CHRONOLOGY OF ALKALI ANORTHOSITE CLAST ‘b’ RECORDS IMBRIUM IMPACT AT ~3.95 Ga.

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Introduction: Alkali-suite rocks constitute one of three major suites of lunar crustal rocks. As such, constraining their formation timescales and petrogenesis is important for understanding the earliest magmatic history of the Moon. However, the magmatic history of alkali-suite rocks is partly obscured by superimposed effects of major basin-forming impact events on the lunar nearside [1]. Consequently, unambiguous crystallization ages of samples from this suite rocks have not been obtained [2]. Prior studies have mainly focused on U-Pb analyses of detrital lunar zircons found mostly in Apollo 14 breccias, which reveal a peak at ~4.34 Ga but a distribution that tapers to the age of Imbrium impact basin around 3.9 Ga [2,3]. This range in ages either implies that alkali-suite magmatism occurred continuously over several hundred Ma, or alternatively, that measured zircons record both igneous and impact events. As such, the exact timescale of alkali suite magmatism remains unconstrained.

An alternative approach for constraining the timing and duration of alkali-suite magmatism is to date igneous rocks belonging to the alkali suite. However, these rocks are only preserved in clasts found in lunar breccias [4]. Until now, only one attempt has been made to date these rocks using isochron techniques. Snyder et al. [5] reported Rb-Sr and Sm-Nd isotopic data for an alkali anorthosite clast from lithic breccia 14304 (clast “b” [6]). The results, however, were inconclusive because Rb-Sr and Sm-Nd chronometry completed on the same mineral fractions yielded discordant ages of 4336±86 Ma and 4108±53 Ma. The initial goal of this study was to derive an accurate age of clast “b” and define the temporal relationships between the alkali suite and other lunar crustal lithologies. Below we report Rb-Sr, Sm-Nd, and Ar-Ar chronological results determined on clast “b”.

Sample and methods: The clast is reported to contain plagioclase, pyroxene, and impact melt [5,6]. Our examination found only a trace amount of pyroxene and an abundance of impact melt revealing that the clast primarily consists of coarse-grained crystalline plagioclase (~95%) and a smaller portion of quenched impact melt (~5%). The size, coarse-grained nature, and pristine texture of the plagioclase imply that it is an igneous phase that formed during slow cooling at substantial depth within the lunar crust [e.g., 7]. By contrast, the quenched texture of the impact melt indicates *in situ* formation by a localized shock event.

After petrographic examination the clast was broken gently in a sapphire mortar and sieved. Minerals were separated using a Frantz magnetic separator and handpicking. This resulted in pure plagioclase fractions (‘Plag-1’ and ‘Plag-2’), an impact melt–enriched fraction (‘IM’), and two fined-grained mixed fractions. All fractions were leached in 2M HCl, digested in mineral acids, and then spiked with mixed ^{87}Rb-^{84}Sr and ^{149}Sm-^{150}Nd tracers. Following separation by ion exchange chromatography, Rb, Sr, Sm, and Nd isotopic compositions were measured on a ThermoScientific Triton TIMS at LLNL. A handpicked plagioclase separate was analyzed for Ar isotopes in the Livermore Noble Gas Lab following [8].

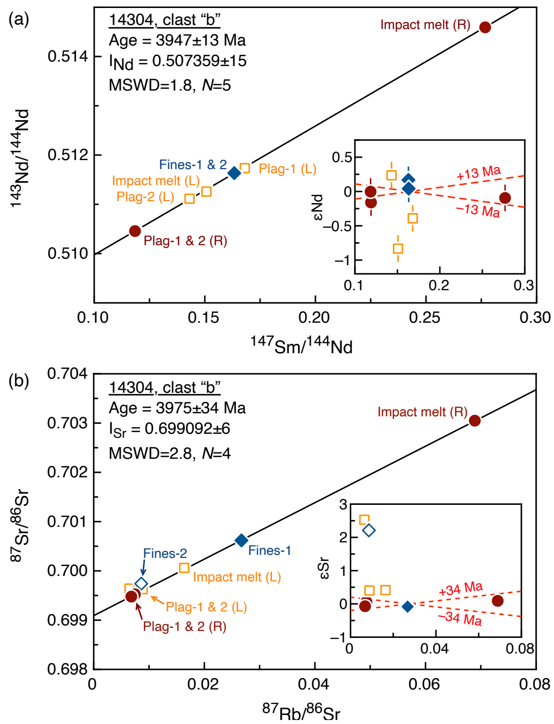

Fig. 1: Isochron diagrams displaying (a) Sm-Nd and (b) Rb-Sr results for 14304, clast “b” from this study.

Results: The Sm-Nd data for the leached fractions exhibit a well-defined ^{147}Sm-^{143}Nd isochron with little scatter (MSWD=1.8), yielding an age of 3947±13 Ma and an initial ε^{143}Nd of –2.64±0.11 (Fig. 1a). The Rb-Sr data exhibit more scatter, but an age of 3975±34 Ma is defined if only leached mineral fractions (i.e., Plag-1. Plag-2, and IM) and the Fines-1 fraction are included in the regression (Fig. 1b). The ^{40}Ar/^{39}Ar step ages of plagioclase from clast “b” define a plateau at higher

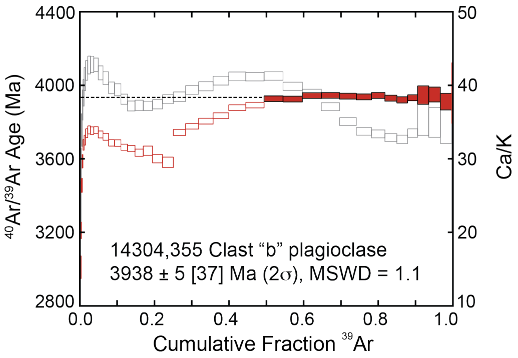

Fig. 2: ^{40}Ar/^{39}Ar age (red) and Ca/K (gray) spectra plotted against the cumulative fraction of ^{39}Ar released.

extraction temperatures (1100–1325 °C) with a weighted mean age of 3938±37 Ma (Fig. 2). Thus, three chronometers independently produce concordant ages, resulting in a weighted mean of 3949±12 Ma. The concordant Sm-Nd, Rb-Sr, and Ar-Ar ages for 14304 ,335 clast "b" contrast with the discordant Sm-Nd and Rb-Sr of ~4.11 Ga and 4.34 Ga obtained previously for clast "b" [5]. The cause of this disparity is not fully clear, but we note that the mineral fractions in the previous study were not leached.

Discussion: Our results provide evidence that isotopic equilibrium between the components in clast "b" was established at 3949±12 Ma. However, the ages are based on components (crystalline plagioclase and impact melt) that are not expected to be in isotopic equilibrium. Thus, a mechanism for establishing isotopic equilibrium between components produced during igneous crystallization and impact metamorphism is required. One possibility is that the ~3.95 Ga age dates igneous crystallization within the lunar crust because the impact melt preserves the isotopic systematics of mafic igneous phases. However, this is unlikely because it is difficult to produce notable quantities of impact melt and not reset the Ar-Ar system. It is also inconsistent with a large amount of plagioclase inferred in the impact melt. Moreover, the initial Sr and Nd isotopic compositions derived from the isochrons are extremely low and do not resemble known lunar samples. Instead, these low initial values are consistent with production of the isochrons during metamorphism of an ancient plagioclase-rich protolith around 3.95 Ga. Mixing models support this conclusion by demonstrating that *in situ* melting of igneous pyroxene and plagioclase followed by incorporation into impact melt can in fact produce isochrons defined by plagioclase and impact melt that record the impact event. Thus, the chronology likely records the age of a major impact event.

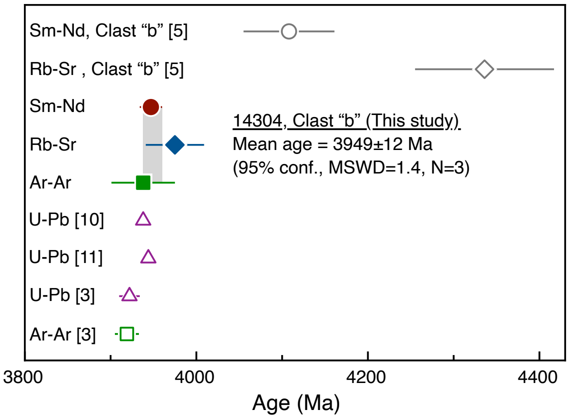

Fig. 3: Ages obtained for 14304 clast "b" analyzed in this and prior work [5] in comparison with Ar-Ar and U-Pb ages of Apollo 14 rocks and other landing sites [3, 10, 11].

The mean Ar-Ar, Rb-Sr, and Sm-Nd age of 3949±12 Ma is in excellent agreement with independent estimates for the formation of Imbrium basin ejecta (Fig. 3) which are thought to have been sampled at the Apollo 14 site [3,10,11]. Thus, although petrologic and geochemical examination suggests that clast "b" is a pristine igneous clast, the chronology determined here, based heavily on analysis of impact melt, does not constrain the timescales of alkali-suite magmatism.

Our results illustrate that the isotopic record of apparently igneous rocks can be severely overprinted by a large basin-forming impact, not only for systems that are typically used to disentangle impact events, (e.g., Ar-Ar), but also for other chronometers that are considered more resilient to impact resetting (e.g., Sm-Nd). For the Rb-Sr and Sm-Nd systems mixing of primary protolith minerals at ~3.95 Ga was likely responsible for establishing Sr and Nd isotopic equilibration between relict minerals that survived the impact process and impact melt that was produced in the process. This offers a cautionary note regarding the need for petrographic examination of all dated materials. The age of clast "b" would almost certainly have been interpreted as an igneous event without the recognition that (1) one end of the Rb-Sr and Sm-Nd isochrons was defined by impact melt, and (2) the concordance of the ages to those postulated for the Imbrium impact. Thus, simply identifying seemingly pristine igneous rocks does not guarantee that the measured ages reliably record igneous events associated with their genesis.

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