Large-Scale Redistribution of Heterogeneous PKT Material by the Imbrium Impact – Evidence from Petrology and U-Pb Zircon Dating of a Complex Apollo 16 Breccia.

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Introduction: The prevalence of isotopic ages at 3.9 Ga in lunar impactites from the Apollo landing sites led to the hypothesis of a spike in the impactor flux in the inner solar system at this time (lunar cataclysm, e.g. [1-5]). Ages >4.0 Ga were much less common in previous isotopic dating studies of Apollo and Luna samples. In contrast, Neukum and Ivanov [6] assumed an exponential decay of the accretion flux after formation of the terrestrial planets and predicted that many of the large lunar basins were formed prior to 4 Ga. Recent work has concluded that the interpretation of the isotopic ages of Apollo rocks sampled in the proximity of the "young" Imbrium basin may be biased because of resetting of chronometers during subsequent impact and an overall sampling bias of Apollo samples caused by the proximity of the young Imbrium basin (e.g. [7-9] and references therein). To address these issues, we present new U-Pb age data for zircons and petrologic information on the complex breccia 67915 and compare these data with previous U-Pb work on zircons that occur in lunar impactites from Apollo 15 and 16 landing sites.

Materials and Methods: Sample 67915 (Apollo 16) has been collected from Outhouse Rock and interpreted to sample the Descartes Formation [10]. The block may have been excavated by a young impact that formed North Ray crater. The sample contains heterogenous clasts, including anorthositic norites, troctolite, ferroan anorthosites, granulites, SiO_2-alkali feldspar enriched clasts and mineral fragments cemented by glass. Ar-Ar age data for clasts and matrix vary from 3.7 to 4.1 Ga [11-13]. To identify Zr-phases and to map the mineralogy of thin sections, Quantitative Evaluation of Minerals by Scanning Electron Micros-copy (QEMSCAN) has been applied at the Institute of Mineralogy and Economic Geology at the Rheinisch-Westfälische Technische Hochschule Aachen. Back Scattered Electron (BSE) and Cathodoluminescence (CL) imaging of Zr-bearing phases have been per-formed on selected grains at the GFZ Potsdam to investigate their texture. U-Th-Pb concentrations and isotope ratios have been measured using the secondary ionization mass spectrometer (SIMS) CAMECA IMS 1280 HR at the GFZ Potsdam. Zircons and spot positions were selected considering zircon size, textures and petrogenetic context. The U-Pb concentration data was calibrated against the zircon reference material 91500 [14] using the empirical relationship between Pb/U vs. UO_2/UO.

Results: Zircons in sample 67915 are either located within rock clasts or occur as mineral clasts in the fragmented matrix. Zircons are commonly small with diameters of 5 – 10 µm, except for one large grain of about 50 µm in diameter. Zircon textures are blocky, granular and skeletal. No distinct features have been observed using CL. Few zircons contain baddeleyite inclusions. The SIMS data has been acquired in two sessions. In the first session, zircon grains in section 67915,84 have been measured (,84 n=7). In session two zircon grains of both sections (,84 n=1, ,76 n=8) were analyzed. Measurements of session one are all slightly reverse discordant yielding a concordia intercept age of 4230 ± 33 Ma. Despite two slightly discordant analyses, the second session yields a concordia age of 4209 ± 16 Ma, in accordance with the first session. $^{207}Pb/^{206}Pb$ ages (n=16) range from 4200 to 4241 Ma (Fig. 1) with typical in run uncertainties of 9 - 35 Ma (2 s. d.).

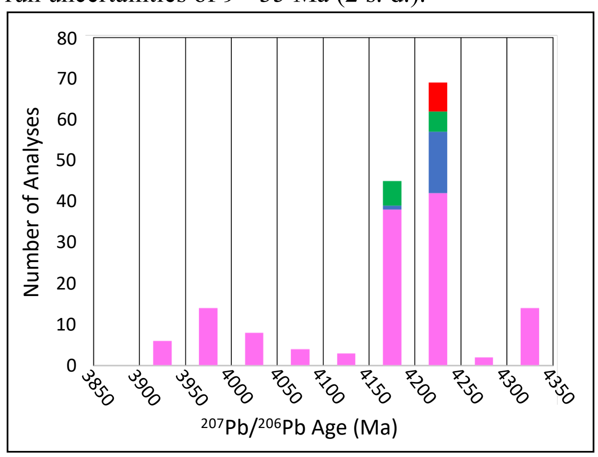

Figure 1: In-Situ $^{207}Pb/^{206}Pb$ spot ages for zircons and zirconolites that (re-) crystallized as a result of heating processes related to impacts from present and previous studies. Blue: 67915 (n = 16), red: 15455 (n = 11), green: 67955 (n = 7), pink: compiled literature data [8, 15-20].

Discussion and Conclusion: Based on textures and petrogenetic context, zircons in sample 67915 represent at least two generations. Early zircons were originally formed in the precursor rock and have been transported into the sample either within rock clasts or as mineral clasts. We also observe delicate skeletal zircon growth textures and granular zircon aggregates.

The latter are sometimes replacing baddeleyite and are similar to zircon textures found in SiO_2-diopside assemblages of the cataclastic anorthositic norite in breccia 15455. Granular zircon aggregates in lunar breccias were interpreted to be the result of local melting-induced crystallization of new zircon and re-crystallization of pre-existing zircon and baddeleyite. Melting may have been triggered by shock heating caused by large impacts [e.g. 20-22]. The same mechanism may have been responsible for the granular zircon aggregates in 67915. A combination of two zircon generations can be observed where fractured zircon clasts have been partly recrystallized along the margin. Newly crystallized domains of such grains appear brighter and lack visible fractures indicating that no further transport or shock took place after re-crystallization. Despite the presence of diverse clasts and different generations of zircons in 67915 the Pb-Pb ages of zircons in 67915 span a narrow range of 4200 to 4241 Ma. Because of the limited precision of the U-Pb ages, any discordance is difficult to resolve. The Pb-Pb ages show no systematic difference in ages between the different zircon generations. The data is consistent with one or several large impacts at around 4.22 Ga. Furthermore, we identified two impact-related zircon grains in a SiO_2 and K-feldspar rich clast of 67915. These clasts are similar to clasts found in Imbrium-related (?) impact melt veins cross cutting the zircon bearing norite of breccia 15455 from the Apollo 15 site. One of the zircons in SiO_2-K-feldspar clasts of 67915 yields a $^{207}Pb/^{206}Pb$ age of 4241 ± 17 Ma which is similar to ages determined for other zircon grains in 67915, 15455 [22] and in the impact melt breccia 67955 [21, 23], the latter also collected from Outhouse Rock (Fig. 1). Previously determined Ar-Ar and U-Pb apatite ages for these samples are predominantly about ~3.9 Ga [8, 10-12, 24-26]. The petrologic similarity of the breccia components at Apollo 15 with material in North Ray crater ejecta at Apollo 16 suggests that the large blocks of the Descartes Formation were derived from the Procellarum-KREEP Terrane (PKT) and likely represent Imbrium ejecta [8, 12]. Mixing of KREEP-rich with KREEP poor lithologies occurred primarily as a consequence of the Imbrium impact. Our new data, combined with previous data [8, 16-17, 20-23] indicate that several large impact events affected the PKT and its surrounding highlands between 4.15 and 4.33 Ga (Fig. 1). Ejecta from these impacts were transported to the Apollo 16 and other landing sites by the Imbrium impact at ~3.92 Ga [27]. The source craters of the early events are unknown, however, the Pb-Pb age range of these zircons overlaps with absolute model ages of some large basins obtained by crater counting, assuming Neukum's lunar chronology function, including Nectaris and Serenitatis [28]. Our data, combined with other recent studies show that zircons from lunar impactites can provide critical information on the bombardment history of the Moon prior to 3.9 Ga.

References: [1] Tera, F., Papanastassiou, D.A., Wasserburg, G.J. (1974) EPSL 22, 1-21. [2] Ryder, G. (2002). J. Geophys. Res. Planets 107, 6-1-6-13. [3] Cohen, B.A., Swindle, T.D., Kring, D.A. (2005) MAPS 40, 755-777. [4] Stöffler, D., Ryder, G., Ivanov, B.A., Artemieva, N.A., Cintala, M.J., Grieve, R.A.F. (2006) Rev. Mineral. Geochem. 60, 519-596. [5] Norman, M.D. (2009) Elements 5, 23-28. [6] Neukum, G., Ivanov, B.A. (1994) Hazard Due to Comets and Asteroids, 359-416. [7] Fernandes, V.A., Fritz, J., Weiss, B.P., Garrick-Bethell, I., Shuster, D.L. (2013) MAPS 48, 241-269. [8] Norman, M.D., Nemchin, A.A. (2014) EPSL 388, 387-398. [9] Michael, G., Basilevsky, A., Neukum, G. (2018) Icarus, 302, 80-103. [10] Korotev, R.L. (1996) MAPS 31(3), 403-412. [11] Venkatesan T.R. and Alexander E.C. (1976) Lunar Sci. VII, 894, #894. [12] Marti K., Lightner B.D. and Osborn T.W. (1973) Proc. Lunar Sci. Conf. 4th, 2037-2048. [13] Norman, M.D., Duncan, R.A., and Huard, J. J. (2010) GCA 74(2), 763-783. [14] Wiedenbeck, M., Allé, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Von Quadt, A., Roddick, J.C., Spiegel, W. 1995, GSNL 19, 1-23. [15] Pidgeon, R.T., Nemchin, A.A., van Bronswijk, W., Geisler, D., Meyer, C., Compston, W., Williams, I. S. (2007) GCA 71, 1370-1381. [16] Grange, M.L., Nemchin, A.A., Pidgeon, R.T., Timms, N., Muhling, J.R., Kennedy, A.K. (2009) GCA 73, 3093-3107. [17] Grange, M.L., Nemchin, A. A., Pidgeon, R. T. (2013) JGR:P 118, 2180-2197. [18] Hopkins, M.D., Mojzsis, S.J. (2015) Contr. Mineral. Petrol. 169(3), 30. [19] Bellucci, J.J., Whitehouse, M.J., Nemchin, A.A., Snape, J.F., Pidgeon, R.T., Grange, M., Reddy, S.M., Timms, N. (2016) Chem. Geol. 438, 112-122. [20] Crow, C., McKeegan, K.D., Moser, D.E. (2017) GCA 202, 264-284. [21] Vanderliek, D.M., Becker, H. (2017) NVM Europe II. [22] Vanderliek , D.M., Becker, H. (2018) LPSC 2018, #1931. [23] Vanderliek, D.M., Becker, H. (2017) Paneth Kolloquium, #0017. [24] Alexander Jr, E.C., and Kahl, S.B. (1974) Proc. Lunar Sci. Conf. 5th, 1353-1373. [25] Bernstein, M.L. (1983) Proc. Lunar Sci. Conf. 14th, 33-34. [26] Kirsten T., Horn P. and Kiko J. (1973a) Proc. Lunar Sci. Conf. 4th, 1757-1784. [27] Orgel, C., Michael, G., Fassett, C. I., van der Bogert, C.H., Riedel, C., Kneissl, T., Hiesinger, H. (2018). JGR:P 123(3), 748-762. [28] Snape, J.F., Nemchin, A.A., Grange, M.L., Bellucci, J.J., Thiessen, F., & Whitehouse, M. J. (2016) GCA 174, 13-29.