al, ^{53}Mn, and Pb-Pb dating of feldspathic clasts (assumed to represent UPB melts) in polymict ureilites [6-8]. This date can be used to constrain a thermal history for the UPB. However, because accretion T and initial ice content are not well known, we cannot determine a unique solution. For example, for an accretion T of 250 K and 10% ice, melting within the ureilite pressure range levels off at ~30% at ~5 Ma after CAI, if the asteroid accreted 1.52 Ma after CAI. However, if the ice content is 1% or 20%, this becomes 1.54 or 1.50 Ma, respectively. We note the additional uncertainty that the petrogenesis of feldspathic clasts in polymict ureilites is not well understood [2, 9-11]; therefore, it is not known whether the 5 Ma after CAI date corresponds to early or late melting. Nevertheless, our modelling shows that for reasonable input parameters, it is possible to produce the entire range of monomict ureilites as residues of ~30% melting, within a time period consistent with age data from polymict ureilites. This result is in contrast to that of Kita et al. [12]. Their thermal model could produce the most ferroan ureilites at ~5.2 Ma after CAI if the UPB accreted at 2.2-2.5 Ma after CAI, but did not retain enough heat to produce the most magnesian ureilites.

Melting and melt migration: Melting is initiated at mineral grain boundaries in the UPB in much the same way as in larger planetary interiors. However, the enlargement and interconnection of grain-boundary melt veins into larger cracks is enhanced in a small asteroid relative to a larger planet, due to the greater ratio of pressure increase (potentially a few tens of MPa) caused by the volume changes due to small amounts of partial melting and the lithostatic stress. We estimate that the characteristic length scale of the smallest interconnected veins increases by a factor of ~10, to a few mm, as the amount of melting increases from 0.5 to 1.5 volume %. The number density of veins is then large enough that multiple connections between veins can occur, and a network of vein sizes is generated between the smallest, a few mm long, and the largest, which are effectively dikes extending to 10s of km. As an example, for UPB formation at 1.52 Ma after CAI time at 250 K with 10% ice content, silicate melting will start at 3.07 Ma after CAI, and will reach ~1% melting, with the formation of an interconnected vein network, just 0.03 Ma later.

The size distribution of the vein-dike network can be used, together with the volume rate of melt flow through the system, to find the speed at which the melt flows through the veins. By evaluating the wavelengths of the Rayleigh-Taylor instabilities that may develop within the UPB as a result of small density inhomogeneities, we infer that about 5 regional vein networks, each draining upward into one major dike, may develop within the asteroid, and assign one fifth of the total melt volume flux (shown above to be up to a few tens of m^3/s) to each. At each vein size melt buoyancy is balanced by wall friction via melt viscosity (taken as ~1 Pa s). The key result is that the removal of melt is extremely efficient: the melt content of the asteroid at any time will be only ~0.3 volume %, and the transit time of a given batch of melt from its point of origin to the surface will typically be very short - between 2 months and a year.

Consequences: Our results show that melt extraction on an asteroid as small as the UPB can be very efficient. Since very little melt is ever present in the mantle matrix, compared to the total produced, diffusive exchange will be extremely limited. This, and the very short melt transit time, justify an assumption of perfect fractional melting, in which melt extraction rate is taken as equal to melt production rate. In [13], we use this assumption, and the melt production rates calculated here, in modelling REE fractionation on the UPB.

References: [1] Mittlefehldt D.W. et al. (1998) In Planetary Materials, *RIM* **36**. [2] Goodrich C.A. et al. (2004) *Chemie der Erde* **64**, 283. [3] Goodrich C.A., this vol. [4] Wilson, L. et al. (1999) *MAPS* **34**, 541. [5] Muenow, D.M. et al. (1992) *GCA*, **56**, 4267. [6] Kita N.T. et al. (2003) *LPSC* **34**, #1557. [7] Goodrich C.A. et al. (2002) *MAPS* **37**, A54. [8] Torigoye-Kita N.T. et al. (1995) *GCA* **59**, 381. [9] Ikeda Y. et al. (2000) *Ant. Met. Res*. **13**, 177. [10] Kita N.T. et al. (2004) *GCA* **68**, 4213. [11] Cohen B.A. et al. (2004) *GCA* **68**, 4249. [12] Kita N.T. et al. (2005) *MAPS* **40**, A82. [13] Goodrich C.A. et al., this vol.