

ORIGIN OF UREILITES BY PARTIAL MELTING AND EXPLOSIVE VOLCANISM ON CARBON-RICH ASTEROIDS; Edward R.D. Scott, Klaus Keil, and G. Jeffrey Taylor. Planetary Geosciences, Department of Geology and Geophysics, SOEST, University of Hawaii, Honolulu, HI 96822.

We propose that ureilites are partial melt residues that formed in one or more bodies that experienced explosive volcanism. If ureilites formed as cumulates, as many authors have suggested [1, 2], we should have other crystallization products from their parent magmas and samples of the materials that prevented these magmas from mixing and homogenizing their oxygen isotopic compositions. Since the oxygen isotopic data [3] and abundance of fragmental and regolith breccias demonstrate clearly that the ureilite rocks and clasts are derived from numerous localities, we believe these materials provide representative samples from major parts of the ureilite parent asteroid(s). We argue that ureilites formed essentially by simple partial melting of isotopically heterogeneous chondritic material as a result of heating by ^{26}Al decay or electromagnetic induction. This process, especially if accompanied by removal of basalts by explosive volcanism [4], could have largely converted C-rich chondritic asteroids into ureilitic mixtures of olivine, pyroxene and graphite.

Ureilites comprise the major rock type on their parent asteroid(s)

Although arguments about the relative abundances of different rock types on specific bodies are always somewhat speculative, two independent lines of evidence suggest that ureilites are the most abundant silicate rocks in a major part of their parent asteroid(s). 1) Five of the 40-odd ureilites are fragmental breccias (North Haig, Nilpena, EET 83309 and 87720, LEW 86216) and one (EET 83309) is a regolith breccia [5, 6, 7]. All are very largely composed of clasts of normal ureilitic material. Much meteorite and asteroid evidence suggests that meteorite fragmental and regolith breccias provide samples from diverse parts of asteroids. 2) Oxygen isotopic data for 23 ureilites show that they are derived from six or more distinct reservoirs [3]. If ureilites were rare igneous products, it is very unlikely that we could sample six different locations without sampling the complementary rock types. The virtual absence of complementary rock types is strong evidence that one process operating in numerous parts of one or more bodies generated vast volumes of ureilitic rocks. Thus, ureilites cannot be volumetrically insignificant products of complex multi-stage igneous processes, as Goodrich et al. [10] suggest.

Origin of oxygen isotopic heterogeneities

The 4‰ spread in the oxygen isotopic compositions of ureilites along an ^{16}O mixing line must be due either to intrinsic variations in the chondritic parent material resulting from nebular processes [3], or to impact mixing of two asteroids with oxygen isotopic compositions at opposite ends of the ^{16}O mixing line [8]. Although both explanations have problems [9], a nebular origin seems much more plausible because 1) potentially analogous isotopic variations are known in chondrites; 2) partial melting could preserve isotopic heterogeneity on km-scales because of slow O diffusion (<<1 m in olivine); and 3) effective impact mixing does not appear compatible with partial melting. Although most chondrite groups have rather homogeneous oxygen isotopic compositions, equilibrated H, L and LL groups define an ^{16}O mixing trend along which $\text{FeO}/(\text{FeO}+\text{MgO})$ is inversely correlated with ^{16}O , as in the ureilites. A similar correlation is observed for chondrule and matrix samples from CV3 chondrites. Whole-rock CV chondrites are also spread along an ^{16}O mixing line, and we predict that analysis of larger samples will not significantly reduce this spread. Nebular processes that correlate ^{16}O with $\text{FeO}/(\text{FeO} + \text{MgO})$ may also be responsible in part for the chemical trends in olivine core compositions that Goodrich et al. [10] attribute to reduction by C in magmas.

Role of explosive volcanism

Basaltic material is rare in ureilites [8, 11]: 'feldspathic melt rocks' and pyroxenes rich in Al and Ti, which may represent this material, have been reported by Jacques and Fitzgerald [6] and Prinz et al. [19]. Wilson and Keil [4] and Muenow et al. [17] argue that an analogous lack of basalts on the aubrite parent body results from explosive volcanism, and that such processes may have been important in the histories of many small solar system objects. Volatiles present in basaltic liquids that approach the surface of asteroids less than 100 km in radius will disrupt the melt into droplets moving faster than the escape velocity. This process may have also have operated on the ureilite body [18] because CO/CO₂ mixtures form readily at pressures below 50-100 bars from FeO-bearing olivine and graphite [10, 12] and ureilites contain 2-5 wt% C [13]. Removal of surface basalts by impact stripping may not be satisfactory because impacts garden as well as strip.

Volatile release from melts may also have been involved in the transfer and injection of fine-grained interstitial silicate melt along grain boundaries in ureilites. This material, which was first identified in RC 027 [14], was believed by Goodrich et al. [10] to have been emplaced during impact.

The presence of pigeonite and high CaO concentrations in olivine shows that all ureilites were quenched from high temperatures [1, 10]. It appears that their parent body was largely disrupted into decimeter or smaller fragments that cooled in a year or so and subsequently reaccreted. We suggest that explosive volcanism could also have played a role in this process, although it may have been triggered by an impact.

Further discussion:

The existence of coarse-grained olivine-pyroxene mixtures in other types of achondrites and stony-iron meteorites such as MAC 88177 and lodranites [15, 16] suggests, as Takeda et al. [16] argue, that some of the igneous processes involved in the formation of ureilites must also have operated on several other bodies. If ureilitic material was a normal product of heating in C-rich bodies, as we propose, we must explain why the heat source was effectively extinguished during partial melting. Because loss of basalts removes most of the Al, this process could be a common feature of ²⁶Al heating. But if ²⁶Al was not the major heat source, the efficiency of induction heating may have changed as a result of conductivity changes on melting. The preservation of ureilitic material is aided by the significant temperature interval over which olivine-pyroxene mixtures are stable (100-200 °C).

Ureilites display strong mineral lineations and layering that Berkley et al. [1] attribute to laminar flow in a crystallizing magma chamber. However, we suggest that these crystal alignments may have been established during convection of a partially melted assemblage, or conceivably during outward movement of basaltic magmas.

References. [1] Berkley J.L., Taylor G.J., Keil K., Harlow G.E. and Prinz M. (1980) GCA 44, 1579. [2] McSween H.Y. Jr. (1989) Ann. Rev. Earth Planet. Sci. 17, 119. [3] Clayton R.N. and Mayeda T.K. (1988) GCA 52, 1313. [4] Wilson L. and Keil K. (1991) EPSL 104, 505. [5] Prinz M., Weisberg M.K., Nehru C.E. and Delaney J.S. (1987) LPS XVIII, 802. [6] Jacques A.L. and Fitzgerald M.J. (1982) GCA 46, 893. [7] Ott U., Lohr H.P. and Begemann F. (1990) Meteoritics 25, 396. [8] Warren P. and Kallemeyn G.W. (1989) Meteoritics 24, 233. [9] Goodrich C.A., Patchett P.J., Lugmair G.W. and Drake M.J. (1991) GCA 55, 829. [10] Goodrich C.A., Jones J.H. and Berkley J.L. (1987) GCA 51, 2255. [11] Takeda H. (1989) EPSL 93, 181. [12] Walker D. and Grove T.L. (1991) LPS XXII, 1457. [13] Dodd R.T. (1981) Meteorites, A Petrologic-Chemical Synthesis, Cambridge. [14] Goodrich C.A. et al. (1987) Meteoritics 22, 191. [15] Prinz M., Chatterjee N., Weisberg M.K., Clayton R.N. and Mayeda T.K. (1991) LPS XXII, 1099. [16] Takeda H., Saito J., Miyamoto M. and Hiroi T. (1991) LPS XXII, 1375. [17] Muenow D.M., Keil K. and Wilson L. (1991) submitted. [18] Warren P.H. and Kallemeyn G.W. (1991) EOS 72, 281. [19] Prinz M., Weisberg M.K. and Nehru C.E. (1988) LPS XIX, 947.