On the relationship between textures and cooling rates of quenched angrites

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Introduction: Angrite is one of the oldest basaltic achondrites and shows either quenched or slowly-cooled textures. Quenched angrites show fine-grained variolitic textures and sometimes exhibit dendritic intergrowth consisting of olivine and anorthite, while slowly-cooled angrites show coarse-grained granular textures [1]. D'Orbigny, LEW 87051, Asuka-881371, Sahara 99555, NWA 1296 and NWA 1670 are quenched angrites and their grain sizes do not change so much in each sample. However, NWA 7203 quenched angrite shows an unusual grain size variation from fine grains (~1 μm) to coarse grains (>100 μm) [2]. NWA 7203 shows a variolitic texture in the fine-grained part, which resembles NWA 1670, while the coarse-grained part shows a dendritic texture resembling Sahara 99555 (Fig. 1). The textural difference between the fine-grained and coarse-grained parts might be caused by change of cooling rates [3]. In this case, the fine-grained part (variolitic texture) might crystallize at a faster cooling rate whereas the coarse-grained part (dendritic texture) might crystallize at a slower cooling rate.

Quenched angrites often contain olivine xenocrysts that have homogeneous Mg-rich cores. These xenocrysts show evidence for atomic diffusion when interacted with the surrounding melts and can be used to estimate cooling rates [e.g. 4]. NWA 7203 contains such olivine xenocrysts in the variolitic fine-grained part [3]. In this study, we estimate the cooling rate of NWA 7203 using these xenocrysts. By the same procedure using olivine xenocrysts in NWA 1670, we also calculated its cooling rate to compare with the fine-grained part of NWA 7203 is texturally similar to NWA 1670. We further performed a 1 ^{o}C/hr cooling experiment of a magmatic composition of quenched angrites to compare textures of NWA 7203 and NWA 1670.

Methods: We observed thin sections of NWA 7203 and NWA 1670 by optical microscope and mineral compositions were analyzed with electron microprobes (JEOL JXA-8530F and JXA-8900L). In the crystallization experiment, we used Siliconit vertical electric furnace (TEXSH-530G). The starting material is an analog of the Asuka-881371 bulk composition ("A8") [4]. We first kept the ~100 mg pellet of the starting material at 1300 °C for 48 hours for homogenization and cooled it at 1°C/hr from 1300 ^{o}C to 900 ^{o}C. Oxygen fugacity was kept at logfO_2=IW+2, by flowing H_2 and CO_2 gases (total 300 mL/min) [5]. Thermocouple was calibrated by Au wire (m.p. 1064.6 ^{o}C).

Results: In calculating cooling rates of olivine xenocrysts, it is important to properly estimate temperature ranges for calculation. As the bulk chemical compositions of NWA 1670 [6], NWA 7203 [3] and A8 [4] are shown in Table 1, NWA 1670 is the most Mg-rich and NWA 7203 is the lowest in Mg. In [7], olivine crystallized at 1430 ^{o}C whose staring composition is close to the NWA 1670 bulk chemical composition [8] (Table 1). In contrast, olivine in NWA 7203 should have crystallized at much lower temperature, perhaps near 1200 ^{o}C. Therefore, we calculated the cooling rates of NWA 7203 from 1200 ^{o}C to 900 ^{o}C and NWA 1670 from 1400 ^{o}C to 900 ^{o}C, respectively. The best-fit cooling rates for the observed diffusion profiles (Fe-Mg) are 20 ^{o}C/hr for NWA 7203 and 3 ^{o}C /hr for NWA 1670, respectively. Therefore, we consider that variolitic textures in these quenched angrites were formed at these cooling rates. The 1 ^{o}C/hr cooling crystallization experiment produced the variolitic texture similar to Sahara 99555, but some anorthites and olivines show dendritic intergrowth (Fig. 2).

Discussion and conclusion: Table 2 summarizes the relationship between textures and estimated cooling rates. Variolitic textures were found in all samples including the run product from the 1 ^{o}C/hr crystallization experiment. Although the difference of cooling rates is subtle, dendritic intergrowth of olivine and anorthite is found only in the slowest cooling (1 ^{o}C/hr) except the coarse-grained part of NWA 7203. Thus, we consider the possibility that the variolitic texture of quenched angrites crystallized at faster cooling rates compared to those forming dendritic textures. This support the crystallization history of NWA 7203 proposed in [3], that the variolitic fine-grained part first crystallized and then dendritic coarse-grained part crystallized after the slowing down of the cooling rate. A possible scenario occurred on the angrite parent body was repeated events of eruption of thin lava flow. Crystallization of NWA 7203 started with xenocrysts as crystallization seeds at relatively fast cooling rate (about 20 ^{o}C/hr), and formed a variolitic texture. However, before the crystallization has been completed, next thin lava flow came. Cooling rate changed more slowly (maybe around 1 ^{o}C/hr) because the burial depth became deeper. Then, crystallization was completed at a slower cooling rate and produced a coarse-grained dendritic texture.

References: [1] Keil K. (2012) *Chemie Erde-Geochem. 72*, 191-218. [2] Mikouchi T. et al. (2012) *The 75th Annual Meeting of the MetSoc.*, #5120. [3] Hayashi H. et al. (2019) *The 82nd Annual Meeting of the MetSoc.*, #6153. [4] Mikouchi T. et al. (2000) MAPS, *35*, A110. [5] Miyamoto M. and Mikouchi T. (1996) GCA *60*, 2917-2920. [6] Jambon A. et al. (2008) MAPS *43*, 1783-95. [7] Mikouchi T. et al (1994) *LPSC 25*, 907-908. [8] Warren P. H. and Kallemeyn G. (1990) *LPSC 21*,1295.

Table 1: Bulk chemical compositions of NWA 1670, NWA 7203, Asuka-881371-like starting material (“A8”) for crystallization experiment and LEW 87051.

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Cr_2O_3	Total
NWA 1670 [6]	42.18	0.67	11.70	18.52	0.22	14.60	11.95	0.14	100.14
NWA 7203 [3]	41		14~15	23~21		7	15		100
“A8” [4]	37.03	1.02	11.48	25.42	0.21	10.49	14.19	0.16	100.00
LEW 87051 [8]	41.1		10.8	17.9	0.25	14.9	12.0	0.16	97.14

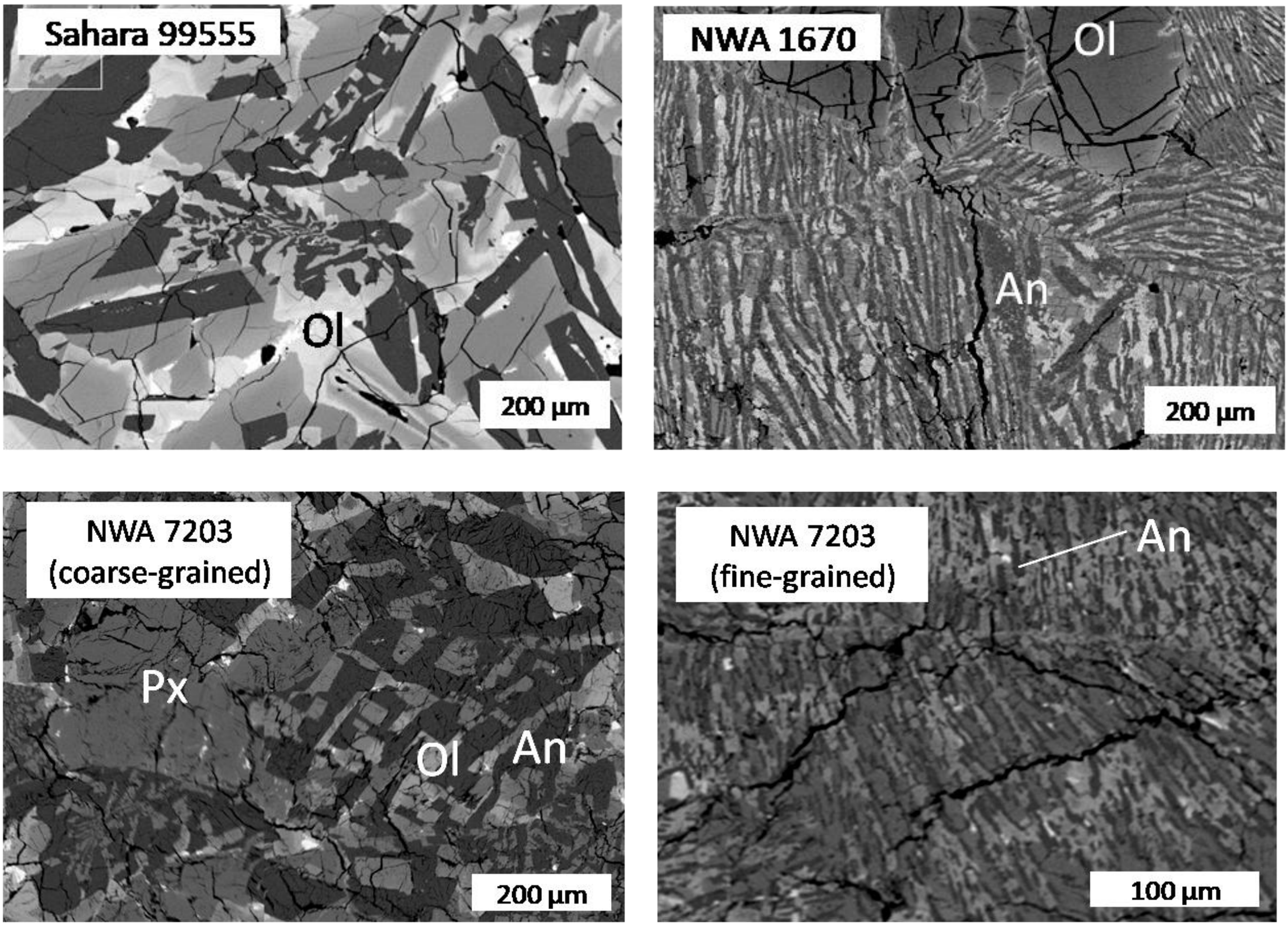

Fig. 1: BSE images of Sahara 99555, NWA 1670 and NWA 7203 (both fine-grained and coarse-grained areas)

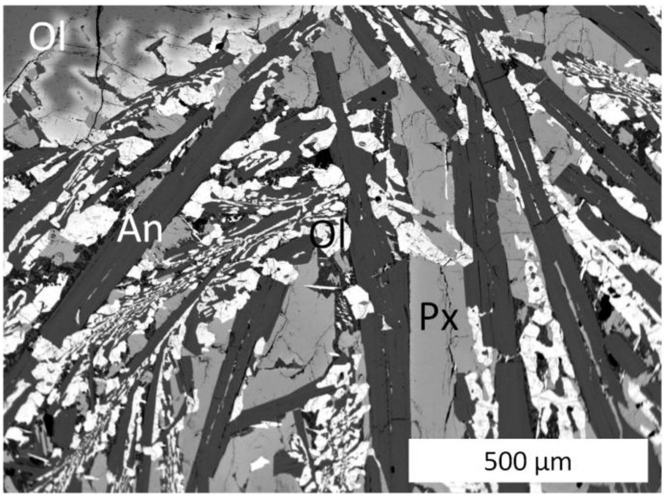

Fig. 2: BSE image of the run product of the 1 ^{o}C/hr cooling crystallization experiment.

Table 2: Relationship between textures and estimated cooling rates

Sample	Texture	Cooling rate
NWA 1670	Variolitic	3 ^{o}C/hr
NWA 7203 (fine-grained)	Variolitic	20 ^{o}C/hr
NWA 7203 (coarse-grained)	Dendritic	?
“A8”	Variolitic/dendritic	1 ^{o}C/hr