Mineralogy of olivine xenocrysts in quenched angrites Asuka-881371 and NWA 1670.

T. Mikouchi, Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan.

Introduction:

Angrite is an enigmatic basaltic achondrite which records magmatic crystallization in the very early solar system [e.g., 1]. Their precise Pb-Pb ages provide a reference point for relative chronometry using short-lived radio nuclides [e.g., 2]. Angrites can be classified into two subgroups by textural differences. One subgroup shows a fine-grained quenched texture ("quenched angrite"), while the other is coarse-grained with a granular texture ("slowly-cooled angrite"). There is a clear relationship between textural subgrouping and their crystallization ages. Quenched angrites have older ages formed at around 4563-4564 Ma. On the other hand, slowly-cooled angrites are ~6 Ma younger [e.g., 2]. Thus, quenched angrite is one of the oldest achondrites and is an important example to understand the formation of an early protoplanet.

Major minerals in angrites are Al-Ti-rich clinopyroxene ("fassaite"), anorthitic plagioclase, and Ca-Fe-rich olivine with small amounts of spinel, troilite, merrillite and silico-apatite [1,3]. Quenched angrites show different olivine mineralogy from slowly-cooled ones because they contain forsteritic olivine megacrysts out of equilibrium with the groundmass and interpreted as xenocrysts [e.g., 4]. The most magnesian olivine xenocrysts reach up to Fo_{96} in NWA 1670 [5]. Olivine of up to Fo_{89} has been reported from Asuka-881371 [4]. These forsteritic olivine xenocrysts are important to understand the petrogenesis of angrites especially pre-crystallization history of the groundmass melt, and here I report mineralogical and petrological study of olivine xenocrysts in Asuka-881371 and NWA 1670.

Samples and Methods:

Polished thin sections of Asuka-881371 (Asuka-881371,81-1) and NWA 1670 were first observed using optical microscopy and field emission gun scanning electron microscope (FEG-SEM) with EDS and EBSD detectors (Hitachi S-4500). The chemical compositions of minerals were determined with electron microprobes (JEOL JXA-8900L and JEOL-8530F) by using well-characterized natural and synthetic standards.

Results

The sizes of olivine xenocrysts are 0.5-2.5 mm and 0.5-3 mm in Asuka-881371 and NWA 1670, respectively. Small xenocrysts are probably due to the cutting effect appearing on the thin section, and they will be similarly megacrysts. Almost all olivine xenocrysts in both meteorites are homogeneous in major and minor element contents except Fe-rich rims and overgrowth adjacent to the groundmass. The size of overgrowth is larger in NWA 1670 than Asuka-881371 although NWA 1670 is much more fine-grained than Asuka-881371. The chemical composition of olivine xenocrysts ranges Fo_{89-70} and Fo_{96-88} in Asuka-881371 and NWA 1670, respectively in spite of homogeneity of each grain (Fig. 1). These xenocrysts are more Cr-rich (up to 0.7 wt% Cr_2O_3) and Ca-poor (<0.2 wt% CaO) compared to the groundmass olivine [4].
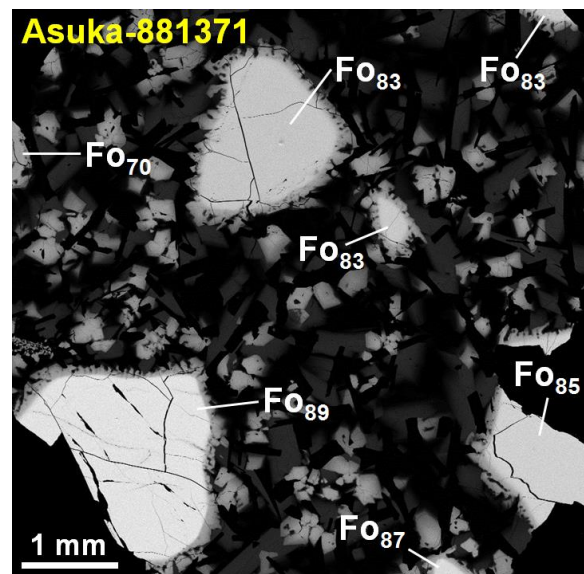

Fig. 1. Mg map of Asuka-881371. Brighter areas are higher in Mg contents. Olivine compositions of xenocrysts are shown by the Fo number.

It is noted that olivine xenocrysts in Asuka-881371 exhibits variable deformation textures. Some grains are completely undisturbed as suggested by sharp extinction under cross polarizers of optical microscope. In contrast some other xenocrysts show extensive deformation such as undulatory extinction and kink bands (Fig. 2). Linear zones of fine-grained polycrystalline olivine domains are present within megacrysts of Asuka-881371 (Fig. 2), forming sub-grain boundaries probably due to recrystallization along planar deformation. There is no obvious relationship between the xenocryst size and the deformation degree. Furthermore, there is no clear relationship between the xenocrysts size and olivine compositions. The variable deformation degrees of olivine xenocrysts is distinct from the groundmass of Asuka-881371 which shows essentially undisturbed nature (e.g., sharp extinction of plagioclase) whereas NWA 1670 shows evidence of shock metamorphism for the entire meteorite (e.g., shock melt vein).
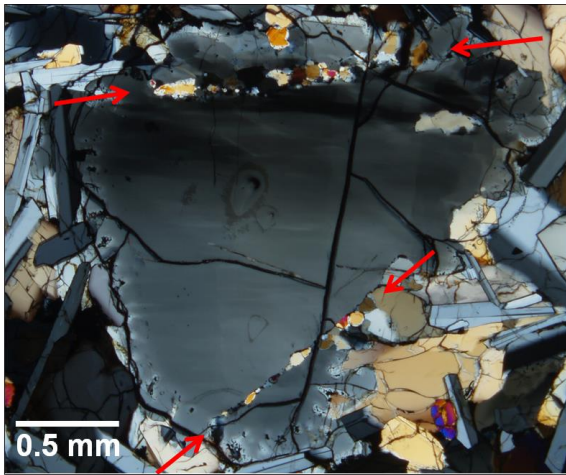
Fig. 2. Optical photomicrograph of olivine xenocryst in Asuka-881371 (crossed polarized light). Note the presence of kink bands. Fine-grained polycrystalline olivine is present (indicated by red arrows).

Tiny inclusions (~5 μm) of FeS and Fe-Ni metal were reported in olivine xenocrysts in NWA 1670 [5] and D'Orbigny [6]. In this study similar inclusions were found in olivine xenocrysts in Asuka-881371 (Fig. 3). These inclusions are sometimes associated with Ca-Al-Si glass and spinel. The Fe-Ni metal is present as both kamacite and taenite, but their chemical compositions could not be well determined because of small sizes (Fig. 3). It is also noted that olivine xenocrysts contain traces of fluid inclusions developed along some crystallographic planes.
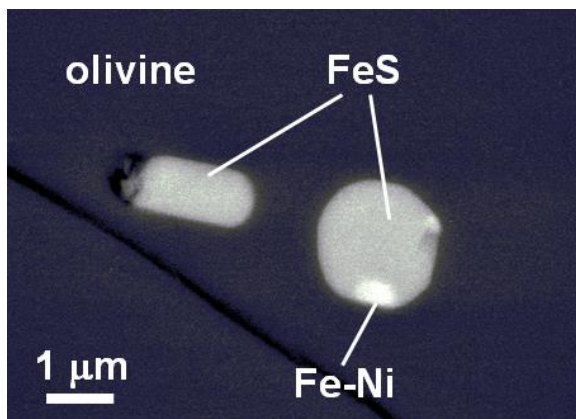

Fig. 3. BSE image of Fe sulfide and Fe-Ni metal inclusions in olivine xenocryst in Asuka-881371.

Discussion and conclusion:

Tiny inclusions composed of Fe sulfide and Fe-Ni metal are commonly found in olivine xenocrysts in Asuka-881371, D'Orbigny and NWA 1670, implying their common origins. This is consistent with their characteristic Mg-Cr-rich and Ca-poor compositions of xenocrysts. Probably similar inclusions are present in olivine xenocrysts in LEW 87051. The presence of Fe-Ni metal is especially important because it suggests formation under reducing condition. Although the oxygen fugacity during the angrite formation is not well constrained, slowly-cooled angrites were estimated to be formed under oxidizing condition ($\log f\mathrm{O}_2$~IW+1) [7]. Quenched angrites contain Fe^{3+}-bearing phases, suggesting formation under similar oxidizing condition. Thus, oxygen fugacity during the formation of olivine xenocrysts was different from the groundmass crystallization. Probably, olivine xenocrysts were formed under reducing condition and incorporated into the oxidizing groundmass magma.

There has been much debate about the heat source forming angrite magma, but decay of short-lived radionuclides such as ^{26}Al is considered to be a likely heat source [1]. In this scenario, olivine xenocrysts in quenched angrites may be fragments of zoned mantle materials of an angrite parent body (APB) that were incorporated into ascending magma [8]. APB was large enough to have core-dynamo magnetism [9] and such a large body can have mantle materials with zoned olivine compositions similar to ureilites [10]. Variable mantle olivine grains were trapped during the rapid eruption of angrite magma from the depth and formed quenched angrites. If this is the case, kink bands and sub-grain boundaries of olivine may suggest rheology of the APB mantle as commonly found in the terrestrial mantle xenoliths [e.g., 11]. Alternatively, the presence of olivine xenocrysts with variable deformation degrees may suggest the formation by shock melting [4]. In this scenario olivine xenocrysts are relict grains originating different portions of the APB mantle and survived shock melting. Similar observation and discussion has been made for olivine-bearing diogenite NWA 5480, which is interpreted to be an impact melt rock [12]. Rapid cooling rates estimated for quenched angrites are consistent with impact melt origin [6]. However, melting forsteritic olivine requires extremely high temperature, and the generation of large amount of melt is expected to result in the formation of angrites with variable cooling rates. Because all quenched angrites experienced near-surface rapid crystallization history, this scenario may be unlikely.

In order to distinguish the above two scenarios and especially to constrain the origin of the xenocrysts, more studies (e.g., oxygen isotopes, fluid inclusions) are required.

References:

[1] Keil K. (2012) *Chem. Erde 72*, 191. [2] Amelin Y. (2008) *GCA 72*, 221. [3] Mittlefehldt D. W. et al. (2002) *Meteorit. Planet. Sci. 37*, 345. [4] Mikouchi T. et al. (1996) *Proc. NIPR Symp. Antarct. Meteorites 9*, 174. [5] Mikouchi T. et al. (2003) *Meteorit. Planet. Sci. 38,* 5218. [6] Suzuki H. et al. (2013) *LPI Contrib. #1768*, 8042. [7] McKay G. et al. (1994) *GCA 58*, 2911. [8] Mikouchi T. et al. (2011) *LPI Contrib. #1639*, 9142. [9] Weiss B. et al. (2008) *Science 322*, 713. [10] Goodrich C. A. et al. (2004) *Chem. Erde 64*, 283. [11] Gueguen Y. and Nicolas A. (1980) *Ann. Rev. Earth Planet. Sci. 8*, 119. [12] Yamaguchi A. et al. (2014) *Meteorit. Planet. Sci. 49* (submitted).