BULLIALDUS: STRENGTHENING THE CASE FOR LUNAR PLUTONS

Carlé M. Pieters

Department of Geological Sciences, Brown University

Abstract. Although many craters expose material of a composition different from that of the local surroundings, Bullialdus has excavated material representing three distinct stratigraphic zones that occur in the upper 6 km of crust, the top two of which are gabbroic and the deepest of which is noritic. This three-component stratigraphy at Bullialdus provides strong evidence that the lunar crust includes pockets of compositionally layered material reminiscent of mafic layered plutons. When combined with previous information on the compositional diversity at other large craters, these remote analyses obtained in a geologic context substantially strengthen the hypothesis suggested from lunar samples that plutons play an integral role in lunar crustal evolution.

Introduction

The lunar crust formed within the first few hundred million years after the origin of the Moon about 4.5 billion years ago. Once formed, this primordial crust appears to have been altered largely by the cumulative flux of large and small bodies impacting the surface at high velocity creating craters, basins and a suite of impact debris (e.g. see Taylor, 1982; Wilhelms, 1987). An unknown amount of endogenous or reprocessed material was also involved in lunar crustal evolution during the first billion and a half years, the most readily recognized of which are the dark mare basalts that fill lowlands (dominantly on the near side) and account for approximately 17% of the lunar surface (Head, 1976). A growing number of "pristine" rock fragments, thought to represent original crustal material, have been identified in the sample collection (e.g. see Warren, 1985). Compositional and petrographic relations among these samples suggest that not only did a major differentiation event occur soon after formation of the Moon (the "magma ocean"), but that unmapped plutonic activity contributed significantly to early crustal evolution. The focus of the following discussion is on related implications of compositional variations of the crust with depth that are inferred from remote compositional analyses obtained in a geologic context.

Although the stratigraphy of the lunar crust has not been sampled directly, large impact craters can be used as probes to the interior. From a combination of laboratory experiments and studies of terrestrial impact craters, it is known that during an impact event material derived from different stratigraphic depths are deposited in a regular pattern around the crater and the depth of material excavated by a crater scales with the diameter of the crater. Maximum excavation depth is roughly 1/10 the crater diameter, and central peaks formed by dynamic rebound represent material from the greatest depth (e.g., see Melosh, 1989). Discussed here are compositional analyses of remotely acquired near-infrared reflectance spectra (0.6 - 2.5 μm) for areas in and around the crater Bullialdus and other large impact craters of the lunar nearside. The tools used to interpret reflectance spectra can be found in many sources; recent summaries for lunar materials can be found in Pieters (1986; 1991) and Pieters and Taylor (1989). Mafic minerals (pyroxenes, olivine) have particularly diagnostic absorptions in this part of the spectrum, and the compositional diversity of materials in the upper 15 km of highland crust can be characterized from reflectance spectra of rock types excavated by large impact craters.

The use of craters as probes of the interior has been recognized for decades. Early in the Apollo era, extended visible spectral reflectance measurements of the rim and floor of the crater Copernicus clearly showed that the crater excavated highland crustal material from beneath what is now known to be a relatively thin cover of mare basalt (McCord et al., 1972). Copernicus is 95 km in diameter and located 350 km north of the Apollo 12 site. It wasn't until a decade later that a near-infrared spectrometer with sufficient sensitivity and spectral resolution was available to expand these earth-based remote analyses (McCord et al., 1981) and identify the type of mineralogy present at a given location. In the case of Copernicus (Pieters, 1982; Pieters et al., 1985), the rim and floor, which represent upper stratigraphic units at the site, were indeed shown to be feldspathic breccias with a noritic component, quite similar to the breccias and soils sampled at Apollo 16. The composition of deep-seated material forming the central peaks, however, was identified as troctolite or dunite, rock types relatively rare within the lunar sample collections. Given the size of the crater, these unusual olivine-bearing mountains represent material from about a 10 km depth within the crust at the Copernicus site.

Since the discovery of compositional differences with depth at Copernicus, a great diversity of crustal materials (gabbros, troctolites, anorthosites) have been recognized at different geologic settings associated with large craters and basins (e.g. Lucey et al., 1986; Hawke et al., 1986; Lucey and Hawke, 1989; Spudis et al., 1984, 1988, 1989). On the other hand, near-infrared spectra of smaller craters indicate that the composition of the uppermost two km of nearside lunar megaregolith is dominated by noritic anorthosite breccias with varying amounts of low-Ca pyroxene (Pieters, 1986; 1991).

Bullialdus Compositions

A general survey of crustal materials that represent depths of 5 - 15 km was undertaken through the study of large impact craters and included the crater Bullialdus (Pieters, 1986). Bullialdus is an Eratosthenian-age crater 61 km in diameter. It is located about one basin radius east of the Humorum basin in a region of thin mare fill. A Tycho ray appears to cross the western edge of the crater. Initial analysis of near-infrared spectra for Bullialdus indicated the composition varied with
depth, but the stratigraphy of the site was unusual -- material with gabbroic affinities appeared to overly noritic material. Bullialdus was thus targeted for additional measurements.

Near-infrared reflectance spectra for 9 small areas in the Bullialdus region were obtained using the 2.2 m telescope of Mauna Kea Observatory. The location of these areas are shown in Figure 1. Although some of the data have lower signal to noise than others, three distinct types of material excavated by the crater can be identified from the scaled reflectance spectra summarized in Figure 2. Although different in detail, all spectra show absorption bands near 1 and 2 μm indicating the presence of pyroxene of some composition. For most lunar spectra, diagnostic mafic mineral absorption bands are superimposed on the overall red-sloped lunar continuum, and continuum removed spectra (spectrum/continuum) are used to evaluate the character of residual absorption bands. These are shown on the right of Figure 2. The mare comparison area exhibits a steeper continuum slope than the others.

The spectrum for Bullialdus' central peak exhibits a strong symmetric absorption band implying the material excavated was relatively crystalline (as opposed to highly brecciated or glass-rich as is commonly observed elsewhere, such as at Apollo 16). The band center occurs near 0.93 and indicates low-Ca pyroxene is the dominant mafic component. This is the deepest material excavated at Bullialdus (from -6 km) and is of a distinctly noritic composition.

Materials exposed on the south wall and rim are from upper stratigraphic zones and exhibit markedly different spectral characteristics. Absorption bands are slightly subdued and, more importantly, occur at longer wavelengths than those of the central peak. The band center for wall material occurs near 0.98 μm indicating high-Ca pyroxene is the dominant mafic mineral and the composition thus has gabbroic rather than noritic affinities. The weaker band strength could be due to a more brecciated material or lower abundance of pyroxene than that for the central peak, but is most likely simply an indication that development of agglutinate-rich soil has been more successful on these terrains since crater formation.

The spectrum for the north rim is similar to that of the wall except for two important distinctions: the band center is at slightly longer wavelengths and the band is broader. These characteristics imply an additional mafic component is present with Ca-rich pyroxene. This could either be a significant component of Fe-bearing translucent glass or of olivine.

Continuum removed spectra for areas in the Bullialdus region that fall into these three distinct groups are shown in Figure 3. Spectra for the noritic central peak were measured on two independent occasions. The repeatability of the spectra is excellent and provides confidence in the overall quality of the data. Spectra for all four areas on the interior wall of the crater are remarkably similar in absorption band characteristics and hence share a similar gabbroic composition. Even the area most likely to be contaminated by a Tycho ray (W Wall) shows only minor deviation from the group as a whole. On the other hand, the distinctive spectral characteristics exhibited by the other areas are clearly evident.
by the north rim area are also exhibited by two other areas, although the precision of the data is less than that for the wall spectra. All three areas of this second gabbroic group are located on the rim or slightly exterior to the crater.

The spectral properties of material excavated by Bullialdus thus form three distinct compositional groups that are highly correlated in a regular spatial pattern centered around the crater. The compositional stratigraphy of this region suggested by the observed concentric pattern is two gabbroic units overlying a crystalline noritic unit which extends to at least 6 km depth. The uppermost gabbroic unit is distinguished by a glass- or olivine-rich composition.

Regional Implications

Since the compositional data presented here provide an assessment of materials at Bullialdus with partial, but not total spatial coverage, it is currently unknown whether additional compositional units exist at the Bullialdus site or how sharp the boundaries are between units. Several geologic interpretations of the origin of the three-component compositional stratigraphy at Bullialdus are possible from the data available, although not all scenarios are equally probable.

Humorum ejecta. Because of its proximity to the Humorum basin, the Bullialdus site would be expected to contain deposits from the Humorum basin. In this scenario, the lower noritic unit could represent local highland crust (consistent with noritic highland regions) and the upper two gabbroic units could represent Humorum deposits, the uppermost perhaps containing a higher concentration of impact melt glass. The principal difficulty with this scenario is that such a gabbroic compositional characterization of Humorum deposits is in disagreement with observations of exposed highland material surrounding the Humorum basin which instead are quite consistent with noritic feldspathic breccias (Pieters et al., 1975; Lucey et al., 1991).

Basalt contamination. Alternatively, the upper two gabbroic units at Bullialdus might be remnants of the thin mare basalt of the pre-impact target region. The isopach estimation of mare basalt thickness across this region (De Hon, 1977, 1979) is 250 - 500 m. Although the high-Ca pyroxene signature for the materials of the wall unit are quite similar to those of the nearby mare (absorption band near 0.98 μm), the albedo of the wall of Bullialdus is too high relative to the mare to account for basalt contamination being responsible for the strength of the observed high-Ca pyroxene absorption band. Additional indirect evidence arguing against this scenario is found when comparing Bullialdus with other craters (e.g. Copernicus which is larger, and Lansberg which is smaller) that occur in a comparable thin mare fill (De Hon, 1977, 1979). No evidence for high-Ca pyroxene (basaltic, gabbroic) contamination is seen in the predominantly orthopyroxene-bearing (noritic) upper stratigraphic zones on the rim and walls of Copernicus and throughout Lansberg (Pieters et al., 1985; Pieters, 1986).

Layered mafic pluton. The three compositional zones observed at Bullialdus may represent three stratigraphic units of a mafic layered pluton tapped by the impact event. The relatively crystalline nature of the noritic unit at 6 km would be consistent with the existence of a pluton that had escaped (or postdated) the period of heavy bombardment. The compositional variations through the stratigraphic column (top to bottom) would have the following affinities: olivine-gabbro, gabbro, and norite. It is, of course, not known whether additional compositional zones occur below the norite, but the uniformity of the gabbroic unit along the wall suggests the size of the pluton would at least have to be on the order of the size of the crater (~60 km).

Nearside Context

The pluton interpretation of the compositional stratigraphy at Bullialdus and the implied importance of plutons in crustal evolution would be more readily acceptable if other potential lunar plutons are recognized. Although this issue can not yet be addressed in a global context, comparisons can be made with crustal material excavated by comparable craters on the lunar nearside available to earth-based astronomers. These data have been limited by observational constraints, but the lunar crust nevertheless has been shown to exhibit substantial diversity with depth. The general stratigraphy of the upper
lunar crust exposed at 13 large nearside craters is summarized in Figure 4 (after Pieters, 1991). Based on the character of mafic minerals present and compositional diversity with depth, most additional candidate areas for pluton excavation appear concentrated in the western hemisphere. The unusual olivine-rich mountains at Copernicus (Pieters et al., 1985; Pieters and Wilhelms, 1985) present an obvious candidate. In Lunar Orbiter II photography the central-most peak appears to exhibit distinct banding, consistent with a layered pluton. The gabbroic compositions trending to troctolite excavated at Aristarchus (Lucey et al., 1986) have been described as another candidate, especially given the high level of volcanic activity of the region. The distinctly gabbroic material excavated by Tycho (Hawke et al., 1986) also contrasts to the predominantly noritic composition of the central highlands.

Although no singular piece of evidence is conclusive, the combined data are highly suggestive of a concentration of lunar plutons on the western nearside. A detailed global survey of the spatial relations of materials excavated by large impact craters is eagerly awaited in order to evaluate the character and abundance of plutons across the Moon and thereby to develop a more accurate understanding of early crustal evolution.

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References


C. M. Pieters, Department of Geological Sciences, Brown University, Providence, RI 02912

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