TESTING THE ORIGIN OF IMPACTITES AT THE APOLLO 17 LANDING SITE: U-Pb AGES OF BADDELEYITE IN BRECCIA 77035.

T. A. Duerr[1], H. Becker[1], W. H. Schwarz[2], D. Vanderliek[1], [1]Freie Universität Berlin, Institut für Geologische Wissenschaften, Malteserstr. 74-100, 12249 Berlin, Germany (t.duerr@fu-berlin.de), [2]Universität Heidelberg, Institut für Geowissenschaften, Im Neuenheimer Feld 234-236, 69120 Heidelberg, Germany (winfried.schwarz@geow.uni-heidelberg.de).

Introduction: Early studies of the geology of the Apollo 17 landing site (A17) proposed that all sampled formations (North and South Massif, Sculptured Hills) may represent ejecta from the Serenitatis impact, because of the close proximity of the Taurus-Littrow valley to the basin [1-3]. Accordingly, ages of around 3.9 Ga from impact melt breccias sampled at the landing site in conjunction with a slightly younger proposed age for the formation of the Imbrium basin (~3.8-3.9 Ga) were used to support the hypothesis of a spike in the impact rate in the solar system at around 3.9 Ga (terminal lunar cataclysm, e.g. [4-6]). More recently, the reinterpretation of geological units near A17 as Imbrium deposits has shown the difficulty to reliably interpret the origin of impactites and their ages (e.g. [7-9]). The improved spatial resolution of recent images of the landing sites might be combined with state-of-the-art approaches of sample analysis to relate lunar samples to specific geological units or to test hypotheses that link samples to basin-forming events. Here we report in-situ U-Pb age data and petrographic details on baddeleyite grains in the noritic impact melt breccia 77035. The breccia was collected near the large boulder at Station 7 that can be traced by a track to an outcrop on the flank of the North Massif interpreted to represent Serenitatis ejecta [8]. Because a derivation from the large boulder is viable, but no age information was available for 77035, this work will help to assess its origin and derivation from geological units of A17.

Methods: Quantitive Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) has been applied to search for trace minerals such as baddeleyite and zircon and to map the mineralogy of thin section 77035,200 at a spatial resolution (pixel size) of 3.7 µm. Baddeleyites have been further investigated by optical microscopy and back scattered electron (BSE) imaging to establish their textural relations with adjacent minerals. U-Th-Pb concentrations and isotope ratios of baddeleyites have been measured using a spot size of ~5 µm on two days at the Heidelberg University with a CAMECA IMS 1280-HR secondary ion mass spectrometer (SIMS). Each session was bracketed by analyses of the Phalaborwa baddeleyite standard [10], 2 analyses before and 10 analyses after the session.

Results: 77035 has been described as a polymict, micropoikilitic impact melt breccia containing clasts of dunite, gabbronorite and anorthosite that were partially dissolved by the melt [11,12]. Thin section 77035,200 consists of 5 chips of rock that are roughly 2 x 1 mm in size. Three distinct domains, occur: (1) A coarse-grained olivine-bearing norite with grain sizes in excess of 300 µm for olivine, plagioclase and enstatite and no adhering impact melt; (2) fine-grained, micropoikilitic olivine norite with average grain sizes of ca. 30 µm, which represents former impact melt as indicated by intrusive relationships and the presence of Fe-Ni metal [10]; The norite is in contact with anorthosite clasts >200 µm, (3) a band of troctolite in one of the chips separates the micropoikilitic olivine norite from an anorthosite clast. The coarse-grained olivine norite comprises more sodic plagioclase and contains far less clinopyroxene (~0.15% vs. ~4%) than the micropoikilitic melt rock. Apatite occurs in all four domains, but is most abundant in the micropoikilitic olivine norite. Fe-Ni metal, K-Feldspar and baddeleyite only occur in the micropoikilitic olivine norite whereas troilite occurs in the micropoikilitic as well as the coarse-grained olivine norite. Fe-Ni metal in the micropoikilitic norite occurs in two different modes – as very small and rare grains (avg. diameter of ~5 µm) and as a single, large, elliptical grain (250 x 140 µm), presumably a former coagulated metal melt droplet. Additionally, the large grain is surrounded by disseminated troilite of varying sizes. Ilmenite is often acicular with sizes of 20-50 µm. Its occurrence is limited to the micropoikilitic olivine norite and the troctolite. The main occurrence of K-Feldspar is as a ~40 µm thick corona around a quartz grain while the K-Feldspar itself is encapsulated by enstatite and clinopyroxene. Small K-Feldspar grains (~5 µm avg. size) are also dispersed in the melt rock.

Anhedral to subhedral baddeleyite grains (about 6.5 x 4 µm) occur only in the micropoikilitic olivine norite. All four baddeleyites are intergrown with poikilitic to skeletal ilmenite (Fig. 1). Two of the four grains show fractures that are unrelated to fractures in the ilmenite and either propagate into or continue existing fractures in the surrounding plagioclase and enstatite.

Except for B1 (which yields concordant U-Pb ages), analyses are slightly reverse discordant, which likely reflects matrix or other measurement-related effects on U/Pb ratios [13]. The $^{207}Pb/^{206}Pb$ ages of the four baddeleyites range from 3924 ± 16 Ma to 3943 ± 10 Ma

and yield a mean age of 3936 ± 14 Ma (2σ, n =4, Fig. 2).

A small fraction of ^{204}Pb is present in all analyses with an average of ~0.3 cps for grains B1, B2 and B3b. B3a showed a decline in the ^{204}Pb signal over the course of the measurement with an average of ~1 cps. Common Pb contributions were corrected, assuming they reflect contamination with terrestrial average upper crustal Pb.

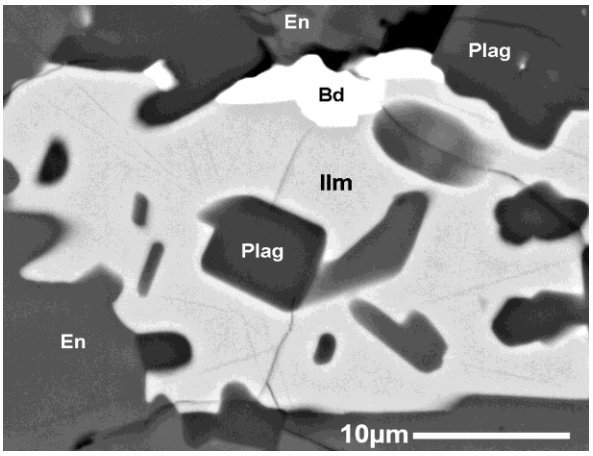

Figure 1: BSE image showing a baddeleyite (Bd) grain associated with poikilitic ilmenite (Ilm). En: Enstatite, Plag: Plagioclase

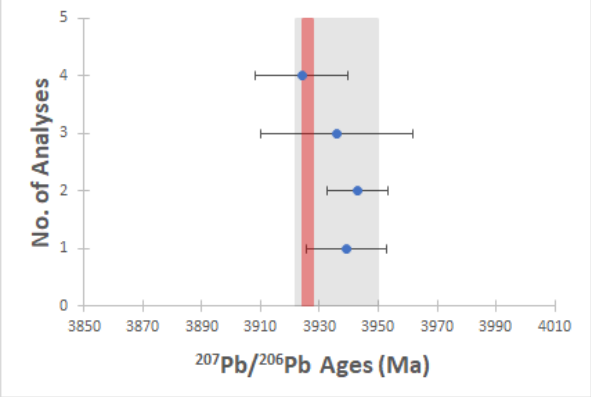

Figure 2: ^{207}Pb/^{206}Pb ages obtained *in-situ* from lunar baddeleyites. The grey line marks the mean ^{207}Pb/^{206}Pb age of 3936 ± 14 Ma while the red line is the mean ^{207}Pb/^{206}Pb age of 3926 ± 2 Ma considered most likely to be the age of the Imbrium impact [14]. Error bars are 2σ.

Discussion and Conclusion:

The presence of Fe-Ni metal in the micropoikilitic olivine norite and intergrowth textures with poikilitic ilmenite (Fig. 1) are clear indications that the baddeleyites crystallized in situ from the impact melt. The abundance of apatite in the micropoikilitic olivine norite (~0.9%) and the presence of K-Feldspar indicate a KREEP-rich component in the melt. Although it appears that the baddeleyites crystallized from the same impact melt, the ^{207}Pb-^{206}Pb ages spread from values consistent with the proposed age of the Imbrium impact (3926 ± 2 Ma, [14]) to values, about 10-15 Ma higher (Fig. 2). Because the highest value occurs in the baddeleyite with the largest common Pb contribution, the higher ages should be treated with caution. In any case, the presence of KREEP rich material in the impact melt portion, combined with the younger ages suggest that the impact melt in 77035, and thus very likely the breccia-forming event, are related to the impact that formed the Imbrium basin. Similar U-Pb ages on Ca phosphates were also reported from Station 3 at the A17 landing site, which sampled the South Massif [15]. Plausible sources of 77035 are either the Sculptured Hills (interpreted as Imbrium ejecta deposits, [7,8]) or the outcrop in the North Massif from which the boulder at Station 7 is likely derived (interpreted as Serenitatis ejecta deposits, [8]). Possibly, 77035 represents a fragment of the boulder from Station 7 as there are similarities in their petrography [12,16]. Ultimately this would mean that 77035 originates from the North Massif which then likely comprises a larger proportion of Imbrium ejecta than previously thought. We note that a smaller impact crater in the Sculptured Hills about 6 km to the east shows a noritic composition of the sub-regolith rock [8], however, it is more difficult to conceive how the rock was transported from there to its sampling site. In any case, the results show the importance of the Imbrium impact and its influence on ejecta at the A17 landing site.

Acknowledgements: We thank CAPTEM Ryan B. Zeigler, C. Guenter and T. Ludwig.

References: [1] Wolfe, E. W., and V. S. Reed (1976) *J. Res. U.S. Geol. Surv., 4*, 171–180. [2] Head, J. W. (1974a) *Moon, 9*, 355–395. [3] Wolfe, E. W. et al (1981) *U. S. Geol. Surv. Prof. Pap.* 1080, 280 pp. [4] Tera, F. et al (1974b) *Earth Planet. Sci. Lett. 22*, 1. [5] Ryder, G. (2002). *J. Geophys. Res. 107* (E4) [6] Stöffler, D. et al (2006) *Reviews in Mineral. & Geochem. 60*,519–596. [7] Spudis, P. D. et al (2011*) J. Geophys. Res., 116*, E00H03. [8] Schmitt, H. H. et al (2016) *Icarus, 298*, 2-33. [9] Bottke, W. F., and Norman, M. D. (2017) *Annu. Rev. Earth Planet. Sci, 45*. [10] Heaman L.M. (2009) *Chem. Geol. 261(1-2)*, 43-52. [11] Neal, C. R., and Taylor, L. A. (1998) *Internat. Geol. Rev., 40*(11), 945-962. [12] Meyer, C. (2011) *Lun. Samp. Comp.* [13] Wiedenbeck, M. (1995) *Chem. Geol. 125*(3-4), 197-218. [14] Snape, J. F. et al (2016) *Geochim. et Cosmochim. Acta, 174*, 13-29. [15] Zhang, B. et al (2019) *J. Geophys. Res. Plan., 124*(12), 3205-3218. [16] Simonds C.H. et al (1974) *Proc. Lunar Sci. Conf. 5th*, p. 337-353.