RYUGU AND THE QUEST FOR UNALTERED CI-LIKE MATERIALS FROM THE EARLY SOLAR SYSTEM. C. A. Goodrich[1], S. Lee[2], P. Mane[1], V. E. Hamilton[3], M. E. Zolensky[4], N. T. Kita[5], R. Harrington[6], and M. J. Jercinovic[7]. [1]Lunar & Planetary Institute, USRA, Houston, TX 77058 USA (goodrich@lpi.usra.edu); [2]Planetary Science Institute, Tucson, AZ 85719 USA; [3]Southwest Research Institute, Boulder, CO 80302 USA; [4]ARES, NASA-JSC, Houston, TX 77058 USA; [5]Wisc-SIMS, University of Wisconsin, Madison, WI 53706 USA; [6]Jacobs/JETS, JSC, Houston, TX 77058 USA; [7]Dept. Geosciences, University of Massachusetts, Amherst, MA 01003 USA.

Introduction: Samples of C-type asteroid (162173) Ryugu returned by the Hayabusa2 mission of JAXA [1-3] have been found to be mineralogically, chemically, and isotopically similar to CI carbonaceous chondrites [3-6]. The rare CI meteorites have bulk chemical compositions closely matching the solar photosphere in all but the most volatile elements, and so are considered to represent the starting composition of the solar system. Paradoxically, however, all known CI have been extensively altered by aqueous fluids (i.e., they are CI1), so that their primary mineralogy, textures, and oxygen isotope compositions have been obscured. Thus, one of the most exciting discoveries from Ryugu samples is that they contain "less-altered" (CI2) areas, which have substantial abundances of anhydrous silicates (olivine and pyroxene) and Ca-Al-rich phases that may be remnants of primordial CI3 materials [4-11]. This discovery has motivated new investigations of CIs that show higher abundances of anhydrous silicate grains than previously recognized [9,12,13]. Such studies are an important step in the search for unaltered CI-like material, a so-called "holy grail" of meteoriticists [14]. To further this goal, we are studying Ryugu samples in the context of a previously unrecognized, potentially Ryugu-like, population of C2 materials that occur as xenoliths in polymict ureilites.

Ryugu sample: We were allocated Ryugu particle C0137 (2.3 mg, 1955 μm max.) by JAXA. The sample was prepared at ARES, JSC by mounting in epoxy, and then ground down in several iterations using diamond paste followed by re-impregnation with low-viscosity epoxy to mitigate plucking. After significant sample area was exposed, it was polished with dry diamond powder and cleaned with dry compressed air. Currently, ~1.7 mm^2 of well-polished sample are exposed. We studied ~20% of this by low-vacuum SEM and EDS at LPI without carbon coating. We then applied ~15 nm of carbon and conducted SEM and EMPA at U. Mass.

CI-Like xenoliths: Polymict ureilites are breccias that represent regolith developed on ureilitic asteroids, and contain numerous types of xenoliths interpreted to be impactor remnants [15-19]. CC xenoliths are especially abundant. They are diverse, but most appear to be CI-like based on mineralogy, chemistry, and/or oxygen isotopes [18-24]. We have surveyed hundreds of CC xenoliths (from few microns to a few cms in size) in >30 sections of polymict ureilites and have identified a population that contain substantial abundances of anhydrous silicates and appear to be CI2. Initial observations show many similarities to the less-altered areas of Ryugu [4-11]. We present first data for two of these xenoliths – clast 25 in Northwest Africa (NWA) 10657_006, and clast 37 in Dar al Gani (DaG) 165.

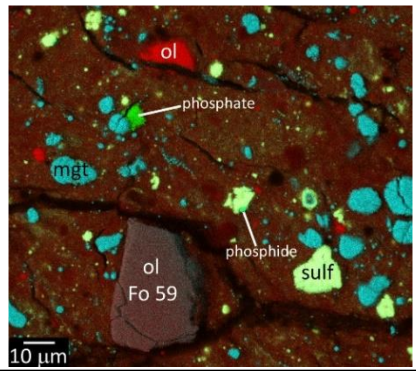

Fig. 1. X-ray map (Mg = red; Fe = cyan; S = yellow; P = green) of Ryugu C0137 showing small grains of forsteritic olivine (red) and a large grain of Fo 59. ol=olivine; mgt=magnetite; sulf=sulfide.

Results: Ryugu C0137 consists of CI1-like material similar to other Ryugu samples [4-6], dominated by Mg-rich phyllosilicates, carbonates (dolomite, breunnerite, rare calcite), magnetite, sulfide, Ca-phosphate, and C-rich globules. In the small fraction of the sample examined so far we observed four discrete areas (up to ~100 μm^2) that show concentrations of anhydrous silicate grains (Fig. 1). These are mostly Mg-rich olivine (Fo 98-99), up to ~10 μm but mostly ≤2 μm in size. One exceptionally large (~25 x 35 μm) and ferroan (Fo 59) grain of olivine was observed (Fig. 1). Ni-rich phosphide (Fig. 1) and small grains of pyroxene occur in these areas. Major and minor element (Mn, Ca, Cr) compositions of olivines (e.g., Fig. 2) are within the range of those in other Ryugu samples and CI [4-13].

Clast 25 (NWA 10657_006) has CI-like mineralogy dominated by phyllosilicates, magnetite, sulfide, and carbonate (calcite). It also contains up to ~15% fragments of olivine and minor pyroxene, inferred chondrule fragments, porous aggregates of forsteritic olivine with Ca-Al-rich inclusions (possible AOAs), and grains of spinel and perovskite (Fig. 3). Most olivine grains have rims (phyllosilicates or carbonates?). Matrix in the most olivine-rich areas is relatively FeO-rich (as seen for some Ryugu and CI samples [12,13,25]). Olivines are mainly Fo 98-99 (one grain of Fo 76 was observed) with minor elements (Fig. 2) within the range of those in Ryugu and CI [4-13].

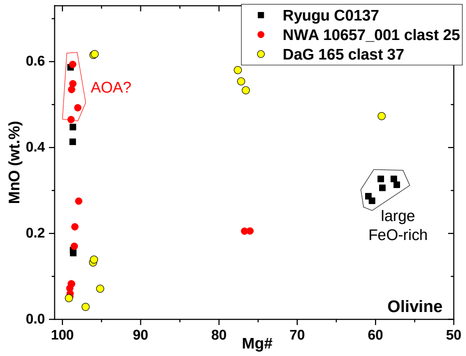

Fig. 2. Compositions of olivine in Ryugu C0137, clast 25 (NWA 10657), and clast 37 (DaG 165).

Clast 37 (DaG 165) is an aggregate of fine-grained anhydrous silicate grains partially embayed by phyllosilicates, with larger grains of magnetite, sulfides, and olivine and pyroxene (Fig. 4). Many of the larger anhydrous silicates are porous, have Ca-Al-rich inclusions (Fig. 4b), and/or show embayed rims. Olivines range from Fo 97-59, with minor elements similar to those in Ryugu, clast 25, and CI (Fig. 2 and [4-13]). Pyroxenes include enstatite (Mg #99, Wo 0.04), and compositions with Mg# 95-85 and Wo 2-27.

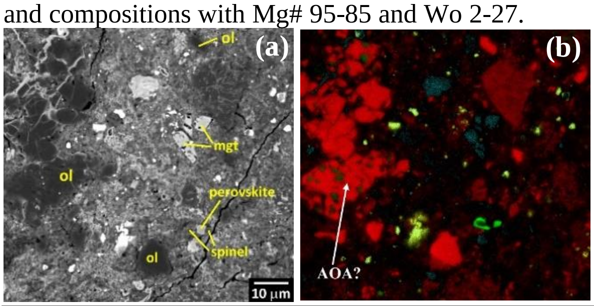

Fig. 3. (a) BEI and (b) corresponding X-ray map (Mg=red; Al=green; Fe=cyan; S=yellow) of clast 25 in polymict ureilite NWA 10657_006.

Discussion: Ryugu C0137 is likely to contain subtantial amounts of anhydrous silicates [10]. We will study the entire particle by progressive polishing, using FIB/TEM to analyze tiny anhydrous grains and SIMS/NanoSIMS to determine their O-isotope compositions. These data will be used to constrain the ratio of refractory materials vs. chondrules in Ryugu's protolith (e.g. [26]). FeO-rich olivines (e.g., Fig. 1) will be used to evaluate cometary origins (e.g., [27]).

CC xenoliths in polymict ureilites offer a rich source of unexplored CI-like materials, possibly even preserved CI3s [14]. These xenoliths were implanted into regolith on ureilitic asteroids in the inner solar system ~50 Myr after CAI [18,19], and may represent a different population(s) from CI arriving at Earth today. The anhydrous silicates and Ca-Al-rich phases in the C2 xenoliths that we have identified show intriguing similarities to less-altered areas of Ryugu. Oxygen isotopes in magnetite in clast 37 showed $\Delta^{17}O$ of ~5‰ [28], higher than in Ryugu [4,29,30], suggesting less alteration. Our studies of these xenoliths will test their similarity to Ryugu. Establishing a genetic relationship between Ryugu and xenoliths in polymict ureilites would provide direct evidence that Ryugu's progenitor was in the inner solar system at ~50 Myr after CAI.

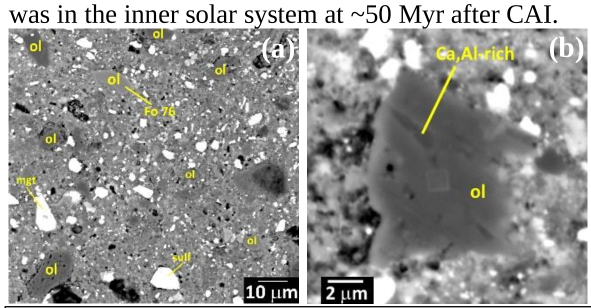

Fig. 4. BEI of clast 37 in polymict ureilite DaG 165. (a) Matrix is an aggregate of tiny anhydrous silicates embayed by phyllosilicates. (b) Olivine with inclusions of Ca,Al-rich phase(s). Square is FIB mark in preparation for SIMS O-isotope analysis.

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