THE AGE OF LUNAR FERROAN ANORTHOSITE 60025 WITH IMPLICATIONS FOR THE INTERPRETATION OF LUNAR CHRONOLOGY AND THE MAGMA OCEAN MODEL. Lars Borg[1], James Connelly[2], Maud Boyet[3], and Richard Carlson[4]. [1]Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore CA USA.[2] Centre for Star and Planet Formation, University of Copenhagen, Denmark. [3]Chargée de Recherche Laboratoire Magmas et Volcans, Clermont-Ferrand, France. [4] Department of Terrestrial Magnetism, Washington, DC USA

Introduction: The Moon formed through accretion of materials ejected from the proto-Earth after impact with a Mars-sized body [e.g. 1]. The heat of accretion resulted in the formation of a lunar magma ocean, many hundreds of kilometers in depth, which cooled to produce a variety of cumulate rocks [2-3]. Early formed cumulates crystallized at high temperature and pressure and are rich in olivine and pyroxene, whereas cumulates that formed later are rich in plagioclase. Some plagioclase-rich cumulates floated on the magma ocean and became the earliest lunar crust, with ferroan anorthosites (FANs) representing the primary rock type of these cumulates. Efforts to determine the age of the Moon have focused extensively on the chronology of these cumulates.

Analytical techniques: We have: (1) obtained a unique mafic-mineral rich sample of FAN 60025 found by examining the lunar collection at the Johnson Space Center in person, (2) applied a new innovation to Pb-Pb chronometry in which samples are washed numerous times until most unradiogenic Pb contamination is removed, and (3) produced a 99.988% pure ^{150}Nd spike that allowed ^{146}Sm-^{142}Nd and ^{147}Sm-^{143}Nd chronometry to be applied to the same mineral fractions without need for correction of ^{142}Nd from the spike.

A photograph of the clast and an illustration of the mineral separation procedure are presented in Figs. 1-2. The sample was crushed into coarse fragments. Mafic (mostly pyroxene) and felsic (mostly plagioclase)-rich fragments were high-graded into two fractions using tweezers. There remained a third fraction that was a 50-50 mixture of mafic and felsic minerals, but was too fine-grained to be high-graded using the tweezers. The coarse mafic and mixed mafic/felsic fractions were crushed in a sapphire motor and pestle and sieved at 75-200, 200-325, and <325 mesh. Pyroxene and plagioclase were magnetically purified from the 75-200 and 200-325 mesh fractions. Pyroxene and plagioclase from the various fractions were combined. Visual inspection indicated that the pyroxene and plagioclase fractions were >99% pure.

Results: We previously reported a Pb-Pb age for 60025 of 4382 ± 8 Ma determined on a 10 mg pyroxene fraction [4]. We have reanalyzed a larger 105 mg pyroxene fraction, as well as determined ^{146}Sm→^{142}Nd ($t_{½}$ = 103 Ma) and ^{147}Sm→^{143}Nd ($t_{½}$ = 106 Ga) ages using pyroxene, plagioclase, and whole rock fractions. The lead isotopic compositions were determined on

Figure 1. Photograph of 60025 sample used in this study. Note large proportion of pyroxene (green) in the sample.

washes and progressive dissolution steps of two splits of the pyroxene fraction and one split of the plagioclase fraction. The last dissolution step from the small pyroxene split and 4 of 6 dissolution steps from the large pyroxene mineral split define a line corresponding to an age of 4359.2 ± 3.4 Ma [Fig. 3].

The washes from the small pyroxene mineral split have an isotopic composition near modern terrestrial Pb and become progressively more radiogenic with washing steps. The dissolution steps from both this split and

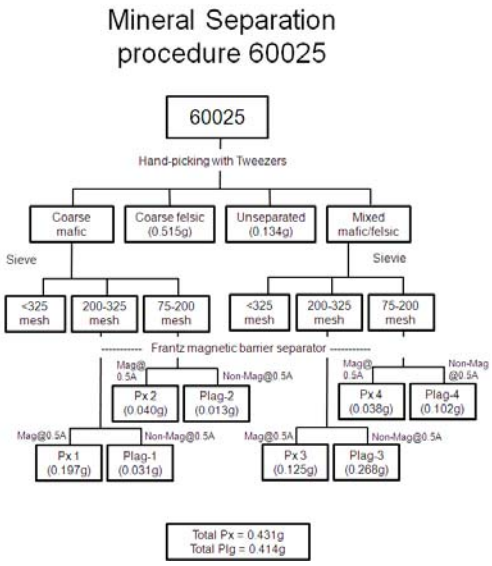

Figure 2. Mineral separation procedure for 60025.

the larger pyroxene mineral split follow the same trend with the most radiogenic fraction having a $^{204}Pb/^{206}Pb$ ratio of 0.000774. The y-intercept is interpreted to represent the closure of the system during crystallization or impact metamorphism.

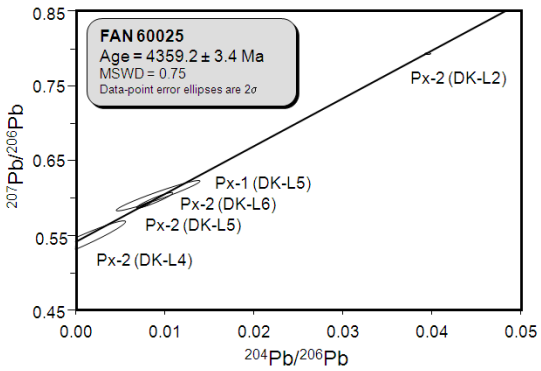

Figure 3. Pb-Pb age of 60025 defined by progressive dissolution of 2 pyroxene splits.

The isochron age determined using ^{147}Sm-^{143}Nd is 4367 ± 11 Ma, whereas the age determined using the ^{146}Sm-^{142}Nd system is 4312 +28/-35 Ma [Fig. 4]. The ^{147}Sm-^{143}Nd age determined here is 73 Ma younger, and outside of error, of that determined previously for 60025 [5]. We do not understand the cause of this discrepancy, but note that the much larger sample sizes used here allow significantly higher precision. This, plus the concordance of Sm-Nd and Pb-Pb ages suggest that the new result improves on the accuracy of earlier work. The two coupled Sm-Nd chronometers are discordant by 16 Ma. This could reflect isotopic disturbance, an underestimation of uncertainty, or an underestimation of the ^{146}Sm half-life. Regardless of the cause of the discrepancy between ^{147}Sm-^{143}Nd and ^{146}Sm-^{142}Nd ages, the extremely limited variation in $^{142}Nd/^{144}Nd$ between the mineral separates is consistent with a young (i.e. < 4.5 Ga) age for 60025.

Discussion: The weighted average of all ages determined in this study is 4360 ± 3 Ma. Lack of evidence for extensive modification by impact metamorphism, combined with the concordance of ages suggest that this represents the crystallization age of the sample. If 60025 is a flotation cumulate of the lunar magma ocean, its young crystallization age requires the solidification of the magma ocean, and formation of the Moon, to have occurred later than most previous estimates [6-8]. In this interpretation, ages older than 4360 ± 2 Ma must be in error. A magma ocean origin for 60025 is supported by the similarity between the ^{146}Sm-^{142}Nd systematics of the mare basalt source regions and 60025, as well as numerous petrologic/geochemical models (e.g. 1-3]. The ^{146}Sm-^{142}Nd systematics suggest that both suites of rocks formed from sources with very similar initial Nd isotopic compositions at roughly the same time [inset Fig. 4]. Alternatively, the young age of 60025 might indicate that it is not a flotation cumulate of the magma ocean, but rather was produced by a more recent melting event [9]. The advantage of this scenario is that it does not require dismissing the older ages determined on lunar samples. The disadvantage is that it requires many samples whose characteristics are used to constrain and develop the magma ocean theory to be produced by a different process.

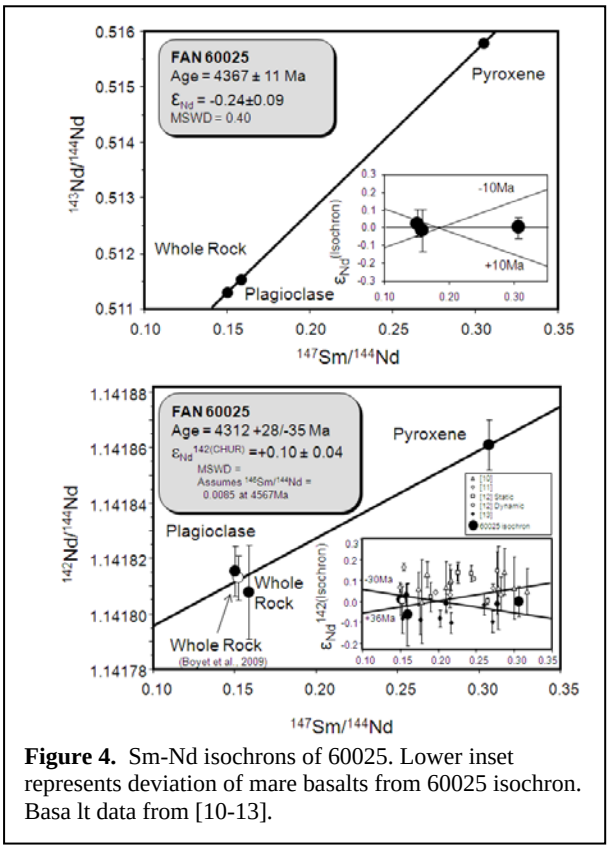

Figure 4. Sm-Nd isochrons of 60025. Lower inset represents deviation of mare basalts from 60025 isochron. Basa lt data from [10-13].

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