

UREILITES: ORIGIN AS RELATED MAGMATIC CUMULATES, J.L. Berkley, G.J. Taylor, and K. Keil, Dept. of Geology and Institute of Meteoritics, Univ. of New Mexico, Albuquerque, New Mexico 87131.

Ureilites are olivine-pigeonite achondrites. Seven individuals are known: Novo Urei (NU), Kenna (K), Goalpara (G), Haverö (H), Dyalpur (D), Dingo Pup Donga (DPD), and North Haig (NH). They are composed predominantly of olivine (Fo_{78-85}) and pigeonite ($\text{En}_{72-81}\text{Wo}_{3-10}\text{Fs}_{13-19}$; clinobronzite in Haverö) (Table 1; Fig. 1) in a carbonaceous matrix including graphite, diamond, lonsdaleite, and metal. The ureilites have been suggested to have formed by shock recrystallization of carbonaceous chondrites (1), as residues of partial melting (2) (3) (4), and as cumulate, ultramafic rocks (5).

We present a new classification scheme for ureilites (Fig. 2) based on bulk $\text{FeO}/(\text{FeO}+\text{MgO})$ and silicate mineral chemistry, which strongly reflects bulk-rock values (Table 1). The data define three chemical groups: Group 1 (D, DPD, and NH), with low bulk Fe/Mg ; "Group" 2 (H only), intermediate bulk Fe/Mg ; and Group 3 (NU, K, and G), with highest Fe/Mg (Fig. 2). This scheme is consistent with the ureilites representing a related group of differentiated, igneous rocks, probably from a cumulate pile. Group 1 may represent early-formed cumulate material relative to the other two groups, and thus may have occurred at the bottom of the stratigraphic succession. Group 3 may represent the highest part of the section sampled. Interestingly, bulk C roughly increases from top to bottom of the postulated pile (Fig. 2).

The idea that ureilites represent cumulate rocks is supported by universal stage mineral orientation studies which show that olivine displays a cumulate-type preferred orientation in NU and K (5); more recently, we have established a similar pattern for olivine in D. Pigeonite also has a cumulate orientation in K (5) and may be a cumulate phase in other ureilites. The heavy rare-earth (HREE) enrichment characteristic of ureilites (3) is consistent with pigeonite accumulation. The light rare-earth (LREE) enrichment displayed by ureilites may be caused by an unknown phase or phases within the carbonaceous matrix.

The origin of the carbonaceous matrix in ureilites has been the source of much debate, largely centering on whether the carbon is primary, i.e. resided in the rock prior to silicate crystallization or recrystallization (1) or, alternatively, was injected or otherwise introduced into the rock during a late event, possibly during the shock event that affected all ureilites (4). Neither hypothesis can be accepted or rejected unequivocally, but in the light of current data we prefer the primary origin for the carbonaceous matrix. The distribution of total C (Fig. 2), for example, is not compatible with C being introduced from above the cumulate body, since total C is higher at the bottom (Group 1; Fig. 2). We suggest that C, mainly occurring as graphite, was distributed as a solid phase within the parent ureilite magma and was trapped by early-accumulating crystals and kept from rising. Later cumulates trapped less and less C. High Ca in olivine (Table 1) and the presence of uninverted pigeonite suggest relatively rapid cooling of the ureilites. This explains why carbon-silicate reduction reactions only occurred on grain boundaries and did not go to

UREILITES, ORIGIN AS CUMULATES

Berkley, J.L. et al.

completion. Additional minor reduction may have occurred as the result of reheating during a later shock event.

The origin of the parental material of ureilites is equally as enigmatic as the origin of the carbonaceous matrix. Using the method of (7), we have calculated that the weight ratio of FeO/MgO in liquids coexisting with olivine in Group 1 and Group 3 range from 1.01-1.61 for average olivine compositions of Fo_{85.5}-Fo_{78.7}, respectively. The lower ratio is compatible with crystallization of Group 1 olivine from a C2 or C3 parent liquid, with the higher ratios representing more FeO-rich liquids that were generated during progressive fractional crystallization. Although other data also suggest some similarity between ureilites and carbonaceous chondrites (4) (6) (8), conclusive data to support this relationship is still lacking. References. (1) Vdovykin, G.P., 1970, *Space Sci. Rev.* 10, 483-510. (2) Wlotzka, F., 1972, *Meteoritics* 7, 591-600. (3) Boynton, W.V. et al., 1976, *Geochim. Cosmochim. Acta* 40, 1439-1447. (4) Wasson, J.T. et al., 1976, *Geochim. Cosmochim. Acta* 40, 1449-1458. (5) Berkley, J.L. et al., 1976, *Geochim. Cosmochim. Acta* 40, 1429-1437. (6) Wilkening, L.L. and Marti, K., 1976, *Geochim. Cosmochim. Acta* 40, 1465-1473. (7) Roeder, P.L. and Emslie, R.F., 1970, *Contr. Min. Pet.* 29, 275-289. (8) Gibson, E.K., 1976, *Geochim. Cosmochim. Acta* 40, 1459-1464.

Table 1: Microprobe analyses of olivine & pyroxene in ureilites. O=olivine; P=pyroxene

NU	high-Fe (grp. 3)						Int (grp. 2)						high-Mg (grp. 1)					
	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P
SiO ₂	39.1	54.6	38.9	55.1	39.6	55.2	39.9	55.2	40.5	55.4	40.4	55.7	40.6	55.2				
TiO ₂	ND	0.10	<0.01	0.08	<0.01	0.03	ND	55.2	<0.01	0.14	<0.01	0.04	<0.02	0.07				
Al ₂ O ₃	—	1.09	—	0.66	—	0.32	—	1.60	—	1.33	—	0.42	—	0.67				
Cr ₂ O ₃	0.59	1.05	0.63	0.99	0.70	0.88	2.46	1.07	0.55	1.08	0.67	0.79	0.85	0.52				
FeO	19.5	11.6	19.3	11.6	19.4	12.5	16.1	10.5	14.2	8.7	14.8	9.7	13.5	8.9				
MnO	0.44	0.58	0.48	0.47	0.40	0.41	0.48	0.51	0.41	0.62	0.40	0.41	0.44	0.44				
MgO	40.5	26.2	41.1	26.3	41.4	27.7	43.7	29.0	44.8	28.0	44.4	29.7	44.7	28.5				
CaO	0.42	4.9	0.42	4.7	0.37	2.20	0.26	1.35	0.34	5.3	0.34	2.38	0.29	4.1				
Na ₂ O	—	0.08	—	0.05	—	0.05	—	0.05	—	0.04	—	0.05	—	0.05				
Total	100.55	100.20	100.84	99.95	101.87	99.29	100.90	99.28	100.81	100.61	101.02	99.19	100.07	98.78				

ND=not detected; —=not determined.

UREILITES: ORIGIN AS CUMULATES

Berkley, J.L. et al.

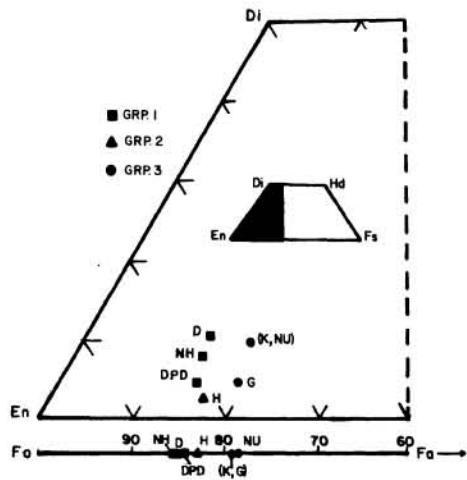


Fig. 1. Pyroxene quadrilateral plot and olivine compositions in ureilites. Dark area in inset shows area of quadrilateral used.

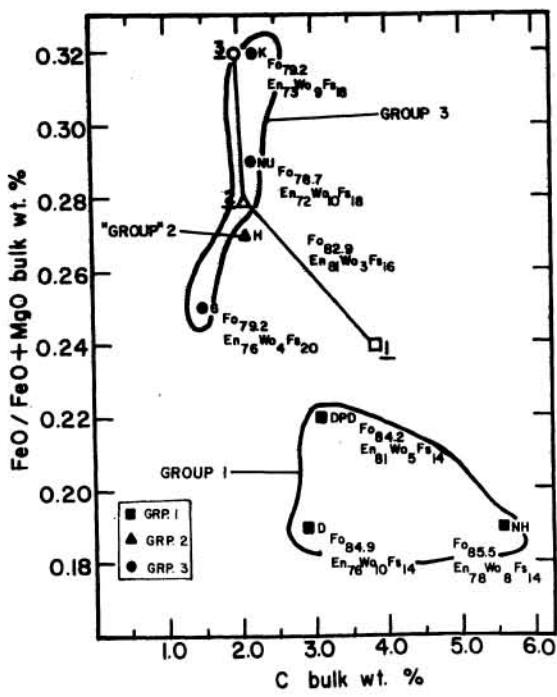


Fig. 2. Filled symbols are normalized values from literature to exclude non-oxides. Open symbols are average group values calculated using modal ol/px and mineral chem. to compute the composition of the bulk silicate portion before reduction.