On the relationship between modal abundances of minerals and degrees of aqueous alteration of the brecciated clasts in the Orgueil CI chondrite

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Introduction

CI chondrites are considered to be the most primitive meteorites in the solar system because their abundance in many elements, except for volatiles, matches well with the photosphere chemical composition of the Sun. Recently, it has been reported that samples from the asteroid Ryugu, brought back by JAXA's Hayabusa2 spacecraft, are consistent with the CI chondrite group in terms of chemical and mineralogical characteristics [e.g., 1-2]. CI chondrites are composed mainly of matrix formed by aqueous alteration and the constituent minerals are Mg-Fe phyllosilicates (nanometer-scale alternating layers of serpentine and saponite), magnetite, pyrrhotite, carbonates, phosphate, olivine and pyroxene [e.g., 3]. CI chondrites are petrologically and mineralogically heterogeneous meteorites, known as breccias, composed of clasts of various sizes and lithologies [e.g., 4-5]. Although previous studies have investigated the differences in modal abundance between different meteorites of CI chondrites [5,6], there is insufficient information on the heterogeneity of clasts within individual meteorites. It is considered that the modal abundance of each clast is more important than that of individual meteorites. In this study, we focused on the modal abundance of clasts in Orgueil, which has been reported to be highly brecciated [e.g., 7], and compared the modal abundance of clasts to discuss the degree of heterogeneity and aqueous alteration among clasts, assuming that the samples of the asteroid Ryugu will be compared in the future.

Samples and Methods

The samples are three 1-3 mm sized particles of Orgueil. Elemental mapping of 15 elements (Si, Al, Ti, Fe, Mn, Mg, Ca, Na, K, Cr, P, Ni, S, F, Zn) was performed for each particle using FE-EPMA JXA-8530F (JEOL) at Univ. of Tokyo. From the elemental mapping results obtained by EPMA analysis, the modal abundance was determined using the ImageJ software. The same analysis was also performed for the breccia clasts in each sample.

Results and Discussions

EPMA analysis clearly showed that Orgueil was a brecciated rock composed of clasts ranging from 200 μm to 1 mm. First, the modal abundance for the entire particle was determined for each of the three particles. Accordingly, the modal abundance of Orgueil was as follows: Mg-Fe phyllosilicate, magnetite, and carbonate were present in the Orgueil meteorite, accounting for about 89-93%, 2-3%, and 1-3% respectively, and olivine and pyroxene were extremely rare. The greatest difference among the three particles was sulfate, which varied in abundance from 2 to 7%. This is thought to be related to the degree of brecciation of each particle since sulfate minerals were present along fractures between each breccia clast. The sample has been affected by terrestrial weathering and is not related to aqueous alteration that the sample originally underwent in its parent body. When the modal abundances of these 3 Orgueil particles are compared to those in previous studies [5-7], it can be seen that our Orgueil samples contain considerably less magnetite and pyrrhotite compared to previous studies. On the other hand, the Orgueil meteorite used in this study is presumed to have been considerably affected by terrestrial weathering, since it contains considerable sulfate although previous reports contain little sulfate [e.g., 5].

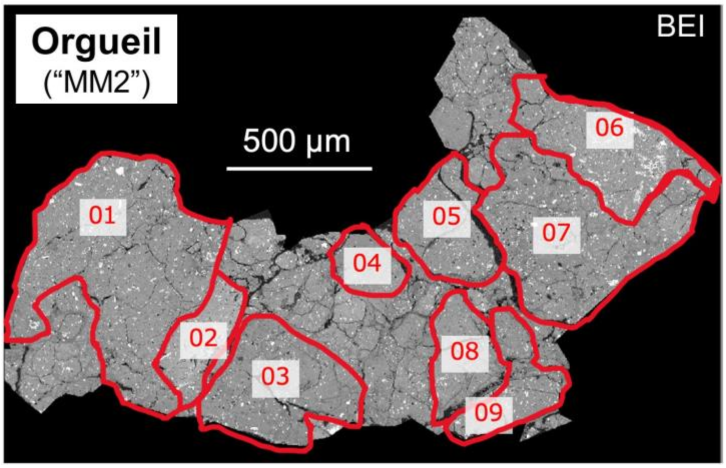

Fig. 1. Nine breccia clasts identified in one of the Orgueil particles studied ("MM2").

In our three particles we could identify totally 21 breccia clasts clearly showing boundaries against surrounding clasts (Fig. 1) and the modal abundance of these clasts were determined in the same way as for the three particles. The obtained mineral mode composition of Mg-Fe phyllosilicates did not differ significantly from that of the three particles, but the abundance of other minerals slightly varied from clast to clast. Magnetite was estimated to be present on average in the clasts of the Orgueil meteorite at 2-3%, but showed a range of abundance from nearly 7% when relatively abundant to nearly 0.8% when not so abundant. When olivine and pyroxene are present in the clasts, the magnetite content also tends to be below average, but it was not so obvious. The analytical results for pyrrhotite indicated that it was not abundant in any of the constituent clasts. Pyrrotite is known to be the most susceptible to weathering when Orgueil was weathered on Earth and has likely been converted to sulfate [e.g., 4,7]. Therefore, it is likely that pyrrhotite did form by aqueous alteration on the parent body and was more abundant before falling to Earth than now. Carbonates were analyzed separately as Ca carbonate, Mg-Fe carbonate (breunnerite), and Ca-Mg carbonate (dolomite), and in the samples observed in this study, carbonates are almost exclusively found as dolomite. Carbonates are known to change to Ca carbonate, dolomite, and breunnerite as aqueous alteration progresses [2,8], but since most of the observed carbonates were dolomite, the aqueous alteration that this sample underwent in the parent body is considered to have been moderate. In fact, it has been reported that the most common lithology in the Ryugu sample also contains dolomite as a major carbonate phase, with only a few lithologies containing Ca carbonate or breunnerite [2]. Dolomite, when combined with quantitative analysis, may be related to the degree of aqueous alteration, as has been done for the Ryugu samples [2]. There is a clear positive correlation between the abundance of dolomite (0→ 2%) and Ca phosphate (0→0.6%) when the dolomite abundance is less than 2%. However, when the dolomite abundance exceeds 2%, the Ca phosphate abundance becomes less than 0.2%. This may imply that Ca phosphate started dissolving at some point during progressive aqueous alteration. In all clasts, phyllosilicates comprise 90% of the total, but since specific quantitative analysis of phyllosilicates has not yet been conducted, it is difficult to argue that the morphology or abundance of phyllosilicates may have changed depending on the degree of aqueous alteration.

Conclusion

Since the Ryugu samples have not been affected by terrestrial weathering, it is important to consider the effects of terrestrial weathering on CI chondrites when comparing CI chondrite samples and Ryugu samples. In addition, it was found that CI chondrites may reflect different properties and different degrees of aqueous alteration in different clasts. Therefore, it is expected that future studies of CI chondrites and Ryugu samples will focus not only on the entire sample, but also on each brecciated clast.

Table 1. Modal abundances of minereals in different clasts in three Orgueil particles (“MM1”, “MM2” and “MM3”).

	MM1_01	MM1_02	MM1_03	MM1_04	MM2_01	MM2_02	MM2_03	MM2_04	MM2_05	MM2_06
Phyllosilicate	96.32	95.43	93.82	93.90	94.10	95.53	94.44	99.11	96.50	92.62
Magnetite	1.56	3.73	3.66	2.78	2.43	3.96	2.85	0.89	2.30	6.61
Pyrrhotite	1.69	0.07	0.14	0.13	0.15	0.26	0.05	—	—	0.12
Dolomite	0.33	0.54	1.79	3.19	1.66	0.21	2.53	—	0.89	0.64
Bruennerite	—	—	—	—	—	—	—	—	—	—
Ca carbonate	—	—	—	—	—	—	—	—	—	—
Ca phosphate	0.10	0.21	0.59	0.00	1.66	0.04	0.14	—	0.31	0.01
Olivine+pyroxene	—	0.03	—	—	—	—	—	—	—	—

MM2_07	MM2_08	MM2_09	MM3_01	MM3_02	MM3_03	MM3_04	MM3_05	MM3_06	MM3_07	MM3_08
93.29	98.08	95.50	95.87	99.10	96.63	96.66	97.10	96.70	96.65	98.45
2.83	1.85	2.68	3.15	0.83	1.82	2.67	2.05	3.11	1.40	1.10
0.02	—	1.06	0.01	—	0.02	0.00	0.01	—	—	—
3.72	0.07	0.72	0.92	—	1.15	0.41	0.44	0.14	0.43	0.41
—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—
0.13	—	0.04	0.04	—	0.39	0.26	0.40	0.05	—	—
—	—	—	0.01	0.07	—	—	—	—	1.52	0.04

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