MAGMA OCEAN-DERIVED ANORTHOSITIC CRUST ON EARLY (< 5 MA) PLANETESIMAL. P. Frossard[1], M. Boyet[1], A. Bouvier[2,3], T. Hammouda[1], J. Monteux[1]. [1]Université Clermont Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, F-63000 Clermont-Ferrand, France, [2]Department of Earth Sciences, Centre for Planetary Science and Exploration, University of Western Ontario, London, Ontario, Canada. [3]Bayerisches Geo-institut, Universität Bayreuth, Germany. Email: paul.frossard@uca.fr.

Introduction: Achondrite meteorites present in collections are principally iron meteorites and mafic to ultramafic achondrites. The growing number of classified ungrouped achondrites highlight the diversity of processes at play in differentiated parent bodies. Magma oceans were certainly common in planetesimals larger than 20 km [1]. Geochemical proxies suggest the HED suite, angrites and iron meteorites parent bodies experienced magma ocean events [2]. The lack of magma ocean record is blatant in known meteorites.

We analysed major and trace elements on the ungrouped achondrite Northwest Africa (NWA) 8486, paired with NWA 7325. This meteorite is a troctolitic gabbro rich in Ca and Mg and poor in Fe and alkalis, which was dated at 4563.4 ± 2.6 Ma [3].

Methods: Geochemical investigations were carried out using both in-situ and solution analysis of NWA 8486. In-situ major elements analysis was carried out with a Cameca SX100 electron microprobe. Trace elements analysis of mineral phases were obtained using a laser excimer 193nm Resonetics M-50E ablation coupled with a Thermo-Fischer Element ICP-MS at Laboratoire Magmas and Volcans. Mineral separates and bulk powder were dissolved prior to trace elements analysis with a Thermo iCAP ICP-MS at Western (see methods in [4]).

Results: NWA 8486 has a different modal composition than NWA 7325, depending on the studies [5, 6, 7]. Pyroxene is more abundant in NWA 8486, reaching about 52 vol. %, while plagioclase and olivine are 44 vol. % and 4 vol. % respectively. The mineral compositions are consistent with previous studies: olivine $Fo_{97.1\pm0.3}$ (n=16), clinopyroxene $Wo_{45.4\pm0.5}En_{53.4\pm0.5}Fs_{1.2\pm0.1}$ (n=21), plagioclase $An_{88.7\pm3.0}Ab_{11.2\pm3.0}$ (n=21). Plagioclase composition is intermediate between the high An and low An groups of [6]. NWA 8486 has a distinct trace element composition when compared to other differentiated achondrites (Fig. 1). The bulk rock data is similar to that of NWA 7325 [5] but slightly enriched in incompatible elements due to the different modal composition. NWA 8486 is highly depleted in incompatible elements, between 0.5 and 0.1 times CI chondrite values. Minerals analysed by in-situ and solution methods are very similar in composition, except for Ba, Nb and Zr that reflect impurities in minerals or insolubility. The scatter in plagioclase HREE and plagioclase and pyroxene HFSE data is due to the very low concentrations close to detection limits.

We observed a large enrichment in Sr and Eu in either whole-rock, plagioclase and pyroxene (Figure 1). This is the first occurrence of positive Eu and Sr anomalies in clinopyroxene in an achondrite. Plagioclase Eu/Sm ratios ranges from 94 to 280 and pyroxene from 0.8 to 2.1.

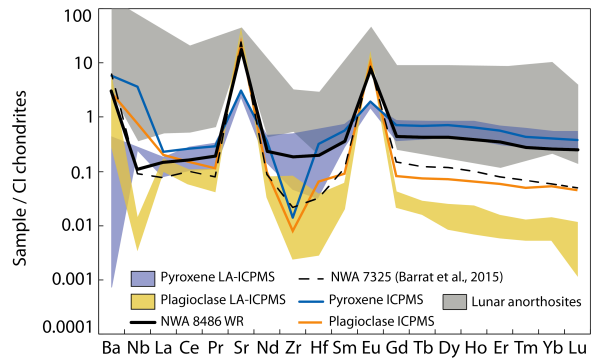

Figure 1: In-situ and solution trace element composition of minerals and whole-rock (WR) of NWA 8486 normalised to CI chondrites [8]. Lunar anorthosites range is plotted for comparison (data from [9, 10, 11]).

Discussion: Europium and Sr are similarly enriched in both plagioclase and pyroxene compared to other incompatible elements. In plagioclase, Eu^{2+} is more compatible than Eu^{3+} and has a partition coefficient very close to that of Sr^{2+} due to similar ionic radii [12]. NWA 7325/8486 is reduced with a f_{O2} of IW -3.1 ± 0.2 [13], thus high positive anomalies are expected in plagioclase. Lunar rocks contain principally Eu^{2+} because the change of valence of Eu occurs around IW and their f_{O2} ranges from IW to IW-2. Thus, plagioclase in NWA 7325/8486 should not have higher Eu and Sr anomalies compared to lunar rocks. Moreover, anomalies are not expected in pyroxene as pyroxene/melt partition coefficients are similar for Eu^{2+} and Eu^{3+}. Therefore, redox conditions alone cannot explain the trace element composition of NWA 7325/8486.

NWA 8486 Sr and Eu positive anomalies in pyroxenes are unique among all reported data for meteorites. Plagioclase, pyroxene and whole-rock composition of achondrites plot in three different fields that slightly overlap in a Sr/Nd vs Eu/Sm diagram (Fig. 2). NWA 8486 data is systematically shifted to higher Sr/Nd and Eu/Sm on the achondrite trend. Altogether, this implies that NWA 7325/8486 formed by melting of a source which was highly enriched in Eu and Sr.

Eucritic cumulate gabbros were proposed to be a potential source of such a parental melt [5]. We tested this hypothesis in a two stage scenario of melting and crystallisation. Cumulate eucrites fail to reproduce high enrichments in Eu and Sr and low contents of incompatible elements. Furthermore, reported ^{26}Al-^{26}Mg systematics on NWA 7325/8486 suggest that the source rock must have formed 1.7 Ma after CAI to explain their compositions [3]. It is unlikely that multiple events of remelting of crustal material occurred within ~3 Ma (timing interval between the first differentiation process and the crystallisation age) as it was suggested in previous studies [5, 6, 7]. The only lithology that can produce such high positive Eu and Sr anomalies is an anorthosite or a plagioclase-rich rock. Whole-rock REE patterns for NWA 7325/8486 can be reproduced with melting of an anorthosite with high Eu and Sr anomalies and a rather high pyroxene mode, around 20%.

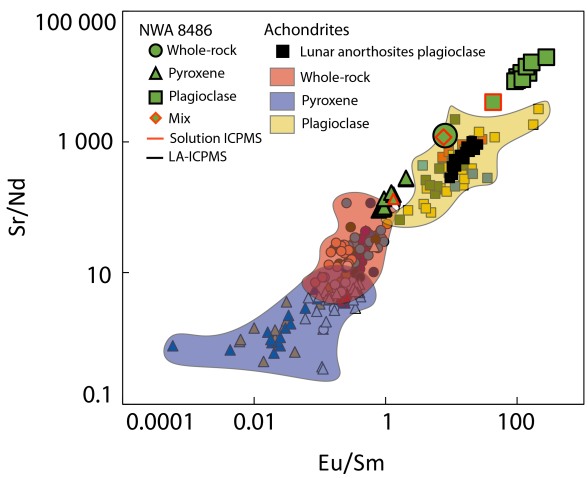

Figure 2: Eu/Sm versus Sr/Nd plot. Plagioclase, pyroxene and whole-rock data for achondrites are represented along with NWA 8486 (green) and lunar anorthosites plagioclase (black) for comparison. Fields show the range of pyroxene (blue), plagioclase (yellow) and whole-rock (red) compositions. Data are from too many sources to cite here.

Anorthosites form by fractional crystallisation of a magma body and flotation of plagioclase. The parent body of the magma reservoir needs to be relatively dry and much smaller than the Earth for plagioclase to crystallise and segregate from the melt [14]. We propose here that this might be the case for the NWA 7325/8486 parent body. However, with a small parent body, crystal settling in low gravity is limited by highly turbulent environment. Several authors suggested that limited crystal settling is possible in turbulent magma oceans [15, 16]. Using Martin and Nokes' [17] equation of the settling velocity of a crystal in a magma, we calculate the time for a plagioclase crystal to reach the surface. This can be achieved within a few tens of thousand years for a wide range of plausible crystal sizes, contrast densities, depths of magma ocean at plagioclase crystallisation, radii of the body and viscosities.

Our results suggest that this meteorite is the first occurrence of an anorthositic crust on a planetesimal, very early in the solar system's history. Our scenario for the formation of NWA 7325/8486 questions the paucity of anorthosite crusts in the solar system. Small planetesimals tend to have basaltic or primitive crusts. Anorthositic crust may be more difficult to produce on small bodies due to the effects of gravity on crystal settling. Larger planetesimals were involved in the accretion of the present planets by runaway growth processes, for example. Therefore, there should be very little crustal material left from these primitive bodies. NWA 7325/8486 possibly samples the crust of a planetary embryo-size body from the inner solar system.

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