Diffusion Chronometry Applied to Plagioclase in Troctolite 76535 to Resolve Magmatic Cooling History

W S Nelson[1], J Hammer[1] , T Shea[1], E Hellebrand, G.J. Taylor[1], [1] Department of Geology and Geophysics, University of Hawaii at Manoa, Honolulu, HI USA.

Introduction: Troctolite 76535 has been called "without a doubt the most interesting sample returned from the Moon [7]. The rock preserves geochemical features that constrain our understanding of the early lunar interior, specifically the model of the Lunar Magma Ocean (LMO) and, as 76535 is a member of the Mg suite, the subsequent cumulate overturn [2,4,6]. The very existence of the Mg suite requires mingling of materials from a range of depths in the post-crystallization LMO; thus, the troctolite parent melt must have formed after cumulate overturn.

Petrographically, this sample appears to be among the slowest-cooled igneous materials in the solar system [1, 4, 5, 8], and yet fine scale Phosphorus enrichment patterns in olivine indicates rapid crystal growth, which is inconsistent with very slow cooling [9]. We are addressing the magmatic cooling history of 76535 using diffusion chronometry, and report here the results of the technique as applied to the distribution of sodium in plagioclase crystals.

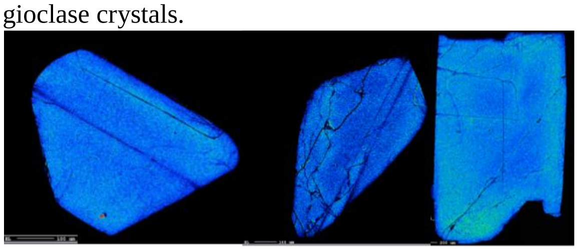

Fig 1: Sodium X-ray intensity maps of three plagioclase crystals surrounded by olivine or orthopyroxene.

Methods: We apply the technique of diffusion chronometry to the coupled substitution of calcium + aluminum for sodium + silicon in plagioclase phenocrysts in sections 46, 52, 53, and 150. Raw data include electron microprobe X-ray intensity maps revealing the relative abundance of sodium at the subgrain scale, and quantitative WDS-EPMA concentration profiles anchoring the sodium abundances at discrete spots. The low (but detectable) abundance of sodium varies coherently within grains, making sodium the best candidate to track diffusion in these crystals. Both the X-ray intensity maps and the microprobe profiles were collected with the JEOL JXA 8900 RL electron microprobe at the University of Hawaii at Manoa.

Plagioclase crystals that are isolated from other sodium bearing phases contain a concentric band of elevated sodium near the outer margins (**Figure** 1). These bands are interpreted as vestiges of normal compositional zoning that formed during growth from a liquid, which has since relaxed via diffusive homogenization. Employing plausible assumptions about initial and boundary conditions, we forward calculate the distributions of sodium through time along various temperature-time trajectories representing linear and decelerating cooling. We quantitatively compare the simulated 2D sections with both the EPMA intensity maps and transects in order to evaluate the model misfit and generate families of preferred solutions.

Modeling: Fick's Second Law was used to simulate, by the method of finite differences, the diffusive relaxation of a (presumably) initially-sharp Na concentration profile. The initial concentration profile was chosen based on total amount of sodium in the sample, elemental concentrations of less mobile elements (eg, magnesium, which is in greater abundances for the anorthite portion of each grain). The diffusivity of sodium was assumed equal to the coupled diffusion of Na and Si for Ca and Al by Grove et al [10].

Results: Preliminary results indicate that initial cooling is rapid. The best fit linear cooling model was found to have a cooling rate of 1235ºC/Myr, and a total cooling time of only 344,000 years. If the rock underwent decelerating cooling, as is consistent with thermal conduction better fits to data are observed (**Figure 2**). In this case 826,000 years elapsed as the sample cooled from 1300 to 900ºC (**Figure 3**). Regardless of the thermal history, the cooling through magmatic temperatures must have been relatively rapid in order for sodium zoning to be preserved at all. The implication of these results is that the magmatic age is likely to be fairly similar to the radiometric age of troctolite 76535 [2,7], and certainly not hundreds of millions of years older than the magmatic age [3]. Initially rapid cooling places a firm constraint on physical models of the emplacement of the troctolite parent magma, and by association, other Mg suite plutonic rocks as well.

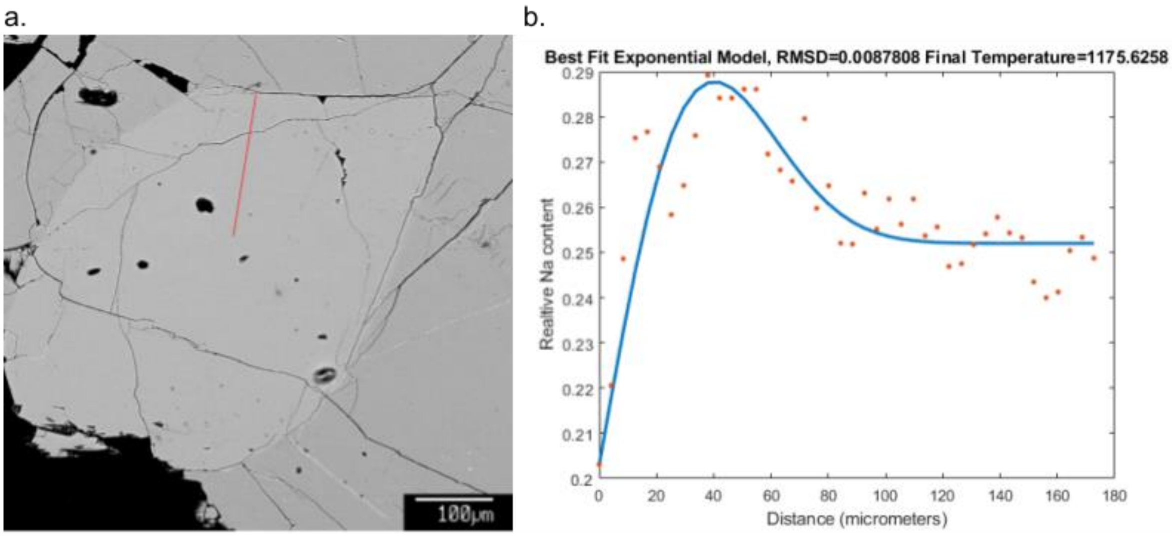

Figure 2: Transect 1 on sample 52.

a) Secondary electron image of grain, with red line showing position of the transect
b) Points found on transect (red), and best fit model (blue). Note Two points with bad totals were found, and were given adjacent point's values.

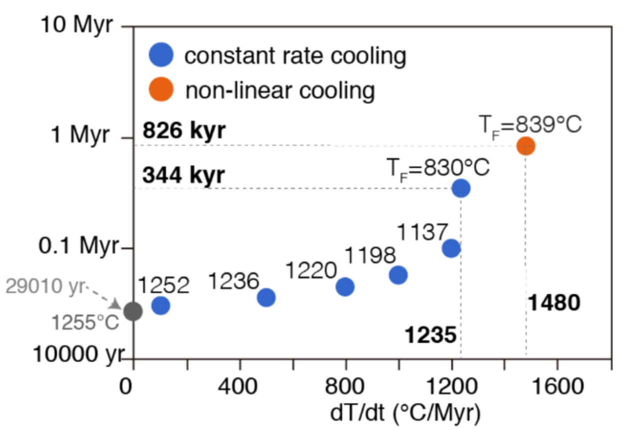

Figure 3: Cooling times for various models plotted against different cooling rates.

References: [1] Borg L, Connelly J, Cassata W, et al (2013) 44th Lunar Planet Sci Conf #1563.[2] Borg LE, Gaffney AM, Shearer CK (2014) Meteorit Planet Sci 732:715–732. doi: 10.1111/maps.12373 [3] Borg L, Connelly J, et al (2017) Geochim Cosmochim Acta 201:377-391, [4] Gooley R, Brett R, Warner J (1974) Geochim Cosmochim Acta 38:1329–1339. Doi: 10.1016/j.coviro.2013.06.011.Epub [5] Lindsley DH, Andersen DJ (1983) J Geophys Res Suppl 88:A887–A906 [6] McCallum IS, Domeneghetti MC, Schwartz JM, et al (2006) Geochim Cosmochim Acta 70:6068– 6078. Doi:10.1016/j.gca.2006.08.009

[7] Meyer, C. (2011). 76535. In Lunar Science Compendium. [8] Nord GL (1976) 76535: Proc Lunar Sci Conf 7th 1875–1888. [9] Hammer J.E et al (2017) 48th Lunar Planet Sci Conf #1274 [10] Grove TL, Baker MB, Kinzler RJ (1984) Geochim Cosmochim Acta 48:2113-2121