Olivine xenocrysts and cooling rates of quenched angrites: Implications for the stratigraphy of their igneous body

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Introduction: Angrite is one of the oldest basaltic achondrites and shows unusual chemistry enriched in refractory elements and depleted in volatiles. Most angrites show two distinct textures, either "quenched" or "slowly-cooled"; NWA 8535 is a dunite [1]. Quenched angrites have older crystallization ages (*ca.* 4564 Ma) compared to slowly-cooled samples (*ca.* 4558 Ma). Quenched angrites usually show diabasic textures, and often include dendritic intergrowth consisting of olivine and anorthite. Some of the quenched angrites contain Mg-rich olivine xenocrysts. There are several discussions about the textures, cooling rates and bulk chemical compositions of quenched angrites. Mikouchi et al. [2] discussed that the variety of bulk chemical compositions in quenched angrites can be explained by incorporation of Mg-rich olivine xenocrysts. Hayashi et al. [3] showed the relationship between textures and cooling rates of quenched angrites, and discussed the geological setting of NWA 7203. However, the geological setting of other quenched angrites is unknown. In this study, we discuss the stratigraphy of an igneous body of quenched angrites by comparing their textures, cooling rates and bulk chemical compositions.

Samples and Analytical Methods: We studied thin sections of Asuka-881371, D'Orbigny, NWA 1670, NWA 7203, NWA 12774 and Sahara 99555. Observation was performed by optical microscope and FE-SEM (JEOL JSM-7200). Mineral compositions were analyzed by FE-EPMA (JEOL JXA-8530F) and EPMA (JEOL JXA-8200).

Results and Discussion: We found that possible olivine xenocrysts are present in Asuka-881371, D'Orbigny, NWA 1670, NWA 7203, and NWA 12774. Xenocrysts are rare in D'Orbigny and NWA 7203. In order to estimate the proportion of incorporating Mg-rich olivine xenocryst, we compiled bulk chemical compositions of quenched angrites ([4-6]; Table 1). There are trends in two elemental compositional systematics, especially in CaO-MgO and in CaO-Cr_2O_3 variations. When we consider that the trend was caused by incorporation of olivine xenocrysts (Fo_{90}, CaO =0.40 wt%, Cr_2O_3 = 0.45 wt%; see [2]), D'Orbigny, Sahara 99555, NWA 1296 and NWA 7203 can be the original angritic melt, while Asuka-881371 and NWA 1670 can be the mixture of the original melt with addition of 20% of olivine xenocrysts. Similarly, LEW 87051 and NWA 12774 can be the mixture of the original melt and 40% of olivine xenocrysts; the Cr content of NWA 12774 is high and it is difficult to explain only by incorporation of olivine xenocryst, and there can be other reason (e.g. incorporation of Cr-rich spinel xenocrysts or inaccurate bulk Cr composition). This result suggests that quenched angrites might come from single igneous body which crystallized from the original angritic melt with varying proportions of incorporating olivine xenocrysts. Whole-rock REE patterns of quenched angrites also suggests the simple mixing of angritic melt and olivine xenocrysts [7].

We estimate the cooling rates of quenched angrites by the Fe-Mg diffusion profiles recorded at the rims of olivine xenocrysts adjacent to the groundmass, with a similar manner to [8] (Table 1). Cooling rates were estimated at the temperature from 1400 to 900 °C for all samples (except for NWA 7203; xenocrysts in NWA 7203 are Fe-rich, thus we estimated the cooling rate from 1200 to 900 °C), because we assume that quenched angrites could come from a single igneous body.

From cooling rates, bulk chemical compositions and textures of quenched angrites (Table 1 & Fig. 1), we propose a model of possible geological setting of quenched angrites (Fig. 2). We consider that a lava flow with Mg-rich olivine xenocrysts was erupted onto the surface of the angrite parent body (APB) (Fig. 2a). Rapid cooling of lava flow and sinking and melting of olivine xenocrysts started when the lava flow reached the surface (Fig. 2b). Cooling rates were faster at the surface and slower at a lower part, producing textual varieties (Fig. 2c). Near the surface, a dendritic texture was formed by rapid cooling, producing such as NWA 1296, Sahara 99555 and NWA 7203. At a lower area of the surface, a relatively coarse-grained part crystallized at ~50 °C/h cooling rate. Here, some olivine xenocrysts remained and incorporation of olivine xenocrysts exceeds toward the deeper, producing D'Orbigny (+~0% Ol) and Asuka-881371 (+20% Ol). Vapors came up around here, but did not reach surface because crystallization has already proceeded near the surface. At the lower area of the coarse-grained part, anorthite laths crystallized at the cooling rates of around several °C/h, producing such as NWA 1670, LEW 87051 and NWA 12774. At the bottom of the lava flow, olivine xenocrysts were accumulated, and dunite such as NWA 8535 formed.

Conclusion: We found correlation between proportion of incorporating olivine xenocrysts [2] and cooling rates of quenched angrites. From these results, we proposed stratigraphy of the igneous body of quenched angrites; First, a lava flow containing Mg-rich olivine xenocrysts was erupted onto the surface of the APB. Next, rapid cooling of lava flow and sinking/melting of olivine xenocrysts started. Then, crystallization completed with variety of cooling rates corresponding to burial depth.

References: [1] Santos A. R. et al. (2016) LPSC, 47, #2590. [2] Mikouchi T. et al. (2004) LPSC, 35, #1504 [3] Hayashi H. and Mikouchi T. (2019) The 10th Symp. Polar Sci., OA-116. [4] Keil K. (2012) Chem. Erde-Geochem., 72, 191-218. [5] Hayashi H. et al. (2019) The 82nd Annual Meeting of the Meteorit. Soc., #6153. [6] Hayashi H. et al. (2020) Annual meeting of Japan Assoc. Mineral. Sci., R5-04 (in Japanese). [7] Mittlefehldt D. W. et al. (2002) Meteorit. Planet. Sci., 37, 345-369. [8] Mikouchi T. et al. (2001) Meteorit. Planet. Sci., 36, A134-135.

Table 1. Bulk chemical compositions of angrites (wt%) [4-6]. Quenched angrites shown in purple cells contain dendrites consisting of olivine and anorthite, those in light blue cells show relatively coarse-grained textures, and those in green cells contain anorthite laths.

		SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Total	Texture	Cooling rates
Quenched angrites	NWA 1296	39	0.93	12.18	0.068	25	0.28	6.71	14.65	100	Dendritic	?
	NWA 7203	40.1	0.6	14.7	0.07	22.2		6.9	15	99.8	Dendritic An laths	>20 °C/h
	Sahara 99555	38.6	0.91	12.5	0.046	23.1	0.26	7.04	15.1	97.72	Dendritic/ Coarse-grained	?
	D'Orbigny	38.4	0.89	12.4	0.042	24.7	0.28	6.49	15	98.38	Coarse-grained	100 °C/h
	Asuka-881371	37.3	0.88	10.07	0.13	23.43	0.2	14.81	12.51	100.77	Coarse-grained	50 °C/h
	LEW 87051	40.4	0.73	9.19	0.17	19	0.24	19.4	10.8	100	An laths	?
	NWA 1670	42.18	0.67	11.7	0.14	18.52	0.22	14.6	11.95	100.14	An laths	4 °C/h
	NWA 12774	40.1	0.55	12.8	0.45	17.6	0.19	18.5	11	101.1	An laths	3.5 °C/h
Slowly-cooled angrites	ADoR	43.7	2.05	9.35	0.21	9.4	0.1	10.8	22.9	98.7	Granular	
	LEW 86010	39.6	1.15	14.1	0.11	18.5	0.2	7	17.5	98.3	Granular	
	NWA 2999	33.4	0.42	4.71		31.2	0.24	19	7.37	96.34	Granular	
	NWA 4590	37.49	1.46	8.5		27.16	0.31	17.84	6.8	100.03	Granular	

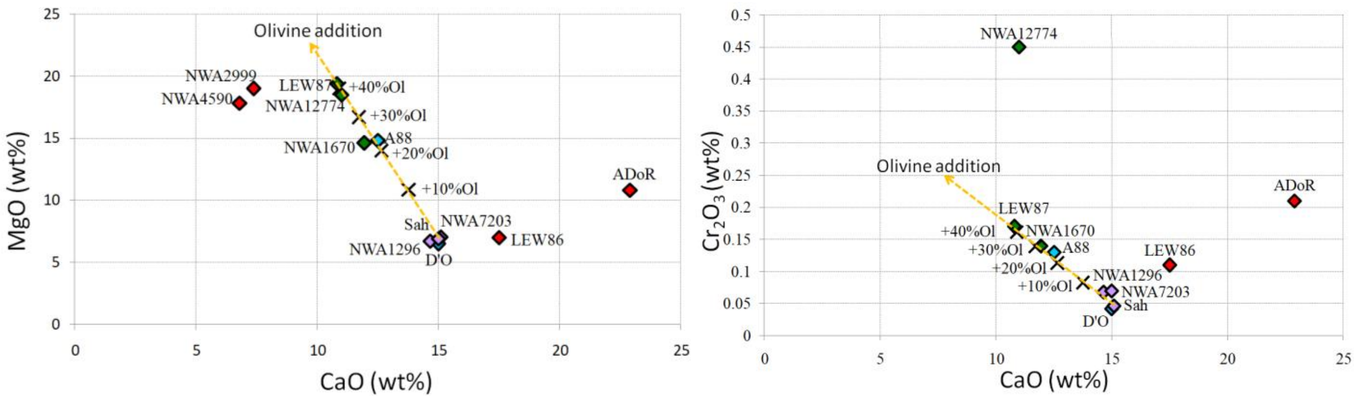

Fig. 1 Bulk chemical compositions of quenched angrites. The color of the samples corresponds to that of Table 1.

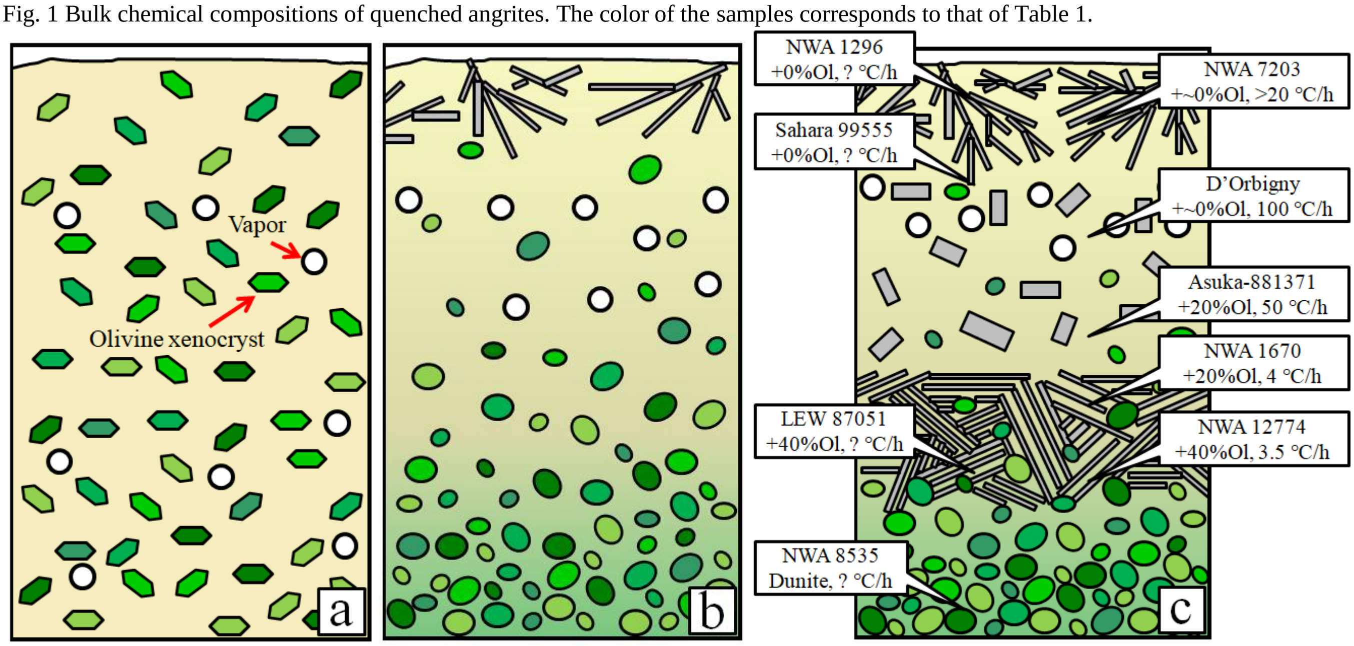

Fig. 2 Schematic illustration showing the stratigraphic formation of the igneous body for quenched angrite. See details for the text.