ELECTRON BACKSCATTER DIFFRACTION (EBSD) ANALYSIS OF UREILITES NORTHWEST AFRICA 11993, 12433, 7630 and 7304: CLUES TO PETROGENESIS FROM DEFORMATION-THERMAL PARAMETERS AND ROCK FABRICS. J. K. Frye[1] and A. M. Ruzicka[1], [1]Department of Geology and Cascadia Meteorite Laboratory, Portland State University, Portland, Oregon 97201, USA. jfrye@pdx.edu.

Introduction: Ureilites are variably shock-deformed olivine-pyroxene achondrites typified by coarse (up to ~1 mm across) olivine and pigeonite and interstitial C-rich domains that include various C polytypes, with FeO-poor reduction rims often developed in olivine adjacent to the C-rich domains [1]. They are thought to have been derived from the mantle of a single differentiated planetesimal that was heated by ^{26}Al decay [2] and that was collisionally disrupted while partly molten [2,3,4]. The mantle equilibration temperature at the time of impact is well-constrained to be ~1200-1300 °C based on 2-pyroxene and olivine-pigeonite thermometry of grain cores [4]. Subsequent cooling rates were fast, of order ~0.05-15 °C/hr, based on zoning profiles across FeO-reduction rims in olivine and spinodal decomposition textures in pyroxene [1,4]. Ureilites often have fabrics that might be the result of cumulate or deformation processes [1,5,6]. However, the characteristics, nature, and significance of deformation and fabrics in ureilites are not yet fully established. The purpose of this study was to better characterize deformation and fabric properties of ureilites, and to test the model of catastrophic disruption, through Electron Backscatter Diffraction (EBSD) analysis.

Methods and Samples: A Leica DM2500 petrographic microscope was used to study nine thin sections of different ureilites from Northwest Africa (NWA) to characterize conventional shock stages [7] and weighted shock stages [8] based on olivine, from which four ureilites were selected for SEM-EBSD study. Of those selected, three (NWA 11993, 12433, 7630) have "typical" textures, whereas the fourth, NWA 7304, has olivine with recrystallized domains and a petrographic lineation composed of coarser and finer domains [9]. The three typical ureilites are relatively ferroan, with Fa ~21-23 olivine and Fs ~17-19 pigeonite, and NWA 7304 is slightly more ferroan (Fa~24, Fs~26) [9]. For SEM analysis, thin sections were hand-polished with a colloidal silica solution for ~60-65 minutes and after drying coated with ~5 nm of C. A Zeiss Sigma VP-FEG-SEM with an Oxford Instruments Symmetry EBSD detector and high sensitivity UltimMax 65 EDS detector at Portland State University was used to acquire EBSD and EDS data for the four ureilites. Data were processed using Oxford Instruments AztecCrystal software and analyzed using methods similar to those previously used for type 6 ordinary chondrites [10,11]. EBSD deformation metrics were determined for olivine and pigeonite including (1) mean Grain Orientation Spread (*GOS*, the average misorientation within a grain), which is a robust metric for deformation intensity; (2) *GOS* skewness (*Sk* = mean/median *GOS*), which is a measure of deformation heterogeneity and which can constrain post-deformation annealing; and (3) $R_{2\text{-}10}$, related to the relative directions of 2-10° rotation misorientations in an olivine crystal frame, which in turn is related to deformation slip system, and which can constrain deformation temperature [10,11]. Thus, for the catastrophic disruption model, *Sk* should be low (rapid post-deformation cooling with minimal annealing) and $R_{2\text{-}10}$ high (high deformation temperature). For olivine and pigeonite, fabric analysis was performed using pole figure plots (1 point per grain) to evaluate lattice preferred orientation (LPO), and the long axes of grains were used to evaluate shape preferred orientation (SPO). Data were analyzed in subsets for coarser and finer fractions in each ureilite, corresponding in the normal-textured ureilites to phenocrysts (coarse fraction), and interstitial regions that included reduction rims (fine fraction), and in NWA 7304 to the coarser and finer fraction of recrystallized grains.

Shock Stages: Conventional shock stages for the three normal-textured ureilites range from S3 for NWA 7630 (weighted shock stage S2.9±0.7) to S4 for NWA 11993 (S3.5±0.6) and NWA 12433 (S4.1±0.6). NWA 7304 is S6 (S6.0).

Deformation-thermal EBSD Metrics: Fig 1 shows olivine ureilite data compared to type 6 ordinary chondrites based on large area maps [10,11]. As *GOS* and likely *GOS* skewness are grain-size dependent [10], and ureilites and chondrites have different grain sizes, we show data for *GOS*, *Sk*, and $R_{2\text{-}10}$ as a function of mean grain size *d*, where *d* = diameter in microns of a circular grain with the same grain area as measured. Grain size distributions for olivine and pigeonite in the four ureilites have inflections at different values of *d* (~120, ~70, ~140, and ~15 µm) for NWA 11993, 12433, 7630, and 7304, respectively, which we take as the dividing line between the coarse and fine fractions. Mean olivine *GOS* values are surprisingly low (~1-2°) for the ureilites (Fig. 1a) and are not strongly related to shock stage. This is unlike type 6 chondrites in which olivine mean *GOS* and weighted shock stage correlate [10,11]. The three normal-textured ureilites have low *Sk* values, suggestive of minimal annealing following deformation (Fig. 1b). NWA 7304, in contrast, has very high *GOS* skewness for both coarser and finer grains (Fig. 1b). This is caused by somewhat incomplete recrystallization, not by annealing, as evident by having high skew even for fine grains. $R_{2\text{-}10}$ values for ureilite olivine are mostly elevated and consistent with "warm-shock" conditions (such as for chondrites shocked while at elevated temperature) (Fig. 1c). However, the $R_{2\text{-}10}$ values are not the same between different ureilites and not always the same between coarse and fine fractions (Fig. 1c). The coarse fraction of NWA 11993 gives the highest $R_{2\text{-}10}$ value yet measured in our lab (Fig. 1c), which could correspond to deformation at magmatic temperatures.

Fabrics: The three normal-textured ureilites have similar LPO patterns that can be described as a strong lineation in <001>, with foliations in {100} and {010} that have embedded lineations. In two of the three ureilites (NWA 12433 and NWA 7630) the trace of the <001> lineation is roughly parallel to the SPO for long grain axes of olivine, which could be taken as evidence for alignment of crystals in a flow regime, and which is not at all what one would expect for crystal settling [12]. In NWA 7304, by contrast, the trace of <100> is aligned with the textural lineation of coarser and finer recrystallized domains, which could be taken as evidence for the importance of *a*-type slip, as expected for deformation at elevated temperature [13].

Assessment: The petrogeneses of the three normal-textured ureilites and NWA 7304 were clearly different. The latter is interpreted as having experienced a strong shock-induced deformation and reheating that completely overprinted the original formation conditions, including texture and fabric. In contrast, the properties of the three normal-textured ureilites can be interpreted as reflecting processes that occurred in the ureilite parent body mantle prior to catastrophic disruption (fabrics?) and as a result of the catastrophic disruption (deformation-thermal metrics). All three normal ureilites show evidence for rapid cooling and minimal annealing, consistent with the catastrophic disruption model. All have evidence for deformation at elevated temperature, but only one (NWA 11993) shows evidence for deformation at temperatures clearly higher than for chondrites that could correspond to magmatic conditions. For NWA 12433 and 7630, the modest $R_{2\text{-}10}$ values can be interpreted as reflecting deformation at subsolidus temperature, or perhaps more plausibly, as reflecting deformation under conditions in which some factor other than temperature affected slip systems. Further study of ureilites investigating the reasons for $R_{2\text{-}10}$ variations are warranted.

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Fig. 1. EBSD-derived metrics (large area map data) for olivine in the coarse and fine fractions of four ureilites compared to type 6 ordinary chondrites [10, 11].