

A petrographic study of a metal nodule in the Bondoc mesosiderite: Implications for the reheating mechanism of mesosiderites

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Introduction: Reheating of mesosiderites is dated at ~40 Ma after the formation of the solar system (Haba et al., 2017; Koike et al., 2017). At this age radiogenic heat by the decay of ²⁶Al is negligible. Also, a metallic core of a projectile planetesimal, accretion of which is the conventional heat source for mesosiderite reheating, cannot be kept unfractionated unless the size is much larger than that of Vesta (Zhou et al., 2013). In search for a better heat source and a formation process of the mesosiderite parent body, we have been conducting petrographic studies of mesosiderites. Here, we report petrographic features of inclusions (mostly silicates but also containing some oxides etc.) in a metallic nodule in the Bondoc mesosiderite.

Experimental: A polished section of a metallic nodule (~1 inch across in size) was observed with a scanning electron microscope (JSM 6510) and mineral compositions were determined with an EDS. The measurement condition was; time =200 seconds, accelerating voltage = 20kV and the electron current = ~2 nA. Our metal nodule is petrographically similar to that described by Axon and Nasir (1977), but our sample appears to have suffered less corrosion.

Results: As described by Axon and Nasir (1977), there are angular and globular inclusions. Globular inclusions are mainly made of devitrified glass and nearly homogeneous. Angular inclusions are made of larger minerals and have large amounts of “rim phosphate” which are located at the inclusion-metal boundary and protrude into the metal. In the case of globular inclusions, phosphate is found mainly in the interior as (1) large idiomorphic grains, (2) long needles, (3) small grains and (4) irregular-shaped relatively large grains near the edge of inclusions. The “rim phosphate” is either absent or low in abundance on globular inclusions.

EDS analyses of devitrified glasses in globular inclusions show that the bulk compositions are close to the eutectic composition of the forsterite (enstatite) - anorthite - silica system. It is more difficult to determine bulk compositions of angular inclusions because they are heterogeneous. But there are inclusions of (a) low anorthite (i.e. made of enstatite + silica), and (b) low silica with abundant anorthite, whose liquidus temperatures are high.

Interpretations: We think that the globular shape is due to nearly complete melting and the angular shape is due to a low degree of partial melting. Implicitly, we consider that the temperatures were the same within the metal nodule. As shown by Harlow et al., (1982), phosphate is produced in a temperature range 1100 ~ 900 C by the following reaction (hereafter, Harlow reaction).
$$3\text{CaMgSi}_2\text{O}_6 + 5\text{FeSiO}_3 + 2[\text{P}] = \text{Ca}_3(\text{PO}_4)_2 + 3\text{MgSiO}_3 + 8\text{SiO}_2 + 5\text{Fe}.$$

At higher temperatures (above 1100°C), the reaction proceeds backward, making atomic P from phosphate. In order to explain the presence of phosphate textures (1, 2, 3 and 4) we have to assume presence of phosphate before the reheating event. This is because the heating rate through 900-1100°C is likely to be fast and not much phosphate can be produced during the heating, and phosphate cannot be produced at/near the peak temperature.

The following is our interpretation of the phosphate textures, which has to be confirmed by petrologic experiments. (1) The large idiomorphic phosphate was mainly produced from an immiscible phosphate liquid, partially overgrown by phosphate-saturated silicate melt during cooling. (2) The long phosphate needles grew from a phosphate-saturated melt. (Phosphate is the liquidus phase.) (3) Small phosphate grains precipitated from a silicate melt at lower temperatures. (Phosphate is not the liquidus phase.) (4) The irregular-shaped phosphate grains are partially dissolved phosphate that existed before the reheating event. Angular inclusions melted to a limited extent. Into that melt, a limited amount of phosphate was dissolved. Therefore, the remaining solid phosphate disintegrated by the backward reaction and atomic P was dissolved into the metal at the peak temperature. Upon cooling, rim phosphate was made at 1100-900°C by the Harlow reaction.

Phosphate and/or silica activities were low in many globular inclusions, making the back-reaction inefficient. (Note that the silica has a coefficient of 8 in the Harlow reaction.) This explains the near absence of rim phosphate on such globular inclusions. There is, however, an inclusion for which this explanation (solely based on activities of reactants) might not be appropriate. In this globular inclusion, both silica and phosphate activities appear to be ~1 (a large silica of possibly immiscible origin and partially dissolved phosphates are present), and yet it does not show the rim phosphate. In such a case, it may be more appropriate to make a kinetic interpretation. This globular inclusion was molten extensively and only a small

amount of solid phosphate (the partially dissolved phosphate) survived at/near the peak temperature, which could disintegrate to atomic P. The reaction rate would be proportional to the surface area of the solid phosphate which is small, resulting in a smaller (negligible) amount of rim phosphate in the end. The phosphate dissolved in the silicate melt had a low activity and reacted slowly, as explained earlier in this paragraph.

Implications: The phosphate textures (1), (2), (3) and (4) require pre-existence of phosphate before the reheating event. It also requires that the peak temperature was kept only for a short time, because such phosphate should be converted to atomic P by the backward reaction if the peak temperature were kept for a long time. The briefness of the reheating event is in accord with the subsequent quick cooling of mesosiderites (Delaney et al., 1981). The pre-existence of phosphate has a far-reaching implication on the mesosiderite reheating process. Accretion of a hot metallic core onto the mesosiderite parent body could happen only once. Therefore, a hot core is ruled out as the heat source. We need a repetitive, brief heat source. In our opinion, induction heating (eddy current induced by changing solar wind magnetic field) is a possible heat source. Heating events by induction heating could be brief, similar to the durations of solar flares. It is repetitive and the largest one may be remembered as the reheating event of mesosiderites. Advantage of the induction heating is that it can explain the very slow cooling (recorded by Fe-Ni metal, Goldstein et al., 2009) at lower temperatures. Usually, this is explained as a result of deep burial into the parent body. But there is no supporting evidence for such a burial event. The induction heating could explain the slow cooling rate if the solar flare intensities diminish slowly with time.

Impacts may seem a promising heat source in terms of briefness and repetition. We need a large impact which reset the chronology of all mesosiderites. A large impact may disintegrate the whole parent body which subsequently reassembled. But impacts are an inefficient heating process. Near-total melting is unlikely based on theoretical considerations (Keil et al., 1997) and is not observed in the case of ureilite parent body. In addition, most mesosiderites do not show evidence for strong shock metamorphism (shock veins or melt pockets). Among mesosiderites we studied, two (NWA 4747 and NWA 1951) showed shock effects but the shock appears to have postdated the reheating event.

Summary: Assuming pre-existence of phosphate before the reheating event, the presence of rim phosphate on angular inclusions and the near absence of rim phosphate on globular inclusions are explained by the Harlow reaction combined with degrees of silicates melting. Pre-existence of phosphate rules out accreting hot metal as a heat source and we suggest that induction heating is the most promising heat source.

References

- Axon, A.J. and M.J. Nasir, A metallographic and microprobe examination of a metallic nodule from the Bondoc Peninsula meteorite. *Mineralogical Magazine*, 41, 121-122, 1977.
- Delaney, J.M., C.E. Nehru, M. Prinz and G.E. Harlow, Metamorphism in mesosiderites. *Proc. Lunar Planet. Sci.* 12B, 1315-1342, 1981.
- Goldstein J.I., E.R.D. Scott, N.L. Chabot, Iron meteorites: Crystallization, thermal history, parentbodies, and origin. *Chemie der Erde*, 69, 293-325, 2009.
- Haba, M.K., A. Yamaguchi, H. Kagi, K. Nagao and H. Hidaka, Trace element composition and U-Pb age of zircons from Estherville: Constraints on the timing of the metal-silicate mixing event on the mesosiderite parent body. *Geochim. Cosmochim. Acta*, 215, 76-91, 2017.
- Harlow, G.E., J.S. Delaney, C.E. Nehru and M. Prinz, Metamorphic reactions in mesosiderites: origin of abundant phosphate and silica. *Geochim. Cosmochim. Acta*, 46, 339-348, 1982.
- Keil, K., D. Stoffer, S.G. Love, and E.R.D. Scott, Constraints on the role of impact heating and melting in asteroids. *Meteorit. Planet. Sci.* 32, 349-363, 1997.
- Koike, M., N. Sugiura, N. Takahata, A. Ishida and Y. Sano, U-Pb and Hf-W dating of young zircon in mesosiderite Asuka 882023. *Geophys. Res. Lett.*, 44, 1251-1259, 2017.
- Zhou, Q., Q.-Z. Yin, E.D. Young, X.-H. Li, F.-Y. Wu, Q.-L. Li, Y. Liu, and G.-Q. Tang, SIMS Pb-Pb and U-Pb age determination of eucrite zircons at < 5 μm scale and the first 50 Ma of the thermal history of Vesta. *Geochim. Cosmochim. Acta*, 110, 152-175, 2013.