SIGNIFICANCE OF APOLLO 16 IMPACT MELTS TO THE GEOLOGY OF THE LUNAR TERRAE.

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INTRODUCTION. Numerous hypotheses have been advanced to explain Apollo 16 site geology and its relation to the geologic history of the lunar highlands (see review in [1]). Interpretation of the geologic history of the site was hampered for several years by a lack of extensive chemical and detailed petrologic information for returned rocks and by reliance on the early PET macroscopic rock classification system [2]. Under the impetus of both the Highlands Initiative and Apollo 16 Workshop, an abundance of data is in hand that enables a new look at the geology of the 16 site and its implications for lunar evolution.

REGIONAL GEOLOGY AND GEOCHEMISTRY. The origin of the Descartes Mountain materials has been a vexing photogeological problem since the pre-mission volcanic interpretation was discredited [3]. Two major contending hypotheses have emerged: (1) they are a lobe of clastic Imbrium ejcta [4, 5]; and (2) they represent Nectaris basin ejecta modified by Imbrium secondaries [6,7]. Three observations suggest that the latter is a more likely interpretation: (1) the Nectaris basin rim is less than a basin radius from the Apollo 16 site and major quantities of material from that impact would be expected. (2) The Descartes mountains are not a unique landform [8]; they extend south of the 16 site from Abulfeda to Sacrosbosco (noted by [9]) in an arc broadly concentric to the Altai scarp of the Nectaris basin. (3) Chaotic, dune-like topography of the Descartes mountains is similar to that of units near the Imbrium Apennines and Orientale Cordillera. The objection that the Descartes materials do not resemble the Nectaris basin Janssen Fm. [5] is irrelevant; wide variations in ejecta morphologies occur concentrically around all basins [9]. The Descartes mountains are most probably Nectaris ejecta and have been partly sculptured by secondary debris from Imbrium.

Orbital data suggest that the regional chemical composition of the circum-Nectaris highlands is dominantly anorthositic gabbro (Al_2O_3 26-28%), with subordinate amounts of low-K KREEP (LKFM) [10, 11]. This composition is in marked contrast to that of terrae surrounding the rims of the Imbrium and Serenitatis basins (KREEP-rich/noritic-Al_2O_3 20%) [10,12]. Moreover, anorthositic gabbro is sparse in Imbrium ejecta both within the Apennines and at Fra Mauro. The chemical composition of ejecta from large, post-Nectaris craters such as Theophilus and Isidorus demonstrate that Nectaris ejecta is not dominantly noritic to depths of less than 10 km. Thus, a 100 km crater near the Apollo 16 site would produce an anorthositic gabbro impact melt.

HOW MUCH IMPACT MELT AT APOLLO 16? Although impact melt breccias make up about 30% of the returned rock sample [13], Apollo 16 site materials are not 30% melt for two reasons: (1) sampling strategy at the site [14] was such that physically coherent melt rocks may be overrepresented, particularly at the key Descartes stations (4, 5); (2) melt rocks by volume are between 65 and 90% melt, the remainder being included cold clasts; in fact, the clast/matrix boundary is usually arbitrary [15]. The ideal way to estimate the total volume of pure melt is to classify the statistically large rake and soil samples petrographically and to make appropriate corrections for clast contents. Such analysis, based on the soil petrographic data of [16], suggests total melt volumes ranging of 4 to 12%. The highest melt fraction seen in any soil is 16%, half the value obtained by lumping all melt breccias as pure melt. Thus, impact melt may constitute less than 10% of site materials by volume. Where does this melt come from?

APOLLO 16 IMPACT MELTS. Lunar melts produced by the same impact tend to be both texturally diverse and chemically homogeneous [17]. Detailed study of Apollo 16 melts has identified four chemically defined melt groups [18]. Of these, two (3 and 4 of [18]) are very aluminous and low in KREEP (Fig. 1). They may have been produced by small-crater impact-melting into Al-rich clastic rocks found at the site.

The other two groups have special bearing on the question of basin provenance. Group 1 (16-20% Al_2O_3; Fig. 1) are mafic LKFM melt rocks, slightly more KREEP-rich than the Apollo 15 "black and white" melt-rock matrix, interpreted as Imbrium basin impact melt by [19]. Age data (new constants) for Apollo 16 melt rocks by compositional group are shown in Figure 2. Although statistics are sparse, two group 1 rocks cluster around 3.86 AE, near the preferred age of the Imbrium basin (3.85 AE; [20]). Group 1 melts are about 10% of the total melt rock population.

Group 2 melt rocks (20-25% Al_2O_3; Fig. 1) form 80% of the melt rock population. These melts have KREEP rare-earth patterns [21] and an aluminous LKFM composition (Fig. 1). The spread in composition within this group is large compared to that of terrestrial impact melt sheets, such as Manicouagan [22], but not much greater than the spread in comparable data for the Apollo 17 "melt-sheet" (Fig. 1). These melt rocks display a pronounced peak at about 3.92 AE (Fig. 2). Chemical and age data suggest single-event formation of these rocks at about 3.92 AE.

The LKFM composition of the group 2 melt rocks suggests that they were formed by an impact that has excavated somewhat deeper than would a large crater in this region (usually << 10 km). Elsewhere on the Moon, the LKFM composition is associated with basin ejecta (Apollo 15-Imbrium; Apollo 17-Serenitatis). The distinctive composition and age of the group 2 rocks suggest a separate basin impact at 3.92 AE: the logical condidate is Nectaris. This date for Nectaris is the same as that proposed as the result of a different line of reasoning [23].

CONCLUSIONS Low-K KREEP melt rocks (most abundant type at Apollo 16) cannot be produced by a small impact into typical highlands crust (Al_2O_3 26-28%). Small cratering of crustal regions of noritic composition could conceivably produce this melt type, but such regions do not exist around the Apollo 16 site. A more plausible explanation is that the group 2 melt rocks were formed by a large basin impact at 3.92 AE, probably Nectaris. The objection that basins do not eject large melt masses is lessened by the inference that pure melt of group 2 composition makes up, at most, 3 to 9% by volume of the deposits at the Apollo 16 site. If group 1 melts represent Imbrium basin impact melt, the fraction of Imbrium melt at Apollo 16 is less than 1% of the total deposit volume.

The interpretation of 3.92 AE as the age of Nectaris is significant to lunar cratering history. If this age is correct, the maximum age of the oldest highlands surface is 4.0 to 4.1 AE (based on the density of primary impact craters > 20 km diameter [20]). Thus, (1) there is no in situ primordial lunar surface dating from the crustal formation period (4.2 to 4.3 AE; [24]); and (2) the crater equilibrium diameter within the lunar highlands may be much larger than is curently believed. The latter interpretation suggests that the total highland megaregolith thickness may be as much as a factor of ten higher than the currently quoted value (1-2 km [25]).

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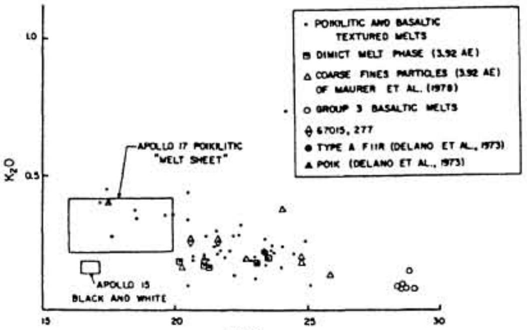

Fig. 1. Chemical data for impact melts from Apollo 16 site. Compositional groups of [18]: 1-16 to 19% Al_2O_3; 2-20 to 25% Al_2O_3; 3-27 to 28% Al_2O_3. Group 4 (30-32% Al_2O_3) not shown. Data from [21].

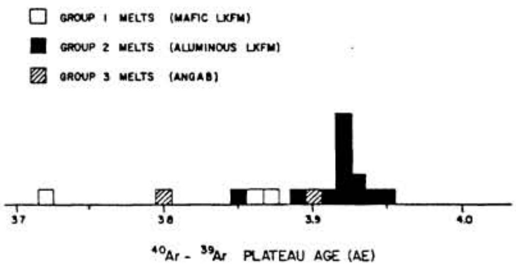

Fig. 2. Histogram of available age data [21] for Apollo 16 impact melts by compositional group.