MINERALOGY AND CRYSTALLOGRAPHY OF SOME ITOKAWA PARTICLES RETURNED BY THE HAYABUSA MISSION. T. Mikouchi[1], M. Komatsu[2], K. Hagiya[3], K. Ohsumi[4], M. Zolensky[5], V. Hoffmann[6,7], J. Martinez[5], R. Hochleitner[8], M. Kaliwoda[8], Y. Terada[4], N. Yagi[4], M. Takata[4], W. Satake[1], Y. Aoyagi[1], A. Takenouchi[1], Y. Karouji[9], M. Uesugi[9], T. Yada[9], M. Miyamoto[1], [1]University of Tokyo, [2]Waseda University, [3]University of Hyogo, [4]JASRI, [5]NASA-JSC, [6]University of München, [7]University of Tübingen, [8]Mineral. State Collection, Munich, [9]JAXA-ISAS. E-mail: mikouchi@eps.s.u-tokyo.ac.jp.

Introduction: JAXA Hayabusa mission successfully returned particles of the asteroid Itokawa to the earth in 2010. The recovered particles were carefully studied by the preliminary examination (PE) team and the obtained results are providing significant and unique information about the formation and evolution of meteorite parent bodies [1-6]. These particles further revealed that their mineral compositions and oxygen isotopes are close to those of equilibrated LL chondrites [1,2], which matches with the observation at the orbit [7]. After the PE, JAXA distributed the samples as international AO study and we received 4 new and 3 PE particles. The new samples may contain some exotic components that have not been found by the PE study, and are of special interest. We have performed a detailed mineralogical and crystallographic study on these particles and here report the results.

Samples and Methods: The PE samples we received are: RA-QD02-0036, RA-QD02-0041 and RA-QD02-0049-2. RA-QD02-0036 and RA-QD02-0041 are polished sections embedded in epoxy. RA-QD02-0049-2 is attached on the glass fiber. The additionally received new particles are RA-QD02-0100 (~29 μm), RA-QD02-0133-01 (~53 μm), RA-QD02-0138 (~49 μm), and RA-QD02-0179 (~50 μm). We made polished sections after we embedded them in epoxy (EPON812) at JAXA.

The polished sections were first observed by optical microscope, and then analyzed by FEG-SEM equipped with EBSD detectors (Hitachi S-4500 and Zeiss Supra 55VP Schottki), electron microprobe (JEOL JXA8900L), and micro-Raman spectrometer (Horiba Xplora). The polished sections and RA-QD02-0049-2 were also analyzed by synchrotron radiation (SR) XRD by using an energy scanning method (BL37XU, SPring-8) [8]. We performed SR Fe-XANES on plagioclase in RA-QD02-100 and RA-QD02-133-1 to determine the presence of Fe^{3+} (BL-4A, PF, KEK).

Results: The optical microscopic observation revealed that most particles were composed of single crystals. We estimated that shock degrees of all samples are roughly S2 because of the presence of minor undulatory extinction of olivine and plagioclase. However, the samples are much smaller than the regular thin section used for shock degree estimate, and may bear some uncertainty.

RA-QD02-0036: This PE particle is composed of olivine and plagioclase. We analyzed both phases by SR-XRD. The obtained diffraction patterns are sharp and we obtained the following cell dimensions. Olivine: a=4.7788(9)Å, b=10.271(4)Å, c=6.0167(8)Å. These values give the forsterite content of $Fo_{67.2}$, $Fo_{73.7}$, and $Fo_{68.0}$, respectively by the Vegard's law [9] and the average value ($Fo_{68.9}$) is close to the value obtained by electron microprobe. The analyzed plagioclase grain gives the cell dimensions of a=8.180(4)Å, b=12.53(9)Å, c=7.125(3)Å, α=93.00(18)°, β=116.36(5)°, γ=90.17(17)° (Fig. 1) Raman analysis confirmed the presence of olivine and plagioclase.

RA-QD02-0041: This PE particle is a single olivine crystal with accessory plagioclase. There is a ~5 μm hole near the center by ion probe measurement [2]. The olivine composition is Fo_{71}. The EBSD mapping of the surface showed that Kikuchi patterns from almost all areas could be well indexed by the olivine structure.

RA-QD02-0049-2: We analyzed this particle only by SR-XRD. We spotted several different areas of the particle, but the obtained diffraction patterns were identical everywhere, suggesting that it is a single crystal. The obtained patterns were indexed by olivine as the following cell dimensions: a=4.7842(15)Å, b=10.289(2)Å, c=6.018(2)Å. The Vegard's law gives the olivine composition of Fo_{64} [8].

The chemical compositions of minerals in the following new particles are summarized in Table 1.

RA-QD02-100: This is the smallest particle among the samples we received. It is composed of polycrystalline plagioclase grains up to 10 μm with a trace amount of olivine. The chemical composition of plagioclase is $An_{82-84}Or_5$. The Fe XANES analysis of plagioclase indicates that Fe^{3+} is surely present ($Fe^{3+}/\Sigma Fe$: ~0.5).

RA-QD02-133-1: This particle is composed of subequal amounts of olivine and plagioclase (Fig. 2). Submicron-sized Ca phosphate was present. Olivine and plagioclase are contacted by the sharp boundary. Olivine is Fo_{71-70} with ~0.4 wt% MnO. Plagioclase is $An_{81-84}Or_{6-7}$. We performed SR Fe-XANES analysis on plagioclase in this particle. The obtained spectrum suggests the presence of minor amounts of Fe^{3+}, but the beam was likely to be overlapped with olivine.

RA-QD02-138: This particle is a single olivine crystal with minor plagioclase. Submicron chromite is also present. Olivine is Fo_{70} with ~0.4 wt% MnO.

RA-QD02-179: This particle is composed of a single crystal of olivine. The olivine composition is Fo_{73} with ~0.4 wt% MnO, which is slightly more magnesian than the other particles. We did not see clear compositional difference in this particle.

Discussion and Conclusion: The analyzed Itokawa particles including new samples are all close to equilibrated LL chondrites in mineral compositions [1]. The presence of Fe^{3+} in plagioclase is consistent with the formation under a slightly oxidizing environment which is also consistent with LL chondrites. Similarly Noguchi et al. [10] reported Fe-XANES analysis of olivine in some Itokawa particles and suggested similarity to Tuxtuac LL5 chondrite.

Because the size of plagioclase crystallites is larger than 2 μm in all samples when plagioclase is present, their petrologic type is ≥5. We did not find any unequilibrated particles as reported in [2] although olivine in RA-QD02-179 has a slightly more Mg-rich composition than the others and is overlapping with the range of unequilibrated particles [2]. The plagioclase crystallography can be used to estimate equilibration temperature [11] and we estimated equilibration temperature of plagioclase in RA-QD02-0036. The Δ131 index of this plagioclase is 1.85° after correction by the anorthite content, showing that equilibration temperature is 780±10 °C. This temperature is slightly higher than 4 particles reported in [1] (RA-QD02-0010: ~570 °C, RA-QD02-0025-01: 560 °C, RA-QD02-0055: ~570 °C, RA-QD02-0067: ~575 °C), but close to RA-QD02-0013 (820 °C).

Unfortunately, no exotic particles were found in this study, but the analyzed Itokawa particles further confirm that they belong to equilibrated LL chondrites with minor shock metamorphism.

References: [1] Nakamura T. et al. (2011) *Science*, *333*, 1113–1116. [2] Yurimoto H. et al. (2011) *Science*, *333*, 1116-1119. [3] Ebihara M. et al. (2011) *Science*, *333*, 1119-1121. [4] Noguchi T. et al. (2011) *Science*, *333*, 1121-1125. [5] Tsuchiyama A. et al. (2011) *Science*, *333*, 1125-1128. [6] Nagao K. et al. (2011) *Science*, *333*, 1128–1131. [7] Fujiwara A. et al. (2006) *Science*, *312*, 1330-1334. [8] Hagiya K. et al. (2010) *Meteoritics & Planet. Sci.*, *45*, Abstract #5083. [9] Akimoto S. and Fujisawa H. (1968) *Jour. of Geophys. Res.*, *73*, 1467–1479. [10] Noguchi T. et al. (2013) *LPS XLIV*, Abstract #1147. [12] Smith J. V. (1972) *Jour. of Geol.*, *80*, 505-525.

Table 1. Average mineral compositions of 4 newly analyzed particles.

	RA-QD02-100	RA-QD02-133-1		RA-QD02-138	RA-QD02-179
	Plagioclase	Olivine	Plagioclase	Olivine	Olivine
SiO_2	63.7	37.0	64.1	37.5	39.6
Al_2O_3	21.7	0.03	21.8	0.01	0.05
TiO_2	0.02	0.02	0.03	0.02	
FeO	0.09	26.3	0.11	26.6	23.5
MnO		0.41	0.02	0.43	0.40
MgO	0.05	34.7	0.02	34.5	36.5
CaO	2.25	0.01	2.25	0.01	0.01
Na_2O	8.75	0.03	8.92	0.04	0.02
K_2O	0.78	0.02	0.99	0.02	
Cr_2O_3		0.01		0.01	0.01
NiO		0.01	0.02	0.01	0.04
P_2O_5	0.02		0.01	0.03	
Total	97.4	98.6	98.3	99.1	100.1
Fo		70.2		69.8	73.4
Fa		29.8		30.1	26.6
An	11.9		11.5		
Ab	83.2		82.4		
Or	4.9		6.1		

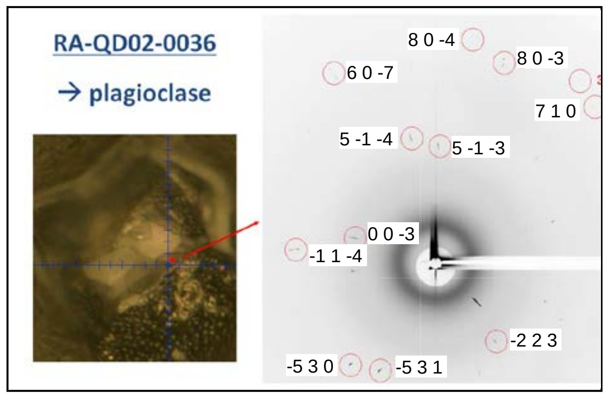

Fig. 1. The obtained SR-XRD pattern from plagioclase in RA-QD02-0036 with indices. The SR beam size was ~1 μm and the energy range was 30-25 keV.

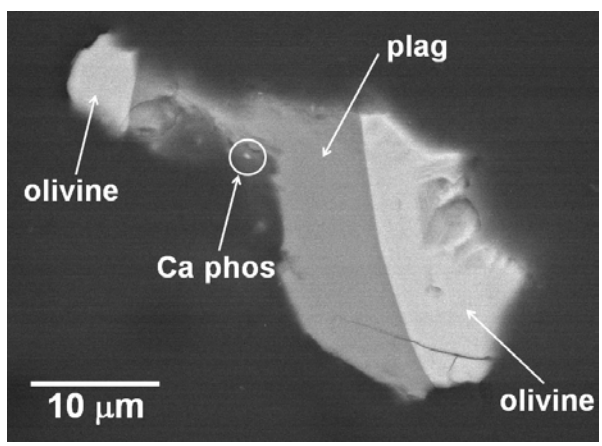

Fig. 2. Back-scattered electron image of RA-QD02-133-1, showing a sharp grain boundary between olivine and plagioclase (plag).