COMPARISON OF RYUGU PARTICLES WITH IDPS AND COMET SAMPLES. D. E. Brownlee1, D. J. Joswiak1, T. Nakamura2, T. Morita2, M. Kikuri2, K. Amano2, E. Kagawa2, H. Yurimoto3, T. Noguchi4, R. Okazaki5, H. Yabuta5, H. Naraoka5, K. Sakamoto5, S. Tachibana6,8, S.-I. Watanabe9, and Y. Tsuchi7. 1Dept. of Astronomy, University of Washington, Seattle, WA 98195, USA (brownlee@astro.washington.edu). 2Tohoku University, Sendai 980-8578, Japan, 3Hokkaido University, Sapporo 060-0810, Japan, 4Kyoto University, Kyoto 606-8502, Japan, 5Kyushu University, Fukuoka 812-8581, Japan, 6Hiroshima University, Higashi-Hiroshima 739-8526, Japan, 7ISAS/JAXA, Sagamihara 252-5210, Japan, 8The University of Tokyo, Tokyo 113-0033, Japan, 9Nagoya University, Nagoya 464-8601, Japan.

Introduction: To mineralogically compare Ryugu particles with IDPs and comet samples, we did a TEM-based survey of 100 Ryugu particles collected during the second touch-down sampling by Hayabusa2, at the artificial impact crater. These particles stuck to a window used in reflectance spectral measurements of the C0107 aggregate sample and were extracted and concentrated using a custom “rubber stamp” made of Sylgard 184. This collection is likely a representative sampling of ~50µm particles near Ryugu’s surface and characteristic of IDP-sized particles that this C asteroid ejects into interplanetary space. We embedded all particles in epoxy, cut microtome sections and studied the sections and potted butts with the TEM/SEM min/pet methods that we use for studying similar size IDPs as well as Wild 2 comet samples returned by the Stardust mission.

We found that Ryugu particles, up to 150µm, microtome beautifully in 50 nm sections and provide excellent TEM samples. Carbonates showed significant plucking but this issue was solved by “painting” a thin collodion film on the cut face before each slice was cut. The mass of Ryugu samples in this study exceeds the total mass of all the stratospheric IDPs and Wild 2 comet particles that have been studied by TEM and these results provide a basis for comparison of Ryugu with comet samples and common IDPs.

Composition: To first order, all of the particles were similar mixes of abundant sulfides, magnetite, carbonates and apatite embedded in a Mg-rich smectite/serpentine matrix. Lesser phases include phyllosilicates, carbon nanoglobules and chromite. In our samples, anhydrous silicates were very rare. Tochilinite, cronstedite, metal and glass were not observed. The similarity among randomly selected particles seemed quite striking when compared to chondritic composition stratospheric IDPs. At the 50µm scale, most particles have distinctive properties and are unusually similar to each compared to the diverse range of collected IDPs, even those dominated by phyllosilicates. Ryugu is dramatically different from comet Wild 2 samples and chondritic porous (CP) IDPs that are uncompacted aggregates of diverse anhydrous components whose elemental and isotopic compositions imply derivation from multiple solar system and pre-solar system sources.

Comparison with hydrated IDPs: The high phyllosilicate abundance of Ryugu and comparatively compact structure is generally similar to hydrated IDPs that are also compact and dominated by phyllosilicates. These often are called CS IDPs because they frequently have smooth surfaces at the micron scale and are fundamentally distinct from CPs. CS types can presumably be formed by aqueous alteration of CP’s but CP’s could not be made from typical CS particles. There are several types of CS IDPs but their distinction is not well defined. Tomoeoka [1] described two main groups: smectite dominated and serpentine dominated, but this is complicated by the likelihood that both types contain smectite/serpentine intergrowths. Some CS particles contain tochilinite and cronstedite, common phases in some CMs but not yet seen (by us) in Ryugu. Many and probably most CS IDPs also contain anhydrous silicates including preserved condensates like LIME forsterite, isotopically anomalous presolar silicate grains, as well as chondrule, and refractory inclusion fragments that are more abundant in CP and comet particles. This appears to be a strong distinction from Ryugu. Some CS IDPs contain magnetite framboids and plaquettes that appear identical to those in Ryugu. They also contain carbonates but it is not apparent that many contain as much dolomite as Ryugu. Ryugu phyllosilicates Mg-rich than those in typical CS IDPs.

At this point in time, it can be said that Ryugu has affinity with hydrated IDP types, but how well this match can be made is to be determined. It is important to understand how Ryugu fits in with CS particles because this will provide a clue to how Ryugu compares to other CI-like materials that formed in the early solar system and survived. Once a good knowledge of the full nature of micron and submicron Ryugu components is determined, this can be used as an excellent base for comparison with CS IDPs. Good comparison with IDPs will probably require focused study of a broad set of hydrated IDPs.

Detailed Mineralogical Composition: We observed two large-scale phyllosilicate morphologies in Ryugu: 1) a dominant host material composed of a mixture of Mg-rich serpentine and saponite hosting abundant Fe,Ni sulfides and 2) discrete serpentine+saponite objects (that we informally called ‘pods’) which were
devoid of sulfides and magnetites but were mineralogically and chemically similar to their host phyllosilicates. The pods, which vary in shape from round to irregular may be pseudomorphs of previous mineral or rock grains or other objects. The lack of sulfides in the pods may be a result of the pre-pseudomorphed minerals not chemically incorporating sulfur species during fluxing of the aqueous fluids. This would result if silicates, for instance, were the host minerals because sulfur would not chemically bond to these phases. Similar, but larger objects were reported in the CM chondrite Murchison where chondrules were pseudomorphed by phyllosilicates from extreme aqueous alteration [2]. The Ryugu phyllosilicates are composed of Mg-rich serpentine and saponite and on a Mg-Fe-Si+Al ternary diagram they most closely resemble the Mg-rich members of CM chondrites and Tagish Lake [3]. They are Fe poor compared to their counterparts in CS IDPs.

Carbonates: Dolomite was the most common carbonate that we observed. Ryugu breunnerites – solid solutions of magnesite and siderite – were rich in MnO with concentrations up to 17.7 wt%. Although we did not observe calcite in any TEM sections, an SEM study suggests that small amounts may be present. The Ryugu carbonate compositions are similar to carbonates in both CM and CI chondrites but are dissimilar to those in Tagish Lake which are richer in Fe and poorer in Mn [3].

Magnetite, sulfide and phosphide: Magnetite is common and we found framboideal, spherical and plaquette morphologies as well as sprays. Fe sulfides were also common including Fe,Ni pyrrhotite and pentlandite. We occasionally observed low-Ni sulfides but were uncertain whether these sulfides were troilites or pyrrhotites. Pyrrhotites were anhedral to euhedral grains ranging from submicron to 10’s of microns.

We observed at least one occurrence of Fe,Ni phosphate. The phosphate – (Fe,Ni)₃PO₄ – is compositionally equivalent to barringerite or allabogdanite and was found on the rim of a pod phyllosilicate in association with pyrrhotite, pentlandite and a Mn-rich chromite. The ~10-20 nm-size crystals along with their petrographic occurrence suggest this phase is a secondary product, perhaps from alteration of a P-bearing phase that was previously present in the adjacent pod phyllosilicate. The phosphate in Ryugu is a subequal mixture of Fe and Ni and contains > 2 wt% CoO and as such is compositionally similar to the high-Ni phosphides of the CM chondrites.

Apatite: The most common P phase was subhedral to euhedral apatite often associated with sulfides. The Ryugu apatites contain up to ~1 wt% fluorine (F) but Cl was not detected. This seems unusual in that small amounts of Cl, but no F, were found in our phyllosilicate analyses. In one apatite we observed numerous submicron, rounded Mg,Al-rich chromites. These were also observed in adjacent phyllosilicates and are believed to be alteration phases.

Anhydrous silicates: Anhydrous silicates were rare, an important distinction from comet samples and primitive IDPs with the highest presolar grain abundances. We found single occurrences of olivine and low-Ca pyroxene. The olivine, found in host phyllosilicate matrix, was a LIME forsterite with Mg# 99.8 and MnO abundance of 1.2 wt%. LIME forsterites are believed to be condensates and are found in IDPs, Wild 2 and chondrites. Texturally the forsterite was in sharp contact with phyllosilicate matrix and did not appear to show any chemical reaction with the matrix. These observations suggest that the LIME forsterite is a primary relict grain that was not altered like most of the Ryugu materials. This may indicate that the olivine accreted to Ryugu after the alteration took place on the Ryugu parent body. The ~1x3 µm low-Ca pyroxene that we observed is Fe-rich (En₉₅Wo₀₅₉) and varies from well-crystalline on one end to partially amorphous on the other. Its Fe/Mg ratio is identical to the Fe/Mg ratio of its host phyllosilicates. These suggest that this pyroxene was partially modified by aqueous alteration on Ryugu.

Numerous submicron carbon nanoglobules were found, always occurring in phyllosilicate matrix. If these are like IDP nanoglobules they would be isotopically distinct from matrix and would presumably predate matrix.

Overall, our observations suggest that the samples we studied underwent extreme aqueous alteration. This is supported by the Mg-rich phyllosilicates, abundance of magnetite, Ni-rich pyrrhotite, chemically complex carbonates, low anhydrous silicate abundance and the pseudomorphed objects (pods). Additionally, it appears that the Ryugu samples experienced minimal thermal metamorphism as indicated by the phyllosilicate morphologies which do not show heating effects, lack of recrystallized secondary olivine, the presence of nanoglobules and the high Cr abundance in the single forsterite observed. The only original components that we saw that appear to have survived parentbody processing inside Ryugu were the nanoglobules and a LIME olivine grain.

The Ryugu results provide a strong rationale for a coordinated analysis program on CS IDPs that also contain abundant Mg-rich smectite, dolomite and the most common Ryugu phases. This effort would provide new insights of the abundance of Ryugu-like materials in the early solar system.