Impact history of the Apollo 17 landing site revealed by U-Pb SIMS ages

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Abstract

Secondary ion mass spectrometry (SIMS) U-Pb ages of Ca-phosphates from four texturally distinct breccia samples (72255, 76055, 76015, 76215) collected at the Apollo 17 landing site were obtained in an attempt to identify whether they represent a single or several impact event(s). The determined ages, combined with inferences from petrologic relationships, may indicate two or possibly three different impact events at 3920 ± 3 Ma, 3922 ± 5 Ma and 3930 ± 5 Ma (all errors 2σ). Searching for possible sources of the breccias by calculating the continuous ejecta radii of impact basins and large craters as well as their expected ejecta thicknesses, we conclude that Nectaris, Crisium, Serenitatis and Imbrium are likely candidates. If the previous interpretation that the micropoikilitic breccias collected at the North Massif represent Serenitatis ejecta is correct, then the average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3930 ± 5 Ma (2σ) dates the formation of the Serenitatis basin. The occurrence of zircon in the breccias sampled at the South Massif, which contain Ca-phosphates yielding an age of 3922 ± 5 Ma (2σ), may indicate that the breccia originated from within the Procellarum KREEP terrane (PKT) and the Imbrium basin appears to be the only basin that could have sourced them. However, this interpretation implies that all basins suggested to fall stratigraphically between Serenitatis and Imbrium formed within a short (<11 Ma) time interval, highlighting serious contradictions between global stratigraphic constraints, sample interpretation and chronological data. Alternatively, the slightly older age of the two micropoikilitic breccias may be a result of incomplete resetting of the U-Pb system preserved in some phosphate grains. Based on the currently available dataset this possibility cannot be excluded.

1. Introduction

One of the main objectives of the Apollo 17 mission in 1972 was to sample highland materials older than the Imbrium impact, since Imbrium ejecta was already thought to be present in some of the Apollo 12, 14 and 15 samples (e.g. Hinniers, 1973). To this end, the Taurus-Littrow Valley, located at the edge of the Serenitatis impact basin and south of the Taurus Mountains and the crater Littrow, was chosen as it offered the possibility to determine the age of the Serenitatis impact. The Serenitatis basin was determined to be older than the Imbrium basin based on its degradation, as inferred from remote sensing data (e.g. Wilhelms et al., 1971).

Prior to the mission, several geological interpretations of the origin of the Taurus-Littrow highlands material had been proposed. The highland samples collected during the Apollo 14, 15 and 16 missions consisted mainly of impact breccias and the Taurus-Littrow highlands were thought to be comprised of similar materials (Scott et al., 1972). Scott et al. (1972) interpreted these materials to originate from the Serenitatis impact and to be mixed with pre-Serenitatis breccias, while Head (1974a) inferred that the Littrow massif exhibits primarily Serenitatis impact breccias and bottom layers of pre-Serenitatis impact breccias which were uplifted during the Serenitatis impact. Moreover, the massifs could have been covered by post-Serenitatis impact ejecta, e.g. from the Imbrium or Crisium impact (Head, 1974a). McGetchin et al. (1973) estimated the Serenitatis impact layer to have an average thickness of ~1655 m at the Apollo 17 landing site, overlain by a thinner layer of post-Serenitatis impact ejecta (~224 m).

The returned breccia samples consist of four different textural impact breccia types: (1) granulitic, (2) poikilitic, (3) micropoikilitic-subophitic and (4) aphanitic (Simonds et al., 1974). Poikilitic breccias were sampled on both the North and South Massifs. Aphanitic breccias were mainly found at the South Massif (Ryder, 1993), although, Jolliff et al. (1996) found some lithic fragments belonging to the aphanitic-matrix breccias in the Station 6 boulder at the North Massif. These two different breccia types were initially interpreted to represent impact melts produced by the same impact, possibly Serenitatis (Wolfe et al., 1981), although the aphanitic breccias exhibit significant petrological and chemical differences compared to the poikilitic breccias (Spudis et al., 1981). In general, the aphanitic breccias have a finer grain size, a larger number of clasts, are darker in color and lack vesicles. The aphanitic breccias also have lower TiO_2 , Na_2O , Eu and Sr concentrations compared to the poikilitic breccias (Spudis et al., 1981; Jolliff et al., 1996). Nevertheless, Wood (1975) and Wolfe et al. (1981) interpret both types as representing the same impact and attribute

differences in texture to different cooling histories. These differences led Spudis et al. (1981) to conclude that these distinctive breccia types probably did not originate from the same impact. Hence, the Apollo 17 landing site may consist of ejecta from both local craters and larger distant craters, not solely ejecta from the Serenitatis basin (Spudis et al., 1981).

Due to the lack of distinctly identifiable stratigraphic relationships between different breccia types, radiometric age dating became a focus of studies subsequent to the sample delivery in an attempt to resolve the existing diversity of interpretations. A precise chronology of different breccia types can help to identify samples that are different in age and hence, cannot have formed by the same impact. Previous $^{40}\text{Ar}/^{39}\text{Ar}$ studies of breccia 76055 (sampled close to Station 6 at the North Massif) produced plateau ages of 3.91 ± 0.04 Ga (Huneke et al., 1973) and 3.92 ± 0.05 Ga (Turner et al., 1973), which were interpreted to be the time of the Serenitatis impact event. Cadogan et al. (1976) obtained $^{40}\text{Ar}/^{39}\text{Ar}$ ages for 15 samples of clasts, matrix and mineral concentrates (North Massif, Station 6 boulder) ranging from 3.86 ± 0.04 Ga to 4.04 ± 0.05 Ga and argued that the age of the Serenitatis impact is 3.90 ± 0.04 Ga, although this age range was also thought to be a reflection of the amount of degassing (Schaeffer et al., 1977). Jessberger et al. (1977) suggested an age of 3.88 ± 0.03 Ga for the Serenitatis impact based on $^{39}\text{Ar}/^{40}\text{Ar}$ dating on one aphanitic matrix breccia (73255) sampled at the South Massif.

The observed scatter in $^{40}\text{Ar}/^{39}\text{Ar}$ ages resulted in uncertainty in the interpretation of the breccias and the suggested timing of the Serenitatis impact. Nakamura et al. (1976) assigned the age of 3.9 Ga to the Serenitatis impact event, while Wilhelms et al. (1987) argued that the age of the Serenitatis impact is 3.86 - 3.87 Ga based on the youngest $^{39}\text{Ar}/^{40}\text{Ar}$ age for sample 73255 (Huneke, 1978) and one single-crystal plagioclase clast from sample 72435 (Station 2, South Massif). Dalrymple et al. (1996) obtained $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra by laser step heating on poikilitic and aphanitic breccias. Three of the poikilitic breccias (from the North and South Massif) yielded a weighted mean age of 3893 ± 9 Ma, which was evaluated as the best estimate for the Serenitatis impact. However, the studied aphanitic samples (72255, Station 2, South Massif) have plateau ages ranging from 3867 ± 16 Ma to 3951 ± 17 Ma, suggesting a complex and prolonged chronological history of the aphanitic breccias (Dalrymple et al., 1996). These ages indicate that the distinct breccias have different impact histories and that the aphanitic samples may in fact not originate from the Serenitatis impact event. However, the majority of the determined $^{40}\text{Ar}/^{39}\text{Ar}$ ages were calculated with the old decay constants and monitor ages, which leads to additional inconsistency and a spread of ages when compared to more recent $^{40}\text{Ar}/^{39}\text{Ar}$ ages.

The present study focusses on the U-Pb system in phosphates in an attempt to shed additional light on the question whether the Apollo 17 impact melt breccias were formed in a single impact, e.g. the Serenitatis impact, or whether different textural types represent distinctive impact events. To distinguish between these hypotheses, $^{207}\text{Pb}/^{206}\text{Pb}$ ages of phosphate grains from the texturally different impact breccia types sampled at the North and South Massifs were determined by Secondary Ion Mass Spectrometry (SIMS). The advantage of SIMS analyses is that single grains can be dated *in situ* and thus, the possibility of measuring unrelated mineral mixtures is reduced and a large number of individual data points can be acquired that define a statistically significant population. Phosphates provide an opportunity for determining impact ages because of their relatively low closure temperatures around 450-550 °C (e.g. Cherniak et al., 1991) when compared to zircon, based on cooling rates of 10°C/Ma and 1°C/Ma and grain radii smaller than 0.5 mm. Hence, the U-Pb system of phosphates is prone to resetting during an impact event (Nemchin et al., 2009; Abramov et al., 2009) and the U-Pb age in phosphates is expected to reflect that of the time of the breccia formation.

2. Geology of the Taurus-Littrow Valley

The Taurus-Littrow area is mainly a highland region close to the intersection of Mare Serenitatis and Mare Tranquillitatis. Originally, Serenitatis had been interpreted as one of the oldest basins on the Moon, occurring during the Pre-Nectarian period (e.g. Stuart-Alexander et al., 1970; Hartmann et al., 1971). Subsequent studies have suggested that it is younger (Nectarian in age), mainly due to the relatively young ages of the Apollo 17 samples, interpreted as Serenitatis ejecta (e.g. Dalrymple et al., 1996), but also based on stratigraphic observations such as secondary craters, which are interpreted as originating from the Serenitatis impact event, superposed on Crisium basin material (e.g. Wilhelms et al., 1987). Nevertheless, analyses of more recent high resolution imagery concluded that Serenitatis is indeed a relatively old Pre-Nectarian basin (Spudis et al., 2011; Fassett et al., 2012).

Wilhelms et al. (1971) mapped the Serenitatis basin as consisting of four rings, with the Apollo 17 landing site positioned between the second and third ring. The Taurus-Littrow valley is interpreted as a deep graben, which is thought to have formed during the Serenitatis impact event (Muehlberger et al., 1973). The highland region is mainly comprised of breccias, most of which are thought to originate from the Serenitatis impact covered by younger ejecta from distant basins (Scott et al., 1972). The area can be divided into (1) high massifs, (2) so-

called Sculptured Hills, and (3) low hills. The massifs cluster around the Apollo 17 landing site and are interpreted to have been uplifted by the Serenitatis impact, and possibly exposing ejecta from older basins (e.g. Tranquillitatis; Head, 1974a). The Sculptured Hills comprise a group of closely-spaced highland hills located between the Serenitatis and Crisium basins. Since the Sculptured Hills resemble the Alpes Formation of the Imbrium basin, Head (1974a) interpreted them as equivalent features generated by the Serenitatis impact. The Apollo 17 highland samples were collected at the massifs close to the Sculptured Hills and were, therefore, also interpreted as being related to the Serenitatis impact (Head 1974a). These samples may consist of fragments of massif material (i.e. originating from older impact basins) or pieces of the Serenitatis impact melt sheet (Warner et al., 1976; Winzer et al., 1977). However, at the time of this interpretation, the morphological differences between the massifs and the Sculptured Hills were not clearly understood (Muehlberger et al., 1973). Spudis et al. (2011) investigated new Lunar Reconnaissance Orbiter Camera (LROC) images, which do not support the previous interpretation of the Sculptured Hills being related to the Serenitatis impact event. The analyzed Wide-Angle Camera (WAC) images show that the Sculptured Hills are not only concentrated around the Apollo 17 landing site, but that they occur widespread within the Taurus Mountains. Moreover, the images reveal that the Sculptured Hills superpose the rims of post-Serenitatis craters such as Le Monnier and Littrow (Spudis et al., 2011). This observation confirms the previous findings from Spudis et al. (1981), who argued that the Sculptured Hills cannot originate from the Serenitatis impact if they overlie stratigraphic younger post-Serenitatis impact basins.

The samples analyzed in the present study were collected from boulders at Station 2 at the South Massif (72255) and near or from boulders at Station 6 at the North Massif (76015, 76215 and 76055) as indicated in Figure 1. These boulders are interpreted to have rolled down the slopes of the massifs to their present locations (Muehlberger et al., 1973). In the case of the North Massif, the boulders are thought to originate from one larger boulder that broke into several pieces. Samples collected at the South Massif probably came from an area near the top of the massif, whereas breccias sampled at the North Massif were likely derived from within the lower third of the North Massif (Muehlberger et al., 1973). This stratigraphic setting suggests that the boulders represent different stratigraphic units. However, the lithologies of the boulders are rather similar and therefore, may also represent a single stratigraphic unit.

The analyzed samples, which can be divided into micropoikilitic (76015 and 76215), aphanitic (72255) and subophitic-micropoikilitic (76055) impact melt breccias are described in detail in the following section (Fig. 2).

167

168 **3. Sample description**

169 ***Thin sections 72255,99; 72255,125; 72255,306***

170 Sample 72255 (2461 g) was collected from the side of boulder 1 at Station 2 on the bottom
171 slope of the South Massif. The boulder consisted of several layers with clasts that weathered
172 out as knobs and sample 72255 is one of these knobs (e.g. Ryder et al. 1975a). The sample
173 has a layered gray aphanitic matrix and is comprised of several dark grey clasts (Simonds et
174 al., 1974). The matrix is fine-grained and heterogeneous and the crystalline melt groundmass
175 consists of plagioclase, pyroxene, ilmenite and metallic iron (Ryder, 1993). The aphanitic
176 breccia has a trace element pattern enriched in KREEP elements (K, REE, and P; Palme et al.,
177 1978; Warren et al., 1979) and it is the only sample containing zircon among all the studied
178 breccias. Phosphates in the investigated thin sections have an average size of 35 x 50 µm,
179 although one grain measures 40 x 75 µm. Most of the phosphate grains occur as fragments,
180 are embedded within the matrix and are subhedral in shape (Fig. 2a). Some of the boundaries
181 to adjacent grains are straight, while other grains show rounded or embayed boundaries.
182 However, some of the grains occur in voids and are attached to adjacent grains. Several
183 different radiometric ages were derived previously for this breccia. A $^{40}\text{Ar}/^{39}\text{Ar}$ age of
184 4.01 ± 0.03 Ga was obtained by Leich et al. (1975) for the matrix, whereas Dalrymple et al.
185 (1996) determined several $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages for different clasts, ranging from
186 3.835 ± 0.016 Ga for the poikilitic melt clast to >3.894 Ga for two aphanitic “blobs”. However,
187 the weighted average age of 3.893 ± 0.009 Ga was interpreted to be the age of the Serenitatis
188 impact (Dalrymple et al., 1996).

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190 ***Thin sections 76055,74***

191 Sample 76055 (6412 g) was collected 10-15 m away from the large boulder at Station 6. It
192 was classified as a micropoikilitic-subophitic breccia by Simonds et al. (1974) and it appears
193 to be compositionally distinct from the Station 6 boulder (Wolfe et al., 1981). Moreover, it
194 exhibits a prominent foliation which is defined by many small lenticular vesicles. Sample
195 76055 can be further divided into three lithologies: vesicular, non-vesicular and an unstudied
196 dense region (Meyer, 2008). In general, it exhibits a fine-grained vesicular groundmass and
197 contains about 41% plagioclase, 24% low-Ca pyroxene, 18% olivine and minor augite,
198 armalcolite and iron metal (Albee et al., 1973). The phosphates occur in voids as euhedral to

subhedral grains. Their average size is 25 x 30 μm , with the largest grain measuring 75 x 90 μm . They often occur together with metallic iron (Fig. 2b). The 76055 breccia has yielded $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 3.98 ± 0.05 Ga to 3.97 ± 0.04 Ga (Turner et al., 1973; Huneke et al., 1973).

Thin sections 76015,9; 76015,98

Sample 76015 (2819 g) is a micropoikilitic breccia, which was sampled from Block 5 of the big boulder at Station 6 at the North Massif. The color and texture is similar to sample 76215. It consists of about 50% feldspar, 40 % low-Ca pyroxene, 5% augite and minor amounts of olivine, ilmenite, metallic iron, spinel and phosphates (e.g. Phinney, 1981). The matrix is primarily composed of a dense network of elongated low-Ca pyroxene oikocrysts, with tabular feldspar found both within and between the pyroxene grains (Ryder, 1993). The matrix is very vesicular with <0.1 mm to 5 cm long irregular voids (Ryder, 1993). As with the subophitic breccia (76055), the majority of phosphates found in this sample occur within voids (Fig. 2c) and are attached to adjacent minerals. They are typically around 50 μm in length, but the largest grain identified measures 75 x 155 μm . The phosphate grains are euhedral to subhedral and some of the grains are fractured. A $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 3.93 Ga for the matrix was reported by Cadogan et al. (1976).

Thin sections 76215,10; 76215,57; 76215,61

Breccia 76215 (644 g) was sampled next to the large boulder at Station 6 at the North Massif, but it was most probably spalled from the top of block 4. It is a vesicular, crystalline matrix breccia and has a poikilitic texture, but some areas exhibit an ophitic texture. It consists of about 50% plagioclase, 15-30 % pyroxene, 5-11% augite, about 7% olivine, 2 % ilmenite and minor amounts of olivine, metallic iron, spinel and phosphates (Simonds et al., 1974; Simonds, 1975). A majority of phosphate grains grew within vesicles and have a euhedral to subhedral shape. The grains are fractured and they usually show straight boundaries to adjacent minerals. Their average length of 70 μm makes them the largest phosphates found in all analyzed samples. The largest grains in the sections have a length of ~100-130 μm (Fig. 2d). Previous radiometric age dating obtained a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 3.94 ± 0.04 Ga (Cadogan et al., 1976).

4. Analytical Techniques

The thin sections were cleaned using an ultrasonic bath with distilled water and ethanol for the purpose of removing surface contamination. The sections were then carbon coated in order to facilitate initial scanning electron microscopy (SEM) analyses of the samples, including the acquisition of backscattered electron (BSE) images and element maps, which were used to determine the locations of the phosphate grains and investigate the textures of the samples. The SEM analyses were performed with a Quanta 650 FEGSEM and accompanying Oxford Instruments energy dispersive spectroscopy (EDS) detector at Stockholm University, using a 20 kV accelerating voltage and 10 mm working distance. The same SEM settings were used to analyze the chemical composition of the phosphates and to distinguish between merrillite and apatite grains.

The sections were then cleaned a second time and coated with gold prior to performing the SIMS analyses. U-Pb isotopic data was collected using CAMECA 1280 ion microprobe at the NordSIMS facility, Swedish Museum of Natural History, Stockholm. The SIMS methodology closely followed the analytical description published elsewhere for zircon (e.g. Whitehouse et al., 1999; Whitehouse et al., 2005) and apatite (Nemchin et al., 2009; Snape et al., 2016). As a U-Pb calibration reference for all analytical sessions the 2058 Ma apatite crystal BRA-1 was used, with 67 ppm of U and $^{206}\text{Pb}/^{204}\text{Pb}$ of 500 (Grange et al., 2009).

The mass filtered $^{16}\text{O}_2^-$ primary ion beam, with intensities between 1.7 and 5.3 nA, was defined by projection through Köhler apertures of 100 μm , 150 μm and 200 μm in order to obtain spot sizes of 10 μm , 15 μm and 20 μm , respectively. Before each analysis, an area of 15-20 μm was pre-sputtered for 80 seconds in order to remove the gold coating from the area around the analytical spot and further limit the effects of sample contamination. Pre-sputtering was followed by automatic centering of the secondary ion beam in the 4000 μm field aperture and centering of the magnetic field. The secondary ions were measured using a “peak-hopping” routine with a single low-noise ion counting electron multiplier. The mass spectrometer was operated at a mass resolution of 5400 ($M/\Delta M$), sufficient to separate Pb peaks from molecular interferences.

Reduction of the SIMS data was performed using in-house developed software at NordSIMS for the CAMECA 1280 analyses and the Excel add-in Isoplot (version 4.15; Ludwig, 2008). In order to correct the data for the effects of contamination from terrestrial common Pb (most likely from the sample preparation, Nemchin et al., 2009) the model of Stacey et al. (1975) and their values for present-day terrestrial Pb isotopic ratios was used. The calculation of U-

Pb ratios of the samples by SIMS requires a correction for matrix effects using independently characterized reference materials such as BRA-1. Additional uncertainties can be associated with minor differences in mineral chemistry, instrumental conditions during the analysis of standards and unknown samples and possible surface relief artefacts, particularly for grains located in voids. Consequently, the $^{207}\text{Pb}/^{206}\text{Pb}$ ratios are considered to give the best estimate of the sample ages. Additionally, several phosphates grains show reverse discordance making the calculation of Concordia ages impossible, and the U-Pb intercept ages can be inaccurate if the reverse discordance is, as suspected, an analytical artefact of small matrix variations and/or surface imperfections. Thus, we primarily focus on $^{207}\text{Pb}/^{206}\text{Pb}$ ages in the following sections.

The obtained average ages discussed in the following sections were calculated with Isoplot at the 95% confidence limit, and individual analyses are shown in the plots with 2σ errors. Following SIMS analyses, further SEM images of the analyzed phosphate grains were acquired in order to determine the exact location of SIMS spots and identify and exclude any likely sources of error in the measurements (e.g. whether the SIMS spots hit fractures or grain boundaries).

5. Results

The analyzed phosphates most likely originated from different source rocks (i.e. fragments vs. crystallization from the impact melt). However, in the simplest scenario their $^{207}\text{Pb}/^{206}\text{Pb}$ ages are assumed to reflect the time of the breccia formation. This assumption is based on the low closure temperatures of the U-Pb system in phosphates around 450-550 °C, which should result in significant Pb mobility during an impact event and complete Pb loss. If the assumption of complete Pb loss is true, the small $^{207}\text{Pb}/^{206}\text{Pb}$ age differences between individual grains reflect the expected analytical scatter and a mean of all grains can be used to calculate average ages for each breccia. The weighted average ages calculated using Isoplot (Ludwig, 2008) include the calculation of a MSWD and probability of fit (P), providing an internal test of this assumption. A probability of fit ≥ 0.05 indicates that the analyses represent a homogeneous population within the uncertainties. The $^{207}\text{Pb}/^{206}\text{Pb}$ ages obtained in three investigated samples form statistically valid age populations suggesting that the U-Pb system of the phosphates was completely reset by the impact that produced the breccias.

In all nine thin sections, a total of 74 analyses were made on 41 phosphate grains, of which five grains were merrillites and 36 grains were apatites. Merrillites occur only in the aphanitic

and subophitic breccias. The apatite grains in the micropoikilitic breccias are larger (average lengths around 50-70 μm) than the merrillite and apatite grains found in the aphanitic and subophitic breccias (average lengths around 30-35 μm). The results are summarized in Table 1.

Sample 72255 (aphanitic)

A total of six analyses were made on five individual phosphate grains (two merrillites, three apatites) in three thin sections. These phosphates yielded an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3922 ± 5 Ma (MSWD = 0.79, P = 0.56). As indicated by the low MSWD, all of the individual $^{207}\text{Pb}/^{206}\text{Pb}$ ages for each analyzed grain match within the error, regardless whether the grains occur as fragments or within voids.

Sample 76055 (subophitic-micropoikilitic)

In this sample 22 analyses on twelve grains (three merrillites, nine apatites) were made, leading to an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3920 ± 3 Ma (MSWD = 0.71, P = 0.83). The individual $^{207}\text{Pb}/^{206}\text{Pb}$ ages range from 3911 ± 20 Ma to 3940 ± 23 Ma and are, therefore, indistinguishable within the error of each other.

Sample 76015 (micropoikilitic)

In the two 76015 thin sections 15 analyses of eleven apatite grains were made. An average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3930 ± 7 Ma (MSWD = 1.3, P = 0.17) was derived. The youngest $^{207}\text{Pb}/^{206}\text{Pb}$ age obtained is 3906 ± 50 Ma, whereas the oldest $^{207}\text{Pb}/^{206}\text{Pb}$ age is 3952 ± 40 Ma.

Sample 76215 (micropoikilitic)

In total 31 analyses on 13 apatite grains were obtained in the three thin sections from sample 76215. The grains have an average size of 50 x 70 μm and therefore, several analyses could be performed in single phosphate grains. Grain #47 is one of the largest (95x 115 μm , Fig. 2d) and exhibits the largest spread of $^{207}\text{Pb}/^{206}\text{Pb}$ ages, ranging from 3904 ± 72 Ma at the rim of the grain to 4051 ± 87 Ma in the center of the grain. It is possible that this large and relatively unfractured grain represents a rare case of incomplete resetting of the U-Pb system. The

weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3957 ± 41 Ma for this grain however, overlaps within the error with the average age of the whole sample, and the statistical fit for individual spots within this grain is considered valid (MSWD = 2.6, P = 0.053). While the determined age of 4051 ± 87 Ma is a unique observation within all the samples, it is hard to tell from a single measurement whether this old age might represent an (unlikely) analytical artefact or whether it reflects a real age. Consequently, this older age was excluded in the average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3931 ± 7 Ma (MSWD = 2.7, p = 0) yielded for this sample. Although a high MSWD and low probability indicates scatter in excess of the analytical uncertainties, this age is taken as the best estimate of the time of the breccia formation.

6. Discussion

6.1 Textural and chemical variability of the Apollo 17 breccias

Relating breccias to specific impact basins is complicated by: 1) the acquisition of samples from the lunar regolith rather than genuine outcrops of bedrock; and 2) a lack of information linking stratigraphic units and specific impacts on the Moon. Nevertheless, in the case of the Apollo 17 samples, the chemical and textural differences between the aphanitic and poikilitic breccias have led to the conclusion that they may represent different impacts (e.g. Spudis et al., 1981). The aphanitic breccias, as a group, show a large range of chemical compositions, but the individual samples are all different from the poikilitic breccias (Spudis et al., 1981). The aphanitic breccia 72255 sampled at the South Massif has a higher Al_2O_3 content (~21%) than the micropoikilitic breccias (76015, 76215) sampled at the North Massif (~18% ; Simonds, 1975; Wolfe, 1975). Moreover, the MgO (11%), TiO_2 (0.8%) and FeO (~8.45%) concentrations of the aphanitic breccia are slightly lower when compared to the poikilitic breccias (MgO ~12.5%, TiO_2 ~1.5% and FeO ~ 8.8 %; Simonds, 1975; Wolfe, 1975). The U and Th concentrations of breccia 72255 (U ~1.41 ppm and Th ~4.3 - 5.8 ppm) and breccias 76015 and 76215 (U ~1.2 - 1.96 ppm and Th ~4.18 - 5.56 ppm) are the same within uncertainty. However, the majority of rare earth element (REE) abundances are slightly higher in the micropoikilitic breccias when compared to the aphanitic breccias (e.g. Palme et al., 1978; Simonds, 1975 and references within). The micropoikilitic breccias exhibit the highest Zr abundances (480 ppm; Palme et al., 1978), but zircon grains occur only within the aphanitic breccia 72255 (Zr concentration of 400 ppm). This indicates that either the target of the impact that produced breccia 72255 contained evolved KREEP-rich rocks or that these rocks were mixed into the ejecta during its deposition at the South Massif at the Apollo 17

landing site, since only KREEP-rich magma has adequate Zr concentrations for zircon to crystallize (Dickinson et al., 1982). The subophitic breccia (76055) is chemically distinct from all the other breccias collected at the Apollo 17 landing site. It exhibits higher MgO concentrations of ~16.5%, lower Al₂O₃ concentrations of ~16% and has slightly lower U (0.88 ppm) and Th (3.52 ppm) abundances (Palme et al., 1978) compared to the aphanitic and micropoikilitic breccias, and the REE concentrations are the lowest among the four analyzed breccias (Palme et al., 1978). These chemical and textural differences indicate different melt compositions and cooling histories, which either requires distinct impact events or at least significant differences in target composition.

The majority of phosphates occurring within the aphanitic and subophitic breccias have higher U contents (50 - 270 ppm) than the average U concentrations of phosphates found within the micropoikilitic breccias (U <70 ppm; Fig. 3), but there is no observed difference between merrillite and apatite grains. However, the five merrillite grains exhibit much higher Th concentrations (~560 - 2070 ppm) than the apatites (~5 - 550 ppm). The Th content of apatites in the aphanitic and two micropoikilitic breccias is similar but apatite grains found within the subophitic breccia have the lowest Th values (<80 ppm). Overall, the Th and U concentrations observed in the apatites and merrillites investigated in the four samples suggest that phosphates in the three textural types of breccias have crystallized in three chemically different source rocks.

Additional information about the origin of the breccias can be obtained by comparing their highly siderophile elements (HSE) signature. The HSE concentrations are directly linked to the impactors that produced the impact melts since the melts incorporate exogenic materials from the impactors, which are typically enriched in HSE compared to endogenic planetary crusts (Liu et al., 2012). Morgan et al. (1974) analyzed 17 elements from several impact melt breccias, including the HSE Au, Ir and Re, from all Apollo landing sites and divided them into six groups based on their Ir, Au and Ge proportions. Two different HSE signatures referred to as Group 2 and Group 3 were observed in the aphanitic (Group 3) and micropoikilitic (Group 2) breccias sampled at the Apollo 17 landing site (Morgan et al., 1974; Hertogen et al., 1977). The Group 2 signature is representative of enstatite chondrites and the Group 3 signature is similar to ordinary chondrites based on the HSE relationships (Gros et al., 1976). However, a subsequent study by Sharp et al. (2014) suggested that all Apollo 17 melt rocks originated from the same impactor which had a HSE signature that is not represented in the studied terrestrial meteorite collection, or that the observed HSE signatures is an average mixture of multiple impactor compositions. Subsamples of the subophitic

breccia 76055 exhibit an anomalous HSE signature according to Sharp et al. (2014) and therefore, it is thought to have formed by an impact other than the one that produced the aphanitic and poikilitic breccias. Regardless of the precise interpretation of the HSE behavior in the investigated Apollo 17 breccias, their distribution appears to support the possibility of several impacts being responsible for the formation of these samples.

Taking the distinctive chemical compositions of the textually different breccias into account together with their different HSE signatures, the simplest interpretation is that the breccias are the products of three different impact events. If they were formed by a single impact, the observed differences would require either a very heterogeneous target and absence of mixing within the ejecta during its transportation or addition of various proportions of older material of different origin and composition into the ejecta during its deposition at the Apollo 17 landing site.

6.2 Ages of the Apollo 17 breccias

6.2.1 The possibility of three distinct impact events

Based on the obtained average $^{207}\text{Pb}/^{206}\text{Pb}$ ages, the subophitic breccia 76055 can be interpreted to have formed at 3920 ± 3 Ma, the aphanitic breccia 72255 at 3922 ± 5 Ma, and the micropoikilitic breccia 76015 at 3930 ± 7 Ma (Fig. 4). The only sample that shows scatter beyond the analytical uncertainties, and thus indicating the possibility of incomplete homogenization, is micropoikilitic breccia 76215. However, its average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3931 ± 7 Ma is notably similar to that of the other micropoikilitic sample and an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3930 ± 5 Ma (MSWD = 0.14, P = 0.71) can be obtained (Fig. 5). This observation suggests that this age may represent the true time of breccia formation. The excess scatter is a result of either slightly underestimated uncertainties of individual spot analyses or a small degree of post-formation disturbance, which is not possible to detect by discordance in the U-Pb system at the level of 3-7% (2σ) precision of U-Pb obtained during phosphate SIMS analysis. If this is correct, the $^{207}\text{Pb}/^{206}\text{Pb}$ age range of ~11 Ma between the two micropoikilitic breccia samples and the subophitic and aphanitic breccias is in excess of the analytical errors and has to represent a real difference in their formation time. The $^{207}\text{Pb}/^{206}\text{Pb}$ age of the subophitic breccia (3920 ± 3 Ma) is indistinguishable within error limits from the aphanitic breccia (3922 ± 5 Ma) and an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3921 ± 2 Ma (MSWD = 0.92, P = 0.34) can be obtained. Even though these ages are indistinguishable within error, the two samples show different textures, distinct compositions, different HSE

signatures and the subophitic breccia does not contain any zircon. These findings indicate that the samples are not derived from the same material and the similarity in age is probably coincidental.

These combined geochronological, textural and chemical observations indicate that the three different textural types of breccias have probably originated from at least three impact events, which occurred at 3920 ± 3 Ma, 3922 ± 5 Ma and 3930 ± 5 Ma (Fig. 5).

6.2.2 Lunar initial Pb and/or the possibility of incomplete resetting

The apparent difference in phosphate ages between different samples can also be interpreted as a result of incomplete Pb loss and/or the presence of minor amounts of lunar initial Pb unsupported by the in situ decay of U following the breccia forming impact. The presence of unsupported Pb is, in principal, easy to detect if its proportion is relatively large, as it should also affect concordance of individual analyses. However, small fractions of unsupported Pb capable of changing the estimated $^{207}\text{Pb}/^{206}\text{Pb}$ ages by 10-15 Ma are difficult to identify, particularly, because laboratory contamination is also present to various degrees in all analyzed samples. Consequently, the interpretation that the observed 11 Ma difference in age between the micropoikilitic (76015, 76215) and the two younger breccias is due to the lower U concentrations in the phosphates from 76015 and 76215 and resulting larger proportion of unsupported Pb in the overall Pb balance cannot be discarded completely.

One available way to test for the small contribution of unsupported Pb is to plot the $^{207}\text{Pb}/^{206}\text{Pb}$ ratios against the $^{204}\text{Pb}/^{206}\text{Pb}$ ratios. The majority of the analyzed phosphate grains have very low $^{204}\text{Pb}/^{206}\text{Pb}$ ratios (<0.0002) and thus, the initial Pb contamination is marginal. Only a minority of grains (mostly in thin section 76215,61) have $^{204}\text{Pb}/^{206}\text{Pb}$ ratios >0.0002 , but no difference between older and younger grains is observed (i.e. there is no apparent relationship between the $^{204}\text{Pb}/^{206}\text{Pb}$ ratios and the ages of the grains). Figures 6a and 6b show that the trend of all analyzed grains (prior to the correction for terrestrial common Pb) points towards modern terrestrial Pb (Stacey et al., 1975), which implies that the samples were largely contaminated by common terrestrial Pb during sample cutting and polishing. With decreasing $^{204}\text{Pb}/^{206}\text{Pb}$ ratios the common terrestrial Pb contamination is decreasing and analyses with low $^{204}\text{Pb}/^{206}\text{Pb}$ ratios (<0.0002) are expected to fall along a steeper trend pointing towards lunar initial Pb, if residual quantities of this Pb are present in phosphate grains. When only these analyses with $^{204}\text{Pb}/^{206}\text{Pb}$ ratios <0.0002 are considered, they still fall along a shallow trend which is suggestive of common terrestrial Pb contamination (Fig. 6c).

Thus, the age range of ~11 Ma between the micropoikilitic and the subophitic and aphanitic breccias still appears to reflect the true difference of their formation time.

The $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3920 ± 3 Ma obtained from the subophitic breccia (76055) can be taken as the true time of an impact as this sample shows extremely low ^{204}Pb concentrations and therefore, the influence of unsupported lunar initial Pb is also smaller than the ± 3 Ma uncertainty determined for this sample. In addition, analyses of individual grains show a relatively narrow range of $^{207}\text{Pb}/^{206}\text{Pb}$ ages, even though the size of the grains varies from about 20 to 100 μm in lengths and incomplete resetting of the U-Pb system would be expected to be more pronounced in the larger grains. Therefore, both inter- and intra-grain homogeneity of $^{207}\text{Pb}/^{206}\text{Pb}$ ages observed in this sample indicates complete resetting of the phosphates in 76055. The aphanitic breccia 72255 exhibits a comparable internal homogeneity of $^{207}\text{Pb}/^{206}\text{Pb}$ ages and relatively small phosphate sizes, which suggests that the average age determined for the breccia is also largely unaffected by either unsupported lunar initial Pb or incomplete resetting of the U-Pb system.

In contrast, the micropoikilitic breccias contain on average larger phosphate grains and exhibit more scatter of $^{207}\text{Pb}/^{206}\text{Pb}$ ages and hence, these may record incomplete resetting and contain some memory of the pre-impact accumulation of radiogenic Pb. However, a correlation between grain size and $^{207}\text{Pb}/^{206}\text{Pb}$ age is not clear, especially in 76215. This sample is the only one investigated in this study with an inter-grain variability of $^{207}\text{Pb}/^{206}\text{Pb}$ ages exceeding analytical error and it also contains the largest analyzed phosphate grains. Nevertheless, breccia 76215 also contains several relatively small grains ($< 40 \mu\text{m}$) that show $^{207}\text{Pb}/^{206}\text{Pb}$ ages in excess of 3940 Ma which apparently have not been completely reset. On the other hand several relatively large grains (80 to 100 μm in length) in both poikilitic breccia samples yield ages at the younger end of the range, between about 3920 and 3930 Ma. This observation suggests that even if there is a small degree of incomplete resetting of the U-Pb system in some of the phosphate grains from 76215, it does not have a simple relation to the size of the grains. While the possibility of incomplete resetting cannot be fully dismissed, it also cannot be confirmed with an absolute certainty. Therefore, the 11 Ma age difference between the micropoikilitic and other types of breccias remains a valid assumption. Additional data obtained using different dating techniques allowing similar level of precision, but exhibiting different resetting behavior (e.g. $^{40}\text{Ar}/^{39}\text{Ar}$), may help to resolve this ambiguity.

6.3 Implications for the impact history of the Apollo 17 landing site

A key assumption made here, with respect to the behavior of U-Pb systems in phosphate grains, is that although lunar breccias are likely to represent a complex mixture of different components, which may include local and foreign materials (e.g. material from different impact events in addition to the primary magmatic rocks sourced at the impacts' target; e.g. Petro et al., 2008; Gault et al., 1974), the Ca-phosphates are prone to Pb loss at relatively mild thermal disturbances. Consequently, temperatures attained during the formation of the studied breccia samples should have been sufficient to reset the U-Pb systems in the analyzed phosphates to the same age, defining formation time of these samples, even if the phosphate crystallization ages were very different prior to the breccia consolidation.

If this assumption is correct, the observed 11 Ma difference in ages between the micropoikilitic and the aphanitic/subophitic breccias combined with the chemical and textural differences of the analyzed samples may indicate three distinct impact events. This creates a substantial problem for the traditional interpretation of the analyzed samples, which suggests Serenitatis and/or Imbrium as likely candidates for the origin of the Apollo 17 breccias. Importantly, the observed age difference also conflicts with the interpretation that all Apollo 17 breccias originate from the same impact (i.e. Serenitatis). Even if the older age of the poikilitic breccias is interpreted as an indication of incomplete resetting of the U-Pb system, the age defined by the aphanitic and subophitic breccias is very similar to that defined for the Imbrium impact based on analysis of Ca-phosphates from Apollo 14 breccias (Snape et al. 2016), Apollo 12 impact melt breccias (Liu et al., 2012) and zircons from SaU169 (Gnos et al., 2004). Consequently, this interpretation would lead to the conclusion that none of Apollo 17 breccias represent Serenitatis impact ejecta.

Accepting a common interpretation that Apollo 17 poikilitic breccias originate from the Serenitatis impact, while the aphanitic breccias from the South Massif are Imbrium ejecta, the average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3930 ± 5 Ma obtained for the micropoikilitic breccias (76215, 76015) might be viewed as the best estimate of the Serenitatis impact and the aphanitic breccia (72255) age of 3922 ± 5 Ma as defining the age of the Imbrium impact. This interpretation appears to be in agreement with the suggestion that the poikilitic breccias were derived from a boulder which is stratigraphically older than the source boulder of the aphanitic breccias (Muehlberger et al., 1973). However, this interpretation of breccia ages also means that about 13 to 25 basins formed within an extremely narrow time interval of a few million years between the Serenitatis and Imbrium impacts, especially if Serenitatis is indeed a relatively old Pre-Nectarian basin (Spudis et al., 2011; Fassett et al., 2012). While the aphanitic breccia (72255) with the age of 3922 ± 5 Ma may not originate from the Imbrium

impact, but rather from a smaller crater of similar age, the issue with short period of time between Imbrium and Serenitatis still exists as long as the poikilitic breccias are viewed as Serenitatis ejecta and the Apollo 14 breccias are interpreted as deposits from the Imbrium impact. Taking the apparent conflict between the U-Pb phosphate data and stratigraphic interpretation of investigated breccias into account, a comprehensive search for possible alternative sources for the breccias is warranted and has to consider all Nectarian and Pre-Nectarian impact basins/craters that have continuous ejecta blankets reaching the Apollo 17 landing site. Although not fully exhaustive and not accounting for all complexities in the ejecta propagation and deposition this can be done to a first order approximation using the following equation for the continuous ejecta radius:

$$R_{ce} = (2.3 \pm 0.5)R^{1.006} \quad (1)$$

where R_{ce} is the radius of the continuous ejecta blanket (in kilometers) and R is the radius of the impact crater (Moore et al., 1974; Melosh, 1989). This formula is only valid for craters with a diameter <436 km. It was nevertheless applied to impact craters ranging from ~1 km up to ~2500 km (South Pole Aitken) to get an approximate estimate of the ejecta distribution. Furthermore, the distance of the basins and craters to the North and South Massifs was estimated in order to assess if the continuous ejecta blankets reach the sample locations. In order to get an estimate of the thickness (t) of ejecta deposits at the Apollo 17 landing site, two additional equations were used. The following equation was used for simple craters (diameter <15 km):

$$t = 0.04 R (r/R)^{-3 \pm 0.5} \quad (2)$$

where r is the distance from the crater center to the Apollo 17 landing site (in meters; Kring, 1995). For complex craters (diameter >15 km) the following equation (McGetchin et al., 1973) was used:

$$t = 0.14 R^{0.74} (r/R)^{-3 \pm 0.5} \quad (3)$$

Based on equation (1), six impact basins (Tranquillitatis, Fecunditatis, Crisium, Nectaris, Serenitatis and Imbrium, Fig. 7) would be expected to have continuous ejecta blankets at the North and South Massifs, and there are two large impact craters within the vicinity of the North Massif (Littrow and Henry, Fig. 8 and Fig. 1, respectively) that might feasibly have a

continuous ejecta deposit reaching Station 6 at the North Massif (Table A1). Moreover, based on equation (3) an ejecta thickness of ~120 m from the South Pole-Aitken Basin impact event is expected to cover the Apollo 17 landing site. Material from the South Pole-Aitken basin as well as from the Tranquillitatis and Fecunditatis impact events might have been incorporated into the analyzed breccias during the last impact event that formed the breccias, but based on the $^{207}\text{Pb}/^{206}\text{Pb}$ ages these relatively old Pre-Nectarian basins can be excluded from the further consideration as sources for the breccias, for the same reason that was used to question the Serenitatis origin of the samples, i.e. formation of large number of basins in a short period of time of about 11 Ma.

A similar issue exists with two possible alternative sources of the breccias, Crisium (~3.89±0.02 Ga, Stöffler et al., 2001) and Nectaris (~3.92±0.03 Ga, Ryder et al., 1987). Based on equation (3) the average ejecta thickness of Nectaris and Crisium at the Apollo 17 landing site is estimated to be ~120 m and ~180 m, respectively (McGetchin et al., 1973) and they can be viewed as potential candidates for the source of the breccia samples. If the micropoikilitic breccias indeed originated from the Nectaris impact and the aphanitic breccias from the Imbrium impact, then twelve basins formed within a short interval between 3922±5 and 3930±5 Ma. In the case of Crisium, the predicted frequency of basin forming events is lower (four to five basins), according to the relative timing proposed by Fassett et al. (2012), Spudis et al. (2011), and Stöffler et al. (2006). In any case, if the $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3922±5 Ma is taken as the time of the Imbrium impact, then previous age estimates for Crisium defined as 3.89 Ga (Stöffler et al., 2001) and the only radiometric age ($^{40}\text{Ar}/^{39}\text{Ar}$) of 3895±17 Ma linked to the Crisium impact (Swindle et al., 1991) based on a few particles from the Luna 20 regolith, contradict the established stratigraphy. The crater “Henry” can also be excluded as it is superimposed on the ~3.8 Ga (Muehlberger et al., 1973) subfloor basalts covering the Apollo 17 landing site. It is a relatively young (Copernican) and small (diameter ~700 m) crater, not large enough to have excavated material from underneath the 1.0-1.4 km (Wolfe et al., 1981) thick basalt layer. An alternative possibility that has to be considered is that some or even all of these breccia samples could have been formed by impacts that are now covered by the extensive basaltic flows within the Serenitatis and/or Tranquillitatis basins. Table 2 provides a summary containing all the individual $^{207}\text{Pb}/^{206}\text{Pb}$ ages, textural descriptions and possible origins of the distinctive breccias.

7. Conclusions

Combined with textural information, the ages obtained in this study potentially define three impact events within the textually distinct Apollo 17 samples: (1) around 3920 Ma (subophitic breccia, 76055), (2) 3922 Ma (aphanitic breccia, 72255), and (3) around 3930 Ma (micropoikilitic breccias, 76015 and 76215). We consider Nectaris, Crisium or Serenitatis as the most likely sources for the micropoikilitic breccias. If we accept the traditional view that the micropoikilitic breccias were derived from the Serenitatis impact, we speculate that the $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3930 ± 5 Ma is the age of Serenitatis impact event, while the aphanitic and subophitic breccias were formed by post-Serenitatis impacts. Whether the aphanitic breccia was excavated during the Imbrium impact or whether it represents different ejecta layers that were accumulated and mixed locally during an impact at 3922 ± 5 Ma is uncertain. The origin of the subophitic breccia remains unclear, especially based on the indistinguishable $^{207}\text{Pb}/^{206}\text{Pb}$ ages of the subophitic and aphanitic breccias. However, due to the differences in chemistry, texture and HSE signatures, we interpret this breccia as being composed of materials that are unrelated to the other breccias sampled in this study. Regardless of our interpretation, it is clear that further studies are necessary to identify the link between sampled breccias and impact basins.

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Fig.1. (a) Map showing the Apollo 17 landing site including the sample locations from breccias analyzed in this study (red dots). The blue dot highlights the Apollo 17 landing site and the white lines represent the traverse track. Also outlined are the edges of the North and South Massifs as well as the Sculptured Hills in the eastern part of the landing site. The lunar rover vehicle (LRV) sampling stations are represented as black dots (LRV 1-13) as well as the traverse stations 1-9. The background image is from the Lunar Reconnaissance Orbiter Camera (LROC), frame M104318871 (NASA/GSFC/Arizona State University). (b) View of the Taurus Littrow Valley and the Apollo 17 landing site as captured by LROC. The approximate location of Station 6 is also indicated. The background image is LROC frame M1096343661 (NASA/GSFC/Arizona State University). (c) The large boulder at Station 6 and astronaut Jack Schmitt after collecting samples from the boulder. The image is Apollo image AS17-140-21496.

Fig.2. Examples of back scattered electron (BSE) images of the phosphate grains (outlined in red) from each of the analyzed samples. (a) Grain #1 is a clast occurring in the aphanitic breccia. (b) Two typical phosphate grains (#707) within the subophitic breccia which occur together with metallic iron. (c) Grain #51 in the micropoikilitic breccia 76015 is an apatite grain, which is loosely attached to the cavity walls. (d) Grain #47 is one of the largest apatite grains and yielded the largest spread of $^{207}\text{Pb}/^{206}\text{Pb}$ ages, ranging from 3904 ± 72 Ma at the rim of the grain to 4051 ± 87 Ma in the center of the grain. Plag=plagioclase, Fe = metallic iron, Px = pyroxene.

Fig. 3. Th vs U (ppm) plot of all analyzed apatite and merrillite grains. The error bars are 2σ .

Fig. 4. $^{207}\text{Pb}/^{206}\text{Pb}$ ages of phosphates analyzed in the breccias 72255, 76055, 76015 and 76215.

Fig. 5. Comparison of $^{207}\text{Pb}/^{206}\text{Pb}$ ages from breccias 72255 (yellow), 76055 (red), 76015 (blue) and 76215 (blue). The $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3930 ± 5 Ma is the weighted average age of the two micropoikilitic breccias 76015 and 76215.

Fig. 6. (a) and (b) $^{207}\text{Pb}/^{206}\text{Pb}$ ratios plotted against the $^{204}\text{Pb}/^{206}\text{Pb}$ ratios prior to correction for common terrestrial Pb shown relative to the composition of modern terrestrial Pb (S-K terrestrial Pb; Stacey et al., 1975). Also indicated is the primordial Pb isotope composition of the Solar System as derived by the Canyon Diablo Troilite (CDT) iron meteorite. The data reveal highly radiogenic composition of the analyzed phosphate grains with minor contribution of initial lunar Pb or terrestrial common Pb. The trend of phosphate grains with higher $^{206}\text{Pb}/^{204}\text{Pb}$ ratios points towards common terrestrial Pb (Stacey et al., 1975) for which the data has been corrected (c) Only the phosphate grains with $^{204}\text{Pb}/^{206}\text{Pb}$ ratios < 0.0002 are plotted and their trend also indicates common terrestrial Pb contamination. The yellow arrow shows the correction for common terrestrial Pb contamination and the red arrow indicates the effect of correcting for initial lunar Pb (μ value > 500 ; Premo et al., 1999).

Fig. 7. Location of pre-Nectarian and Nectarian impact craters (yellow circles) with continuous ejecta blankets reaching the Apollo 17 landing site (orange star). The Procellarum KREEP terrane is outlined by dashed green lines (after Jolliff et al., 2000). The background image is from the Lunar Reconnaissance Orbiter Wide Angle Camera mosaic of the lunar nearside (NASA/GSFC/Arizona State University).

Fig. 8. The location of larger impact craters (dashed yellow circles) in the vicinity of the Apollo 17 landing site (orange dot). Only the continuous ejecta blanket of the crater Littrow reaches the North Massif at the Apollo 17 landing site, and is therefore a possible source for the breccias sampled at the North Massif. The background image is a part from the Lunar Reconnaissance Orbiter Wide Angle mosaic of the lunar nearside (NASA/GSFC/Arizona State University).

Table 1. All SIMS data obtained for the four samples.

Sample/Spot #	U (ppm)	$\pm 2\sigma$ (%)	Th (ppm)	$\pm 2\sigma$ (%)	Th/U	$\pm 2\sigma$ (%)	$^{206}\text{Pb}/^{204}\text{Pb}$ measured	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 2\sigma$ (%)	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 2\sigma$ (%)	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 2\sigma$ (%)	ρ	$^{207}\text{Pb}/^{206}\text{Pb}$ age (Ma)	$\pm 2\sigma$ (Ma)	Mineral
72255,99																	
1,1	93.28	5.83	2068.59	5.97	22.18	1.31	12057	0.4024	0.98	48.35	7.33	0.8729	7.26	0.99	3916	15	Merrillite
1,2	82.19	8.53	1814.57	8.58	22.08	0.97	14082	0.4062	1.18	42.16	7.31	0.7538	7.22	0.99	3930	18	Merrillite
72255,125																	
27,1	187.38	6.38	113.51	6.67	0.61	1.93	32043	0.4056	0.90	45.17	7.26	0.8078	7.21	0.99	3930	13	Apatite
34,1	2.23	11.72	719.55	12.91	323.00	5.40	355	0.4055	8.91	46.99	11.88	0.8405	7.85	0.66	3930	131	Merrillite
72255,306																	
1,1	275.00	29.61	214.19	29.67	1.78	0.89	48046	0.4027	0.54	52.26	5.27	0.9417	5.24	0.99	3918	8	Apatite
68,1	120.66	32.09	390.60	33.12	8.17	4.08	67019	0.4041	0.57	49.38	5.76	0.8865	5.74	1.00	3924	9	Apatite
76055,74																	
266,1	255.09	15.60	1257.00	15.81	6.37	2.61	26186	0.4028	0.88	52.98	7.24	0.9540	7.18	0.99	3919	13	Merrillite
268,1	83.41	16.52	611.19	16.65	6.93	2.06	18157	0.4017	1.35	56.85	7.98	1.0263	7.87	0.99	3916	20	Merrillite
495,1	142.08	19.71	971.38	19.83	5.35	2.16	25625	0.4030	1.05	49.99	7.71	0.8995	7.64	0.99	3920	16	Merrillite
578,1	209.42	17.25	82.52	17.38	0.46	2.13	*	0.4039	1.11	48.21	8.04	0.8658	7.96	0.99	3924	17	Apatite
627,1	127.34	16.29	12.64	16.47	0.09	2.44	6682	0.4017	1.65	46.24	7.51	0.8350	7.33	0.98	3915	25	Apatite
627,2	133.09	20.76	10.05	21.21	0.15	4.31	*	0.4027	1.04	46.75	7.42	0.8421	7.34	0.99	3919	16	Apatite
627,4	147.15	15.04	29.58	15.11	0.21	1.48	*	0.4027	0.88	44.02	7.26	0.7927	7.21	0.99	3919	13	Apatite
627,5	138.36	15.84	30.53	15.94	0.18	1.74	*	0.4027	1.12	41.24	7.33	0.7429	7.25	0.99	3919	17	Apatite
627,7	210.81	14.69	27.60	14.75	0.19	1.39	*	0.4030	0.88	45.75	7.27	0.8234	7.22	0.99	3920	13	Apatite
627,8	146.89	16.10	19.00	16.21	0.16	1.90	*	0.4034	1.00	42.91	7.25	0.7715	7.18	0.99	3922	15	Apatite
627,9	119.78	15.03	30.33	15.12	0.19	1.71	*	0.4007	1.00	38.68	7.60	0.7002	7.54	0.99	3912	15	Apatite

654,1	155.94	18.58	32.97	18.69	0.37	2.08	13811	0.4024	1.00	45.36	7.49	0.8176	7.42	0.99	3918	15	Apatite
654,2	89.50	17.90	29.54	17.96	0.52	1.43	*	0.4004	1.36	38.59	7.40	0.6990	7.27	0.98	3910	20	Apatite
706,2	46.74	14.86	22.19	15.13	0.30	2.84	*	0.4082	1.51	43.56	7.34	0.7740	7.19	0.98	3940	23	Apatite
706,3	73.16	14.92	22.47	15.22	0.31	3.03	*	0.4009	1.27	41.54	7.30	0.7514	7.19	0.98	3913	19	Apatite
707,1	72.93	15.62	57.30	15.90	0.42	2.96	*	0.4011	0.89	45.67	7.25	0.8258	7.20	0.99	3913	13	Apatite
707,2	137.83	14.67	15.36	14.82	0.14	2.11	*	0.4036	1.11	37.68	7.37	0.6771	7.29	0.99	3923	17	Apatite
719,1	129.33	14.50	19.96	14.62	0.19	1.88	*	0.4007	1.17	38.15	7.44	0.6904	7.35	0.99	3912	17	Apatite
719,2	106.56	15.31	31.91	15.39	0.26	1.61	*	0.4065	0.98	45.90	7.30	0.8188	7.23	0.99	3933	15	Apatite
719,3	122.80	14.59	29.66	14.68	0.25	1.62	*	0.4007	1.03	54.12	7.27	0.9795	7.20	0.99	3912	15	Apatite
719,4	119.92	16.15	70.66	16.32	0.42	2.34	*	0.4026	1.04	41.63	7.26	0.7501	7.19	0.99	3919	16	Apatite
719,5	168.79	17.95	36.84	18.02	0.24	1.56	*	0.4053	0.85	47.36	7.33	0.8476	7.28	0.99	3929	13	Apatite
76015,9																	
23,1	13.28	3.66	117.79	5.84	8.87	4.55	241	0.3992	3.36	40.20	5.96	0.7305	4.92	0.83	3906	50	Apatite
51,1	35.77	3.45	134.00	3.76	3.75	1.49	153	0.4020	2.63	44.93	6.37	0.8106	5.80	0.91	3917	39	Apatite
53,1	55.17	6.04	554.01	6.17	10.04	1.26	6706	0.4034	1.11	50.90	4.62	0.9151	4.48	0.97	3922	17	Apatite
57,1	9.81	4.28	67.35	4.76	6.87	2.09	885	0.4117	2.70	54.65	5.20	0.9629	4.45	0.85	3952	40	Apatite
57,2	60.89	3.33	91.33	4.40	1.50	2.87	1648	0.4075	1.11	51.93	4.58	0.9243	4.45	0.97	3937	17	Apatite
57,3	54.07	3.83	200.19	4.06	3.70	1.36	439	0.4094	1.61	43.93	5.34	0.7783	5.10	0.95	3944	24	Apatite
76015,98																	
6,1	47.75	10.35	7.61	11.51	0.16	5.05	*	0.4003	1.23	45.21	4.61	0.8192	4.44	0.96	3910	18	Apatite
17,1	35.29	9.04	123.67	9.55	3.50	3.09	7096	0.4094	1.42	46.07	4.74	0.8161	4.52	0.95	3944	21	Apatite
22,1	69.02	9.19	93.84	9.37	1.36	1.84	5696	0.4035	1.11	43.56	4.64	0.7830	4.51	0.97	3922	17	Apatite
64,1	16.84	8.76	150.24	8.95	8.92	1.82	10577	0.4082	1.81	52.55	5.07	0.9336	4.73	0.93	3940	27	Apatite
68,2	35.51	10.54	254.87	10.60	7.18	1.12	27558	0.4068	1.29	49.89	4.70	0.8895	4.52	0.96	3934	19	Apatite
68,3	59.82	8.60	270.22	8.71	4.52	1.40	30390	0.4039	1.17	50.25	4.68	0.9024	4.53	0.97	3923	18	Apatite
69,1	36.60	10.37	11.78	10.56	0.32	1.99	15694	0.4032	1.46	42.90	4.68	0.7716	4.45	0.95	3921	22	Apatite
70,1	33.33	8.75	109.41	8.89	3.28	1.57	48824	0.4112	1.40	47.91	4.78	0.8450	4.57	0.96	3951	21	Apatite
70,2	32.66	8.64	130.80	8.72	4.01	1.14	5169	0.4045	1.44	50.47	4.87	0.9049	4.65	0.96	3926	22	Apatite

76215,57

6,1	36.69	16.31	46.79	18.74	1.28	9.23	1490	0.3983	1.26	46.64	5.36	0.8492	5.21	0.97	3903	19	Apatite
12,1	11.07	14.76	67.65	14.85	7.88	1.17	2572	0.4134	1.75	48.82	5.39	0.8564	5.09	0.95	3959	26	Apatite
12,2	24.24	14.74	191.06	14.79	6.66	1.14	10172	0.4072	1.35	49.57	5.10	0.8828	4.92	0.96	3936	20	Apatite
12,3	34.87	15.00	232.32	15.05	3.48	0.57	15670	0.4042	1.01	51.54	5.21	0.9250	5.11	0.98	3925	15	Apatite
13,2	24.35	15.87	90.18	14.67	11.02	4.04	11675	0.4160	1.17	52.42	5.05	0.9139	4.91	0.97	3968	17	Apatite
13,3	22.62	14.64	249.19	15.19	13.86	2.45	4291	0.4077	1.34	50.47	5.15	0.8979	4.97	0.97	3938	20	Apatite
13,4	19.44	14.96	269.55	15.16	6.45	7.36	9380	0.4126	1.39	47.68	5.13	0.8381	4.94	0.96	3956	21	Apatite
13,5	26.03	15.20	167.96	16.89	1.59	1.64	*	0.4101	1.29	50.59	5.10	0.8946	4.94	0.97	3947	19	Apatite
32,1	12.01	14.71	8.81	15.48	0.73	4.81	1007	0.4127	1.78	49.96	5.22	0.8780	4.90	0.94	3956	27	Apatite

76215,10

17,1	48.31	2.73	17.64	3.35	0.37	1.95	84456	0.4022	0.79	47.53	3.13	0.8571	3.03	0.97	3917	12	Apatite
17,3	40.90	3.09	11.08	3.48	0.27	1.60	14450	0.4017	0.87	49.73	3.50	0.8980	3.39	0.97	3915	13	Apatite
20,1	30.12	3.01	151.79	3.49	5.04	1.76	19736	0.4066	0.95	48.81	3.27	0.8707	3.13	0.96	3934	14	Apatite
20,2	33.61	2.37	172.17	3.30	5.12	2.29	100000	0.4034	0.95	45.42	3.10	0.8166	2.95	0.95	3922	14	Apatite

76215,61

47,1 ¹	2.29	10.06	24.13	10.93	10.52	4.27	641	0.4398	5.91	57.70	7.55	0.9517	4.69	0.62	4051	87	Apatite
47,3	2.92	10.39	21.49	11.08	7.36	3.86	381	0.4026	6.43	40.47	8.40	0.7291	5.41	0.64	3919	95	Apatite
47,4	4.09	10.74	26.96	11.23	6.58	3.27	1429	0.3986	4.82	41.37	6.74	0.7528	4.72	0.70	3904	72	Apatite
47,5	3.32	8.26	25.65	9.59	7.73	4.86	1056	0.4169	5.34	46.77	7.05	0.8137	4.60	0.65	3971	79	Apatite
49,1	11.87	6.45	4.80	9.19	0.40	6.54	330	0.4132	3.20	45.95	6.25	0.8065	5.36	0.86	3958	48	Apatite
50,1	51.47	6.35	61.24	6.49	1.19	1.36	1774	0.4097	1.45	46.75	4.67	0.8277	4.44	0.95	3945	22	Apatite
50,2	49.17	5.46	46.83	5.66	0.95	1.50	6676	0.4049	1.49	45.49	4.79	0.8148	4.55	0.95	3928	22	Apatite
50,3	33.25	8.03	64.21	9.09	1.93	4.25	7700	0.4069	1.91	38.16	4.85	0.6801	4.45	0.92	3935	29	Apatite
50,4	5.95	8.16	50.58	9.15	8.50	4.14	110	0.4113	6.27	53.45	19.82	0.9427	18.80	0.95	3951	92	Apatite
53,1	16.82	7.01	136.24	10.15	8.10	7.34	488	0.4097	3.03	51.57	7.51	0.9130	6.87	0.92	3945	45	Apatite
53,2	33.53	5.15	204.41	5.33	6.10	1.38	3510	0.4048	1.64	52.80	4.85	0.9459	4.57	0.94	3927	25	Apatite

56,1	20.59	5.35	16.01	5.79	0.78	2.20	617	0.3968	2.18	47.08	4.96	0.8606	4.45	0.90	3897	33	Apatite
56,2	25.08	6.82	14.87	7.38	0.59	2.83	548	0.4118	2.61	44.35	5.82	0.7811	5.21	0.89	3953	39	Apatite
58,1	12.17	5.86	136.24	7.09	11.19	3.99	5245	0.4110	2.58	50.60	5.43	0.8930	4.78	0.88	3950	38	Apatite
58,2	11.61	7.30	96.68	8.48	8.32	4.30	852	0.3979	3.15	39.66	5.44	0.7229	4.44	0.82	3901	47	Apatite
58,3	13.13	7.62	132.89	8.24	10.12	3.14	7661	0.4103	2.63	46.76	5.45	0.8266	4.77	0.88	3947	39	Apatite
58,4	11.43	8.13	107.79	8.37	9.43	2.00	3067	0.3928	2.86	40.42	5.50	0.7464	4.70	0.85	3882	43	Apatite
59,1	4.36	6.89	41.27	7.63	9.47	3.29	533	0.4187	3.92	59.39	6.69	1.0286	5.42	0.81	3978	58	Apatite

¹ The data was removed from the average
²⁰⁷Pb/²⁰⁶Pb average age for the whole sample.

Table 1. All SIMS data obtained for the four samples.

Table 2. Summary table. All errors are shown with 2σ .

Breccia	Texture	Sampling location	$^{207}\text{Pb}/^{206}\text{Pb}$ age [Ma]
72255	aphanitic	South Massif, Station 2	3922 $\pm$ 5
		North Massif, 10-15 m away from the Station 6	
76055	subophitic	boulder	3920 $\pm$ 3
76015	micropoikilitic	North Massif, Station 6	3930 $\pm$ 7
76215	micropoikilitic	North Masssif, Station 6	3931 $\pm$ 7

906

907 **Appendix**

908 Table A1. Calculation of the ejecta distribution and thickness of ejecta deposits for basins and
909 impact craters, which might have contributed material to the Apollo 17 landing site.

910

911 Fig. A1. Tera Wasserburg concordia diagrams for each of the analyzed samples.

912

913 Fig. A2. Conventional U-Pb concordia diagrams for each of the analyzed samples.

914

915 Fig. A3a-d. BSE images of all Ca-phosphate grains analyzed in this study (outlined in red).

916 Plag=plagioclase, Fe = metallic iron, Px = pyroxene, Ilm = ilmenite.

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