Reassessing the formation of CK7 Northwest Africa (NWA) 8186. P. Srinivasan[1,2], F. M. McCubbin[2], T. J. Lapen[3], M. Righter[3], C. B. Agee[1]. [1]Institute of Meteoritics and Dept. of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, USA. [2]NASA Johnson Space Center, Mail Code X12, 2101 NASA Parkway, Houston, TX 77058. [3]Department of Earth and Atmospheric Sciences, University of Houston, Houston, Texas 77204. Email: psrinivasan@unm.edu.

Introduction: The classification of meteorites is commonly determined using isotopes, modal mineralogy, and bulk compositions [1]. Bulk rare earth elements (REEs) in meteorites are additionally utilized to understand parent body processes. Numerous authors have shown that chondritic groups exhibit REE patterns that may be attributable to their parent bodies [e.g. 2-4], and variations in abundances and concentrations of REEs may reflect early nebular processes, thermal metamorphism, and aqueous alteration on the parent body [5-6].

Chondritic meteorites can further be classified based on their increasing degree of thermal metamorphism: petrologic type 3 to 6. One of the leading ideas for the increase in petrologic type is prograde-metamorphism, in which undifferentiated material is increasingly heated by the decay of ^{26}Al on the parent body [e.g. 1,7]. Any continuation of petrologic sequence should therefore have the same requirement. The petrologic 'type 7' classification, which was first introduced by [8], still remains controversial because of ambiguous heat sources associated with these meteorites (i.e. decay of ^{26}Al or impact-related heating). A handful of ordinary and enstatite chondrites are classified as 'type 7 chondrites' [e.g. 1-2, 8-9], but carbonaceous chondrites have yet to be regarded under this classification.

The CK (Karoonda-like) chondrites are a highly oxidized (>FMQ) group of carbonaceous chondrites [2,10]. All of the CKs plot on/near the CCAM line for oxygen isotopes, contain refractory lithophile abundances ~1.2x greater than CIs, have little to no metal grains, and NiO-rich olivine [2,11]. CKs are the only group of carbonaceous chondrites that have experienced the full range in chondritic thermal metamorphism (i.e. types 3 to 6). Geochemical analyses show this temperature range equates to ~576-867 °C [12]. Some CKs have also exhibited shock and melt veins, indicating the CK parent body has possibly experienced higher temperatures and/or pressures [2,13].

Northwest Africa (NWA) 8186 was originally classified as an ungrouped achondrite that showed similarities to the CK chondrites [14-15]. It was later shown that an 'achondritic' classification may be unfitting [16], and this meteorite more closely resembles a recrystallized chondrite. NWA 8186 is isotopically and geochemically similar to the CKs [14-15], contains similar rare mineral phases like arsenides [17], and is comparable in oxygen fugacity (>FMQ) [15] to the CKs. While this meteorite strongly resembles a CK, it texturally appears to be of a higher petrologic type than CK6.

In this current study, we present bulk REE abundances in NWA 8186 and U-Pb ages to assess the relationship between NWA 8186, CK3-6 chondrites, and the CK parent body.

Methodology: A 1 x 0.5 cm polished mount of NWA 8186 was used to obtain rare earth element (REE) abundances in silicates and phosphates, and U, Th, and Pb concentrations from merrillite and apatite by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) at the University of Houston. The Varian 810 ICP-MS was equipped with a 193 nm excimer laser that we focused to a 50 µm diameter and operated at a repetition rate of 8 Hz. We used U.S.G.S. basalt glasses BHVO-2G and BIR-1G as standards for the silicates, and a NIST glass and three apatites (Yates Mine, Madagascar, and Bear Lake) as standards for the phosphates. Trace element concentrations were processed using the Glitter Software, and MgO and CaO concentrations were linked to previously obtained electron microprobe data [15]. Bulk REE values were calculated through modal recombination, excluding oxides and sulfides since the elements of interest are negligible in these phases. U-Pb and Pb-Pb ages were obtained using the Wavemetrics Igor Pro software, and Concordia diagrams were plotted with IsoPlot. Corrections for common Pb used solar system initial Pb isotope compositions of ^{206}Pb/^{204}Pb = 9.307 and ^{207}Pb/^{204}Pb = 10.294. Random and systematic uncertainties follow the methods in [18].

Results: Bulk REE patterns from NWA 8186 and CK chondrites [4,6] normalized to CI chondrites [19] are given in Figure 1. CK meteorites from different petrologic types (3-6) are given to compare the compositional effect of heating. With the exception of Y-82191, NWA 8186 contains a higher abundance of REEs compared to the majority of the listed meteorites, especially light REEs. An Eu anomaly was not observed, and there was a slightly positive Tm anomaly (Tm/Tm*=1.166) in NWA 8186.

U and Pb isotope analysis of seven merrillite grains yield a weighted average ^{207}Pb/^{206}Pb date of 4553 ± 21 Ma (Figure 2).

Discussion: The concentration of REEs in NWA 8186 is within the range of the lower REE-bearing CKs and Y-82191, which contains an exceptionally high REE concentration [6]. NWA 8186 contains a higher

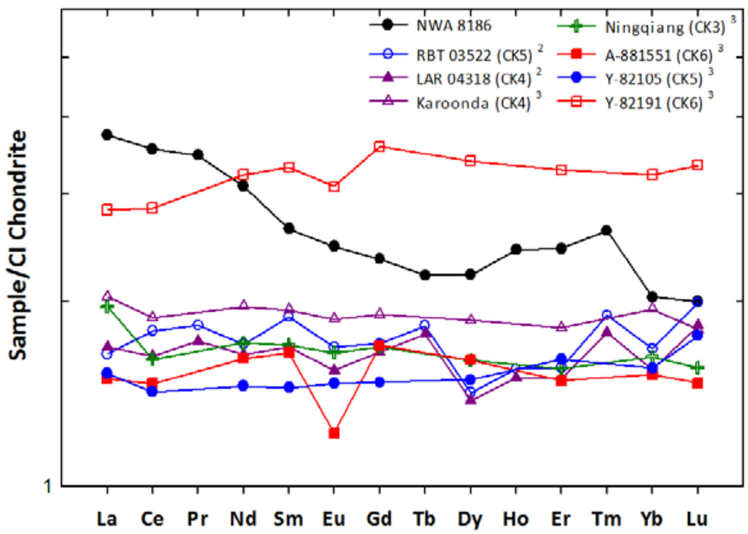

Figure 1. *NWA 8186 and CK chondrite [4,6] REE patterns normalized to CI chondrite. NWA 8186 has higher REE abundances than the other CKs, with the exception of Y-82191 [6]. A Tm anomaly is also observed in NWA 8186, similar to some of the other CKs.*

abundance of phosphates (1 vol.%) compared to other higher petrologic type CKs, so the elevated light REE concentrations may be due to modal variations. Petrologic type does not correlate with REE concentrations [6], as the two CK6 chondrites overall have the lowest and highest REE values, and NWA 8186 plots between these two samples. CKs typically display a negative Eu anomaly [4,6] or none at all [6], comparable to NWA 8186. The positive Tm anomaly seen in NWA 8186 has also been observed in other CK and CV chondrites [4,5]. Geochemically, NWA 8186 plots within the range of CK meteorites with respect to REE abundances.

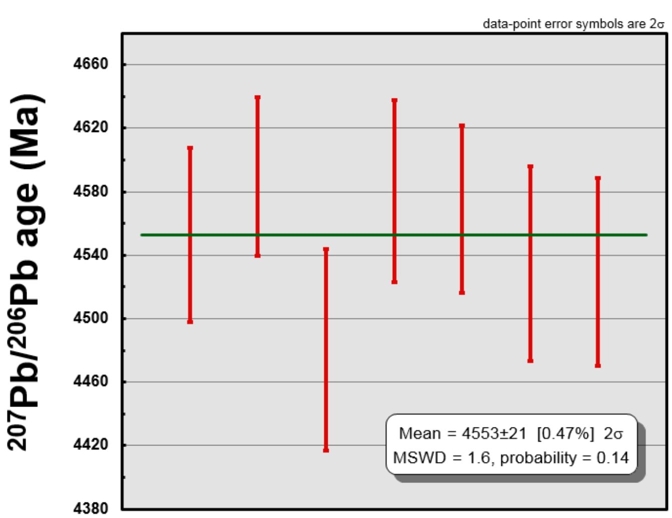

Figure 2. *Weighted average plot of $^{207}Pb/^{206}Pb$ from merrillite grains in NWA 8186 giving a date of 4553 ± 21 Ma.*

The CK parent body is thought to have accreted ~2.6 ± 0.2 Ma after CAI formation [20]. Merrillite can be easily reset by impacts, so the old merrillite date of 4553 ± 21 Ma rules out heating by late impact processes. We interpret this to be a crystallization age. However, this age can imply that either: 1) NWA 8186 was heated by the decay of short-lived isotopes on the CK parent body, or 2) NWA 8186 was heated by early impacts immediately following formation on the parent body.

Due to the similarities in bulk composition (major, minor, and trace), mineralogy, and isotopes [14-17], we are classifying NWA 8186 as a CK chondrite. Texturally, NWA 8186 differs from all known CK6 meteorites, and it appears to have undergone a higher degree of heating. Therefore, we are further classifying NWA 8186 as a type 7 CK chondrite. The age we obtained of 4553 ± 21 Ma leads us to believe that this meteorite crystallized and was heated on the CK parent body. Although an impact origin may be possible as a heat source, NWA 8186 lacks any clear evidence for melting or high pressure phases. All of the silicate phases are homogeneous (including plagioclase), and many triple junctions are present between mineral phases, indicating slow cooling. Although the 'type 7' classification has not previously been used to describe carbonaceous chondrites, we believe it is more fitting than an 'achondritic' or 'CK6' classification.

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