OLIVINE XENOCRYSTS IN QUENCHED ANGRITES: THE FIRST "DIFFERENTIATED" MATERIALS IN THE SOLAR SYSTEM? T. Mikouchi[1], G. A. McKay[2], M. Miyamoto[1] and K. Sugiyama[3], [1]Department of Earth and Planetary Science, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan (mikouchi@eps.s.u-tokyo.ac.jp), [2]NASA Johnson Space Center, Houston, TX 77058, USA (deceased), [3]Institute for Materials Research, Tohoku University, Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan (kazumasa@imr.tohoku.ac.jp).

Introduction: Angrites form a small but important group of basaltic achondrites that records igneous crystallization at the very early stage of the solar system history. Their precise Pb-Pb ages are used as benchmarks of the early solar system chronology and provide a reference point for relative chronometry using short-lived radio nuclides [e.g., 1]. Angrites can be texturally divided into two subgroups: fine-grained "quenched" angrites (e.g., Asuka-881371, D'Orbigny) that formed by rapid cooling of their parent melts and coarse-grained "slowly-cooled" angrites (e.g., Angra dos Reis, LEW 86010) that experienced slow cooling history possibly involving some degree of thermal metamorphism. Interestingly, there is a clear relationship between textural classification and their crystallization ages. "Quenched" angrites show the older ages (4563-4564 Ma), whereas "slowly-cooled" angrites clearly show younger ages, crystallized at 4557-4558 Ma [e.g., 1]. Thus, quenched angrites are the better samples to study the earliest differentiation of the angrite parent body, which probably corresponds to the formation of an early protoplanet. The other characteristic of angrites is their unusual chemistry enriched in refractory elements and depleted in volatiles, which makes their mineralogy very unique [e.g., 2]. 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 [e.g., 2]. In spite of these chemical and mineralogical interests, the origins of angrites have not been well understood. In this study, we paid attention to olivine megacrysts observed in quenched angrites and discuss their origins and relationship to other meteorite groups because they are possibly the first differentiated materials in the solar system.

Olivine Megacrysts in Quenched Angrites: LEW87051, Asuka-881371, Sahara 99555, D'Orbigny, NWA1296 and NWA1670 are quenched angrites that show porphyritic to ophitic textures [e.g., 2-5]. Both olivine and Al-Ti-rich pyroxene are extensively zoned, suggesting rapid cooling from magmas. In LEW87051, Asuka-881371, D'Orbigny, and NWA1670, olivine megacrysts reaching several mm across are present (Fig. 1). These olivine megacrysts have large homogeneous cores and are essentially more Mg-rich ($Fo_{96\text{-}70}$), Cr-rich (0.2-0.7 wt% Cr_2O_3) and Ca-poor (0-0.7 wt% CaO) than the groundmass olivines (phenocrysts) (Fig. 2). These cores are out of equilibrium with the groundmass melt and are possibly xenocrysts [e.g., 3]. The similar mineralogy of the groundmass minerals as well as the presence of compositionally similar olivine xenocrysts indicates that these quenched angrites are petrogenetically related [6].

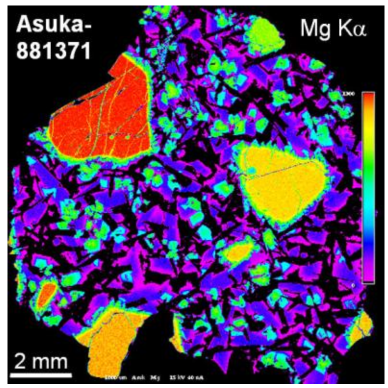

Fig. 1. Mg X-ray map of Asuka-881371. Note the presence of Mg-rich olivine megacrysts reaching a few mm in size. They have variable homogeneous compositions.

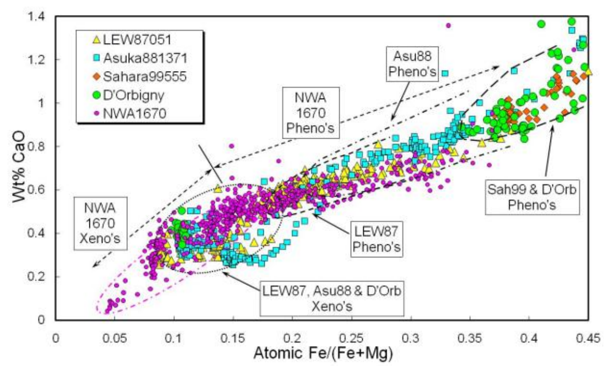

Fig. 2. Fe# and Ca variations of olivine grains (xenocrysts and phenocrysts (groundmass)) in quenched angrites. Xeno's: xenocrysts. Pheno's: phenocrysts.

Bulk Compositions of Quenched Angrites: We previously reported strong correlations between major element compositions and the abundance of olivine xenocrysts in quenched angrites [6]. The range of bulk compositional variations is best explained by olivine addition [6]. Because olivine xenocrysts are nearly absent in Sahara 99555 and D'Orbigny, we suggest that their bulk compositions represent an angrite parent magma composition that is not contaminated by the xenocryst component. In contrast, LEW87051 and Asuka-881371 contain ~10% olivine xenocrysts and, based on bulk compositions, appear to contain larger amounts of dissolved olivine xenocryst components.

Origin of Olivine Xenocrysts: Quenched angrites are closely related in bulk composition with identical old crystallization ages and probably originated from the same parent melt, either with or without olivine xenocryst incorporation [6]. The origin and the heat source of the angrite magma are unclear, but abundant Al and their ancient crystallization ages suggest that ^{26}Al was a plausible heat source. Also, partial melting of CV3 chondrite at ~1200 ^{o}C with high fO_2 produces silica-undersaturated melt similar to the angrite parent magma [6]. The origin of olivine xenocrysts is unclear. Especially, the variable composition of xenocrysts (although each grain is homogeneous) makes the interpretation of their origin more complex (Fig. 1). NWA1670 may be a key sample because it contains the most magnesian olivine xenocrysts (Fo_{96}). It is difficult to produce such Mg-rich olivine by normal igneous differentiation processes. Therefore, some reduction process may have been involved or it may be a completely exotic component related to some other meteorite groups. Olivine xenocrysts in NWA1670 contain tiny inclusions (~10 μm) of Fe-Ni metal and sulfides. Because angrites formed under relatively oxidizing conditions, the presence of Fe metal is unusual. This suggests that olivine xenocrysts formed under different conditions from the groundmass.

If we consider an exotic origin of olivine xenocrysts in quenched angrites, there are not so many meteorite groups that contain similar olivine grains (compositional range of Fo_{96-70} and reaching mm size). The candidates are olivines in chondrites (Fo_{100-70}), ureilites (Fo_{95-74}), and primitive achondrites (Fo_{97-87}) [e.g., 7]. However, minor element contents of olivines in ureilites and primitive achondrites are CaO=0.3-0.45 wt% and Cr_2O_3=0.5-0.8 wt% and CaO=~0.05 wt% and Cr_2O_3=~0.05 wt%, respectively, that are clearly different from those in olivine xenocrysts in quenched angrites. Chondrites show variable olivine compositions in each group. The most similar olivines are found in CO3 chondrites that have 0.05-0.7 wt% CaO and ~0.2 wt% Cr_2O_3 with an Fe/Mn ratio close to olivine xenocrysts in quenched angrites (Fig. 3) [e.g., 7]. Nevertheless, minor compositional difference is present and it seems unlikely that olivine xenocrysts in angrites are fragments of olivine in some other meteoritic groups.

The oxygen isotope ratios of NWA1670 fall within the angrite field although it contains abundant olivine xenocrysts [8]. Therefore, it is likely that olivine xenocrysts in quenched angrites are "angrite" materials. There is no doubt that the formation of these large homogeneous Mg-rich, Cr-rich and Ca-poor olivine with various compositions predated the formation of the angrite groundmass. We consider that these olivine grains may be fragments of zoned mantle materials of an angrite parent body. Recently, it is suggested that the angrite parent body was large enough to have core-dynamo magnetism [9]. Such a large body can have mantle materials with zoned olivine compositions as proposed for ureilites [10]. Thus, olivine xenocrysts in quenched angrites are possibly the earliest known differentiated materials in the solar system with the formation age of ≥4.564 Ma, and they may be the zoned mantle materials in an early-formed protoplanet.

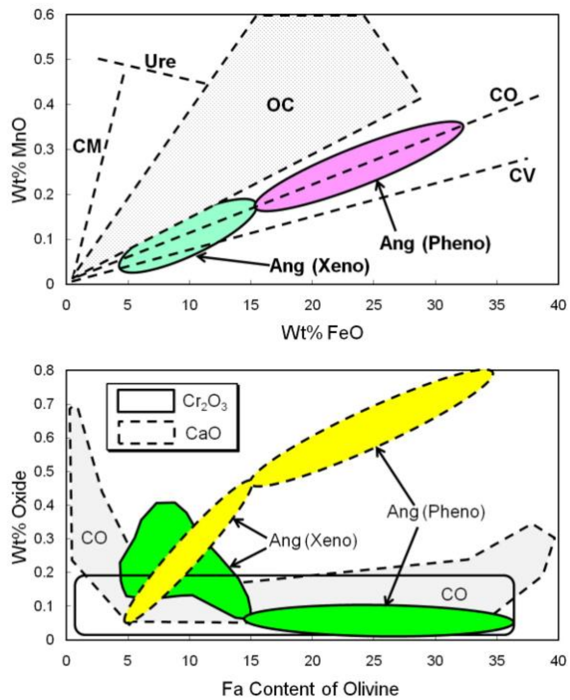

Fig. 3. Above: Fe-Mn variations of olivines from several meteorite groups. Ure: ureilite. CM: CM2 chondrites. OC: ordinary chondrites. CO: CO3 chondrites. CV: CV3 chondrites. Ang (Pheno): phenocrysts in angrites. Ang (Xeno): xenocrysts in angrites. This diagram shows that CO3 chondrites are most similar to angrites in Fe/Mn ratio. Below: Comparison of Ca and Cr contents in olivine between angrites and CO3 chondrites.

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