Eclogitic clasts found in NWA 801 CR2 chondrite: Formation of high pressure minerals in deep interior of a Moon-sized planetesimal.

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Introduction:

Eclogitic clasts found in the NWA 801 CR2 chondrite (Figs. 1 and 2) has significant importance in planetary sciences, because such an eclogitic mineral assemblage (including garnet and omphacite) has never been found previously in meteorites [1]. It is also interesting that one of the two lithologies contains lath-shaped graphite (graphite-bearing lithology; GBL), suggesting some affinity to ureilites. The estimated formation condition of the clasts is ~3 GPa and ~1000 ^{o}C, but the origin of the high *P-T* condition has not yet been clarified by mineralogical study only [1], either it is due to shock loading or static pressure in deep interior of a large planetesimal. In the present study, based on newly obtained ion microprobe data of O isotopes and REE abundances, combined with detailed diffusion calculations and mineralogy and bulk chemistry, we examined the two possibilities in detail. We couclude that the clasts probably came from deep interior of a Moon-sized planetesimal. Preliminary O and REE data were presented before [2] and details of the discussion given here will be seen elsewhere [3]. Here we present several important points of our discussion for help in understanding the formation history of the unique clasts and their implications to the early history of the solar system.

Summary of the results:

Analytical conditions for ion microprobe analyses of O and REEs are given in [3] and briefly in [2]. The followings are the summary of the results.

(1) Incompatible elements (except for P and REEs) are enriched in GFL (graphite-free lithology) but depleted in GBL, suggesting their gain or loss of a melt (or a fluid) component, respectively.

(2) Similarity in the presence of high pressure minerals (garnet and omphacite) in spite of the clear chemical and mineralogical contrast between GBL and GFL suggests that (i) the high *P-T* event occurred *after* GBL and GFL became juxtaposed and (ii) the high *P-T* event did not erase the mineral/chemical contrast between the two lithologies.

(3) Phosphorous and REEs, in contrast, are not much fractionated between GBL and GFL, suggesting their redistribution in a later heating event (either the high *P-T* event or a later metamorphism).

(4) Major element abundances, Mn/Mg ratio, and bulk REE abundances as well, show almost no fractionation. This suggests that planetary-scale differentiation did not occur on their parent body.

(5) The Fe/Mg ratios in olivine and most of opx (except for a few large grains) are almost homogeneous. This indicates that equilibration of Fe/Mg ratio occurred at a high temperature, either in the high *P-T* event, or in a later metamorphic event.

(6) Oxygen isotopic compositions are homogeneous in GFL but highly variable in GBL and all the data are plotted on a single correlation line with a slope of ~0.6, slightly below the data fields of CH-CB-CR chondrites.

(7) A set of conventional geothermobarometers (7 formulas for 4 mineral pairs of opx-cpx, gar-ol, gar-opx, gar-cpx) consistently indicate a high *P-T* condition of ~1000 ^{o}C and ~3 GPa for the formation of the clasts [1].

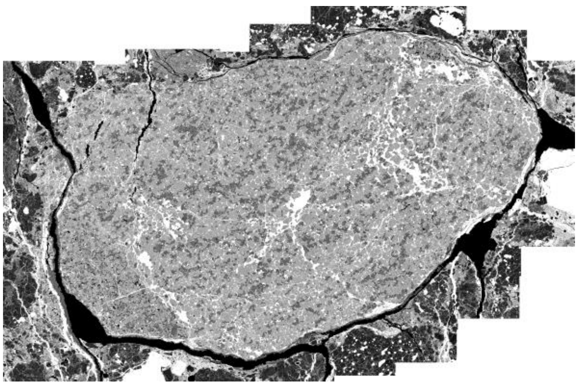

Fig.1 A backscattered electron image of an eclogitic clast (#2) found in the NWA 801 chondrite. The central part is GFL and small areas on the upper right and lower left corners are GBL.

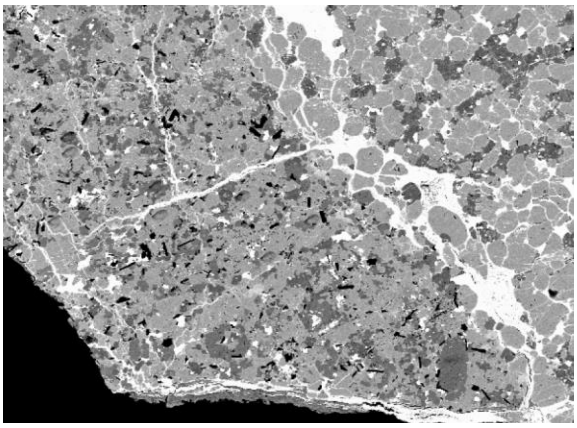

Fig.2 An enlarged view of the lower left corner of Fig. 1. Lath-shaped graphite (black grains) can be seen in the GBL area.

Discussion:

In order to explain the above observations, we conducted detailed diffusion calculations. Important results and discussions are as follows.

Formation of garnet of ~30 µm size in a silicate melt is very difficult [4] in a short duration of a shock event (typically <10 seconds) [5].

The heating duration to explain almost homogeneous Fe/Mg ratios in olivine and opx (except for large opx grains) is 30-200 years at one atmospheric pressure [6] and 10^2-10^3 years at ~3 GPa [7]. During this heating event, redistribution of P and REEs must also occur between GBL and GFL. (A later metamorphic event is excluded as shown below.)

The diffusion timescale for oxygen in olivine or opx [8] is by far (2-4 orders of magnitude) longer than the Fe-Mg diffusion timescale given above. Hence, the O isotopic variation in the clasts (esp. in GBL) must have been established *before* the event which homogenized the Fe/Mg ratios in olivine and most of opx.

We speculate that the O isotopic variation in GBL was probably generated by various degrees of smelting reactions [9] heterogeneously occurred in GBL. During the smelting reactions, O isotopes were partitioned between silicates and CO gas with the latter being isotopically heavy [10]. Alternatively, the starting materials of the clasts were highly heterogeneous in O isotopic composition.

Consistency of the geothermobarometers indicates that equilibration of various elements (including Fe and Mg) was mostly attained among different minerals at this high *P-T* condition. This clearly precludes a shock HP model due to very short duration of a shock (<10 seconds). Hence, a static HP model is strongly suggested and the duration of the high *P-T* condition is estimated to be 10^2-10^3 years at ~3 GPa.

Considering the Fe-Mg diffusion timescales in garnet and opx, a later metamorphic event at a low pressure can be clearly excluded, because it would completely reset the geothermobarometers to indicate a low pressure.

Frequent violent collisions:

A static HP model requires formation of a large planetary body with a radius of ~1500 km to achieve a pressure of ~3 GPa near its center [1]. Two successive large collisions are inferred. First, an energetic collision between two large planetesimals formed the large planetary body of ~1500 km in radius and at the same time the clasts (GBL plus GFL) became placed near its center. Second, 10^2-10^3 years later, the large planetary body was disrupted by another large collision, which expelled the fragments of the eclogitic material out of the planetary body. We speculate that such frequent collisions and disruptions of large planetary bodies occurred during an active stage of planetary formation after dissipation of the solar nebula.

A possible scenario for the history of the clasts:

(1) The parent body (or bodies) of GBL and GFL accreted at sometime close to ~2 My after CAI formation (to support igneous activities but not completely melt the whole planetesimal).

(2) Due to igneous activities, GBL and GFL became depleted and enriched in a melt (or a fluid) component, respectively.

(3) Smelting probably occurred in GBL but not in GFL. The large O isotopic variation in GBL was probably generated during smelting reactions heterogeneously occurred in GBL.

(4) After solidification of GBL and GFL, numerous collisions formed regolith layers on the surface of a planetesimal, where fragments of GBL and GFL were buried together.

(5) A large collision between two large planetesimal (~1000 km in size), whose center region had already been warmed, resulted in formation of a large planetary body of ~1500 km in radius. At this time, the clasts were placed near its center, where the high *P-T* condition (~1000 ºC and ~3 GPa) was attained.

(6) During this high *P-T* event, decomposition of the preexisting minerals (e.g., plagioclase and diopside) and formation of the high pressure mineral assemblage (including garnet and omphacite) occurred in the clasts. Also homogenization of Fe/Mg ratio and redistribution of P and REEs occurred in the clasts.

(7) After 10^2-10^3 years, another violent collision disrupted the large planetesimal. Fragments of the eclogitic material were transported to a shallower depth or out of the planetesimal itself, which resulted in rapid cooling of the clasts.

(8) Finally, a fragment of the eclogitic material ejected from the disrupted large planetesimal was transported to the accretion region of the CR parent body.

References:

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