ALTERNATIVE INTERPRETATIONS FOR THE REVERSED ZONING IN PLAGIOCLASE OF ALKALI ANORTHOSITE 14305,303.

Hejiu Hui[1] and Clive R. Neal[1], [1]Department of Civil & Environmental Engineering & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556.

Introduction: Deciphering the origin and evolution of the lunar highland crust is crucial to understanding of the Moon's early magmatic (and impact) history. Three major groups of highland rocks have been discovered based on the returned Apollo samples and lunar meteorites: ferroan anorthosite suite (FAN), Mg suite (HMS) and alkali suite (HAS). HAS is only a minor component of the lunar crust in terms of total volume based on the available samples. As its name suggests, HAS has anomalously high alkali contents (generally >0.1 wt% K_2O and >0.3 wt% Na_2O) while the bulk Moon is known to be depleted in alkali elements [1]. Despite its unique high alkali contents and importance to understanding of lunar petrogenesis, study of these rocks is difficult due to their small size.

It has been recognized that the HAS was not related to mare basalts [2], nor had a close affinity to ferroan anorthosite [3]. However, the incompatible trace element data and Sm-Nd isotopic systematics suggest a link between HMS, HAS and KREEP [1]. It has been suggested that both HMS and HAS were cumulate products of continuous crystallization of parental basaltic magmas similar to the KREEP basalts [e.g., 1,3,4]. Shervais and McGee [4] further concluded that magma mixing, anorthosite assimilation and post-cumulus reequilibration involved in the formation and evolution of alkali anorthosite in addition to fractional crystallization in a KREEP-like basalt parental magma.

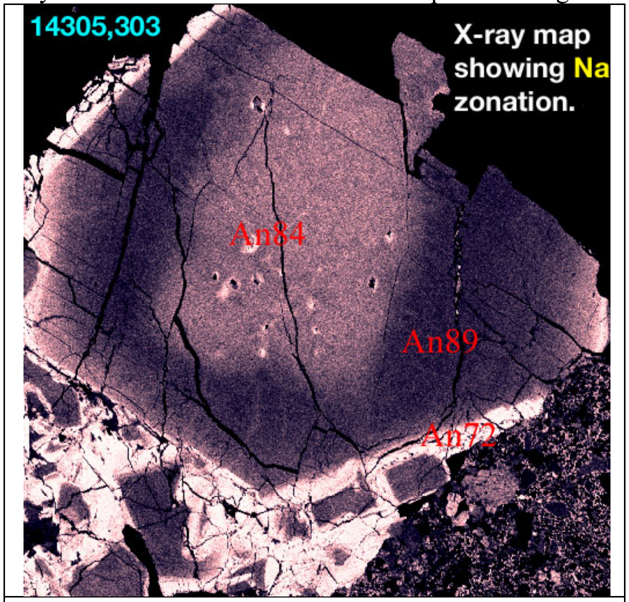

Fig. 1. X-ray map of one large plagioclase grain showing Na zonation. Lighter shades mean more Na. The view is ~2 mm in the largest dimension.

Reversed zoning in plagioclase of alkali anorthosite 14305,303 has been cited as evidence for magma mixing [5,6] (Fig. 1). Cumulus plagioclase grains in alkali anorthosite 14305,303 have cores of ~An_{84}, rims of ~An_{89} and overgrowth of An_{72} (Fig. 2). The cores consist of irregularly shaped patches, while the rims have euhedral shapes (Fig. 1). In this study, we focus on reconstructing this reversed zoning by adjusting temperature, pressure and melt composition. The results from this modeling provide further insights into the petrogenesis of this unique alkali anorthosite.

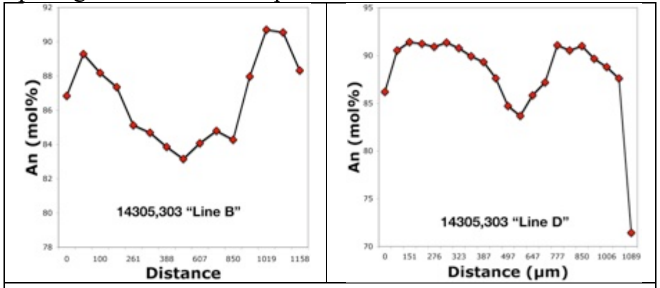

Fig. 2: Traverses "Line B" and "Line D" of [6] across the large plagioclase shown in Figure 1

Reconstruction of Reversed Zoning: Recent data have shown that urKREEP could have contained up to ~1.4 wt% water [7]. Therefore it is possible that water played a role in petrogenesis of the HAS. It is recognized that the anorthite concentration in plagioclase increases strongly with both temperature (e.g., [8]) and water concentration in the melt (e.g., [9]). It is also well known that increasing pressure favors a more sodic plagioclase (e.g., [10]). The presence of the reversed zoning in plagioclase of 14305,303 could be caused by any or a combination of these three factors. A thermodynamic model for the plagioclase-melt equilibrium [11] has been used to test the effects of these three melt properties on the plagioclase composition.

Due to the nature of the cumulate rock, it is extremely difficult to infer the parental magma of this type of sample. Indeed, there is no definitive major element composition for the parental magmas of alkali anorthosite confirmed in the literature [12]. However, it has been demonstrated that KREEP-like basalts may be the parental magmas of alkali anorthosite [1,12]. The average composition of Apollo 15 pristine KREEP basalts [1] was used as the melt equilibrated with the plagioclase core in Fig. 1. The plagioclase cores were assumed to crystallize at 5 kbar, roughly the depth where the first plagioclase crystallization occurred in the lunar magma ocean [12]. Using the plagioclase-melt hygrometer/thermometer [11], a temperature of

1423 K was calculated for plagioclase cores of ~An_{84} to crystallize in the dry melt (Fig. 3). The temperature, pressure and water content in the melt were also calculated that produced the rim of ~An_{89} (Fig. 3).

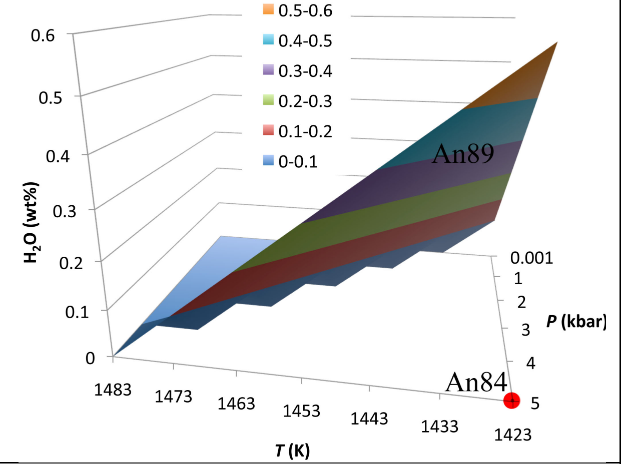

Fig. 3. The conditions of pressure, temperature and water content of the KREEP parental melt, at which plagioclase of An_{84} or An_{89} were equilibrated with Apollo 15 KREEP basalt [1].

Discussion: Calculations indicate that either of adding 0.6 wt% of water in the melt or increasing the melt temperature by 60 K alone could increase the anorthite content in plagioclase rims to An_{89} from An_{84} in the cores. Melt decompression from 5 kbar to 1 bar alone does not appear to be adequate to increase the anorthite content observed in alkali anorthosite 14305,303 (Fig. 3). Therefore, we examined a combination of factors in order to generate the observed zonation. In addition to decrease of pressure, either an increase of water in the melt of only 0.1 wt%, or an increase in melt temperature of only 10 K would increase the anorthite content in plagioclase from 84% to 89% (Fig. 3). However, these small changes are at the limits of precision for the methods used to calculate them [11].

Crystallization of alkali anorthosite 14305,303 occurred from a KREEP-rich melt [6] at some depth within the lunar crust. Apollo 15 KREEP basalts crystallize plagioclase from ~An_{90} to <An_{75} (e.g., [13]). While the modeling calculations require better fidelity, it is possible that water played a role in creating the zonation patterns in 14305,303. We suggest the following scenarios to explain the zonation within plagioclase of 14305,303 as alternatives to magma mixing (cf. [5,6]). It has been demonstrated that increase of melt temperature is possible in any hydrous magma that decompresses slowly to permit crystallization [14]. Owing to the release of latent heat of crystallization, the temperature of ascending magma could increase by up to 100 K [14]. This suggests that the reversed zoning in plagioclase of alkali anorthosite 14305,303 could be caused by decompression heating process in the ascending KREEP parental magma. The irregular boundary of cores (Fig. 1) is consistent with those of terrestrial plagioclases that have reversed zoning [14].

Alternatively, crystallization of plagioclase occurred from a parent magma similar to KREEP basalt, which increased the H_2O content of the residual magma by ~0.1 wt%, causing subsequent plagioclase to crystallize with a higher An content. During this crystallization, the magma migrated toward the lunar surface. The precipitous drop in An content at the very edge of the plagioclase (Figs. 1 and 2) is consistent with magma degassing. 14305,303 potentially contains further evidence that KREEP lunar magmas contained significant water.

Conclusion: While further work is needed to refine the modeling for the thermometer/hydrometer used in this study, other scenarios are possible that could account for the reversed zonation in plagioclase from 14305,303. One of these involves an increase in water content of the parent magma, which could imply that the role of water in the petrogenesis of the HAS needs to investigated.

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