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Igneous activity in the southern highlands of the Moon

B. Ray Hawke,[1] Thomas A. Giguere,[1,2] D. T. Blewett,[1,3] Paul G. Lucey,[1] G. A. Smith,[1] G. Jeffrey Taylor,[1] and P. D. Spudis[4]

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[1] Detailed investigations of both endogenic and exogenic dark-haloed craters can provide critical information concerning the geology, composition, and evolution of portions of the lunar surface. Several dark-haloed and dark-rayed craters have been identified in the Maurolycus region in the southeastern nearside highlands. Clementine and Galileo multispectral imagery as well as Earth-based remote-sensing data were used to investigate the composition and origin of dark-haloed craters in the region. A striking albedo anomaly is associated with Buch B crater, which exhibits both a dark halo and dark rays. The result of a morphologic analysis clearly indicated that Buch B is an impact structure, not a volcanic vent. The optical maturity image shows that the Buch B ejecta deposits are immature and the radar and thermal data indicate a high abundance of fresh rocks and fragments in the 1–50 cm size range. FeO and TiO_2 data as well as five point spectra extracted from Clementine UV-VIS images indicate that the dark ejecta is composed of immature mare-like material and may contain minor amounts of highland debris. Buch B excavated either an isolated cryptomare or, more likely, a mafic intrusion. One or more dikes of basaltic composition are possible candidates. Minor low-albedo anomalies have been identified around three other impact craters (Maurolycus A and B and Barocius M) in the region. While small FeO enhancements are seen in portions of the ejecta deposits associated with these craters, they do not approach the FeO values (12–14 wt.%) exhibited by the dark deposits of Buch B, and they do fall within the range of FeO abundances (5–9 wt.%) exhibited by highland terrain in the Maurolycus region. Hence the presence of a basaltic component is not required, and it cannot be concluded that either cryptomare or mafic intrusions were present in the target sites of these craters. *INDEX TERMS:* 5410 Planetology: Solid Surface Planets: Composition; 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 5464 Planetology: Solid Surface Planets: Remote sensing; 1060 Geochemistry: Planetary geochemistry (5405, 5410, 5704, 5709, 6005, 6008); 6250 Planetology: Solar System Objects: Moon (1221); *KEYWORDS:* Buch B crater, dark-haloed craters, dark-rayed craters, cryptomare, dike, Maurolycus

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1. Introduction

[2] Prior to the Apollo missions, the nature and origin of lunar dark-haloed and dark-rayed craters were the sources of much controversy. Most lunar scientists supported a volcanic origin for these features, but some advocated formation by impact processes [e.g., *Shoemaker and Hackman*, 1962; *Wilhelms and McCauley*, 1971; *Scott*, 1972; *Head and Wilson*, 1979]. During the Apollo 17 mission, the astronauts actually visited and sampled the dark-haloed Shorty crater, which proved to be of impact origin [e.g., *Wilhelms*, 1987]. As a result of sample, geologic, and remote-sensing studies in the immediate post-Apollo era, our understanding of lunar impact and volcanic processes was greatly increased, and a number of investigators developed criteria for determining the origin of dark-haloed craters (DHCs) [*Schultz and Spudis*, 1979, 1983; *Head and Wilson*, 1979; *Hawke and Bell*, 1981]. Some DHCs were found to be of endogenic origin. These volcanic features were the source vents for the surrounding dark, localized pyroclastic deposits emplaced by vulcanian-style explosive eruptions [*Head and Wilson*, 1979; *Hawke et al.*, 1989; *Gaddis et al.*, 2000]. A much larger number of DHCs are of exogenic origin. Most of these impact craters exhibit dark ejecta deposits because they have excavated buried mafic units [*Schultz and Spudis*, 1979, 1983; *Hawke and Bell*, 1981]. These mafic units are most commonly buried mare basalt flows, but in some instances, may be intrusions (i.e., dikes, sills, etc.) of basaltic composition. Some exogenic DHCs were formed by the emplacement of a dark

[1]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, Hawaii, USA.
[2]Intergraph Corporation, Honolulu, Hawaii, USA.
[3]NovaSol, Inc., Honolulu, Hawaii, USA.
[4]Lunar and Planetary Institute, Houston, Texas, USA.

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glassy veneer of impact melt near the crater rim crest [*Hawke and Head*, 1977; *Schultz and Spudis*, 1979]. Numerous studies have demonstrated that detailed investigations of both endogenic and exogenic DHCs can provide critical information concerning the geology, composition, and evolution of selected portions of the lunar surface [*Schultz and Spudis*, 1979, 1983; *Hawke and Spudis*, 1980; *Hawke et al.*, 1985, 1989; *Blewett et al.*, 1995; *Antonenko et al.*, 1995; *Gaddis et al.*, 2000].

[3] Several dark-haloed and dark-rayed craters have been identified in the Maurolycus region of the lunar nearside [*Shoemaker and Hackman*, 1962; *Scott*, 1972; *Giguere et al.*, 1998, 2000; *Hawke et al.*, 1998, 1999]. The Maurolycus region (Figures 1 and 2) is located in the southeastern highlands and includes densely to moderately cratered terrain with many craters larger than 45 km in diameter. *Scott* [1972] noted that the major stratigraphic units included the pre-Imbrium aged Janssen Formation, hummocky terra and pitted plains materials, and extensive clusters of bowl-shaped craters. The purposes of this study are to determine the composition and origin of DHCs in the Maurolycus region and to assess the implications for intrusive and extrusive igneous activity in the southern highlands of the Moon.

2. Methods

[4] A wide variety of remote-sensing and photographic data was utilized to investigate volcanic processes in the Maurolycus region. The lunar imagery included Earth-based telescopic photographs, Lunar Orbiter IV and V photographs, and Clementine images.

[5] Both Galileo SSI [*Belton et al.*, 1992] and Clementine UV-VIS [*Nozette et al.*, 1994] images were used in this study. The most recent calibrations of each data set were utilized to produce FeO, TiO_2, and optical maturity maps of the Maurolycus region with a variety of spatial resolutions (35 km/pixel, 1 km/pixel, 125 m/pixel). The methods described by *Lucey et al.* [1995, 1998, 2000a, 2000b] and *Blewett et al.* [1997] were used to produce these composition and maturity images.

[6] The 3.8 cm radar images of *Zisk et al.* [1974] were utilized to investigate particle size distribution in the near-surface environment. Finally, the thermal data of *Shorthill and Saari* [1969] were used to study thermal anomalies in the Maurolycus region.

3. Results and Discussion

[7] The most striking albedo anomaly in the Maurolycus region is associated with Buch B crater. This circular feature (diameter = 6 km) is located at 17.0°E, 39.9°S and is centered near the southern rim crest of Buch C crater (Figure 2). The crater exhibits a dark halo and dark rays (Figure 3a). However, some portions of the exterior deposits are relatively bright. *Shoemaker and Hackman* [1962] first described this unusual feature and suggested that it was the product of relatively recent volcanic activity. Buch B was mapped by *Scott* [1972]. He noted the dark rays appear to interrupt bright Tycho rays and that the apparent superpositions of dark rays on Tycho rays, as well as a high infrared thermal anomaly, indicated a late Copernican age.

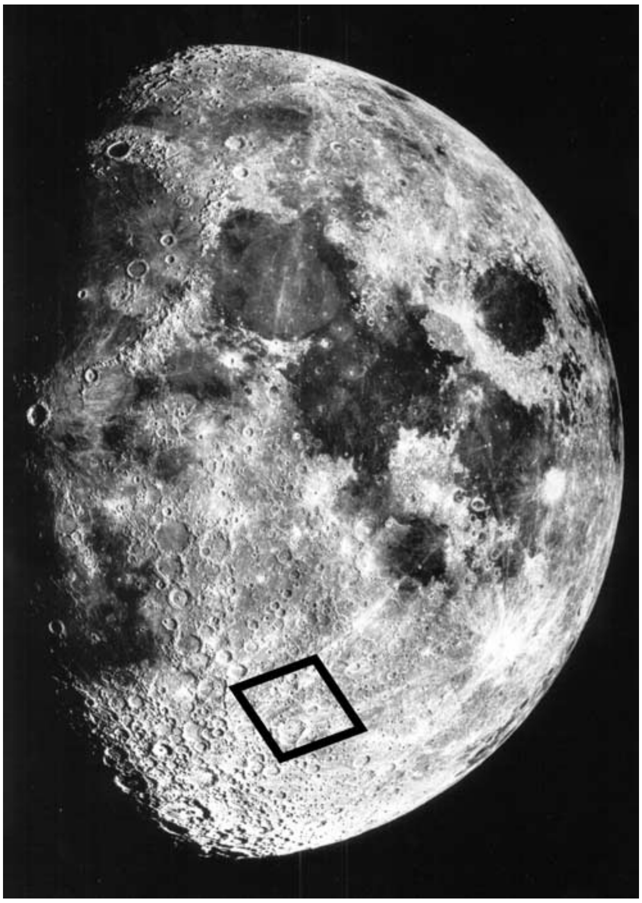

Figure 1. Portion of the lunar nearside. The box in the southeastern highlands identifies the study area and is shown in Figure 2. Lick Observatory photograph.

Scott [1972] interpreted Buch B as possibly volcanic in origin and noted that the dark rays may be new volcanic material from an explosive maar-type vent.

[8] As discussed above, firm criteria for determining the origin of lunar craters were developed and tested in the post-Apollo era [e.g., *Schultz and Spudis*, 1979, 1983; *Head and Wilson*, 1979]. Application of these criteria to Buch B leaves little doubt that it was formed by impact processes. For example, Buch B has a well-defined raised rim and a depth/diameter ratio typical of fresh impact craters. The crater is circular, not elongate in shape and there is no obvious association with well-developed faults or fractures. Buch B is clearly a dark-haloed impact crater, not a volcanic vent.

[9] A major effort was made to determine the composition and origin of the dark ejecta associated with Buch B crater. Previous studies have demonstrated that some very young impact craters exhibit low-albedo exterior deposits composed of dark, glassy impact melt [*Hawke and Head*, 1977; *Schultz and Spudis*, 1979]. For craters less than ten kilometers in diameter, these exterior impact melts typically occur as a narrow fringe of glassy veneer immediately adjacent to the rim crest. The Buch B dark exterior deposits exhibit none of the characteristics of glassy impact melt deposits associated with craters in this size range.

[10] The absence of glassy melt is confirmed by the optical maturity image (Figure 3c). The net effect of glassy

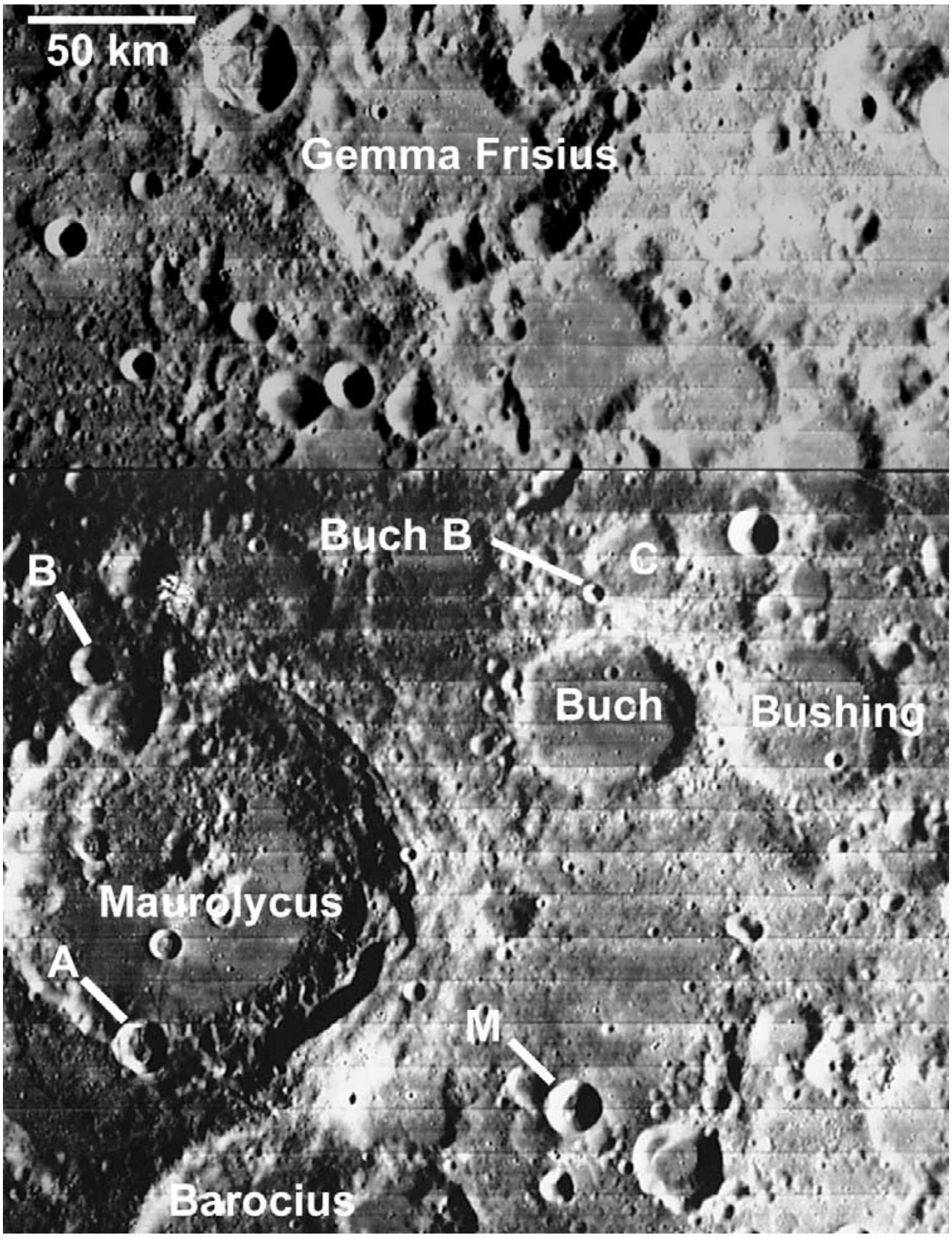

Figure 2. Area around Maurolycus crater (114 km diameter) which is located at 14.0°E, 41.8°S. The crater Buch B (6 km diameter) is located to the northeast at 17.0°E, 39.9°S. The craters mentioned in the text (Barocius M, Maurolycus A and B, and Buch B) are identified. Lunar orbiter IV images 95-2 and 95-3.

impact melt on spectral properties is to lower the albedo and to reduce the depth of the one-micron absorption feature [*Hawke et al.*, 1979; *Smrekar and Pieters*, 1985]. These spectral changes would be reflected in the maturity image as areas of greater optical maturity [*Lucey et al.*, 2000a]. No abnormally mature areas can be seen in Figure 3c. Hence, impact melt plays no role in producing the dark halo and rays associated with Buch B.

[11] Additional evidence for the composition and origin of the Buch B dark ejecta is provided by the 0.75 μm albedo image and the FeO map (Figures 3a and 3b). There is a good correlation between low-albedo exterior deposits and areas with high FeO values (12–14%). These values approach those exhibited by lunar mare basalt deposits (15–18%) [*Lucey et al.*, 1995]. In contrast, typical highland material in the Maurolycus region have FeO abundances that range between 5 and 9%. The darkest portions of the exterior deposits appear to be composed almost exclusively of basaltic material. The higher-albedo ejecta deposits exhibit a range of FeO values (5–11%). The lower values are consistent with the presence of local highland material while the higher values suggest a mixture of local highland debris with minor amount of basaltic material.

[12] Additional support for the dominance of mare basalt in the dark exterior deposits of Buch B is provided by the TiO_2 map of the Maurolycus region. The highland terrain in the region exhibits TiO_2 values of less than 1%. In contrast, portions of the Buch B dark ejecta have TiO_2 values

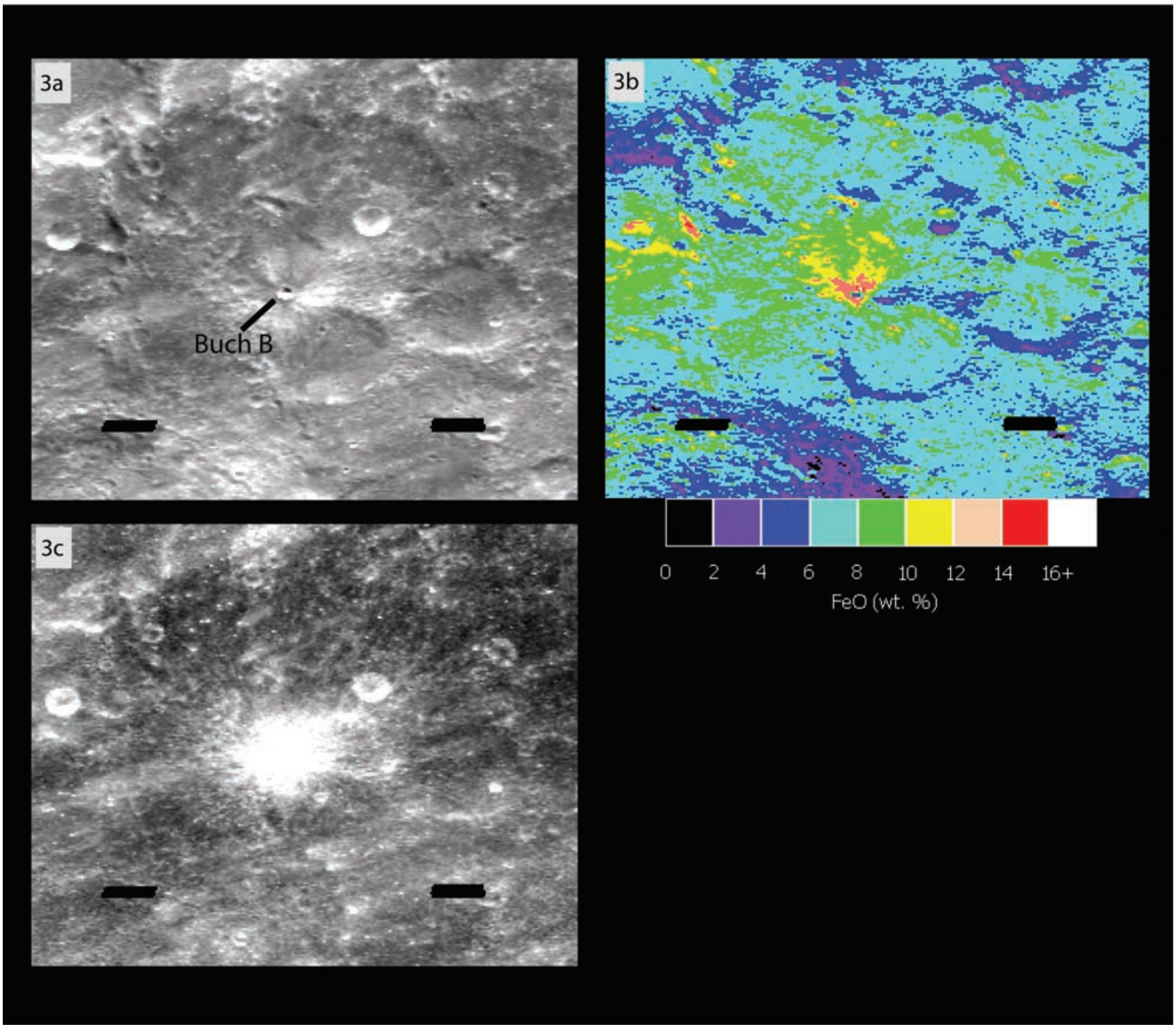

Figure 3. (a) Clementine image (0.75 μm) of the Buch B area (1 km/pixel). Buch B is six km in diameter and exhibits a dark halo and dark rays. North is at the top of the image. (b) FeO image of Buch B area derived from Clementine images (1 km/pixel). The image was produced using the method of *Lucey et al.* [2000b]. Relatively high FeO values (12–14%) are exhibited by the darker portions of the Buch B ejecta deposit. Colors indicative of high FeO values are seen in small areas away from Buch B. These colors are the result of shadows associated with crater walls and do not indicate the true FeO abundances of the shadowed areas. (c) Optical maturity image of crater Buch B derived from Clementine images (1 km/pixel). The image was produced using the method of *Lucey et al.* [2000a]. Immature areas are bright and mature areas are dark.

between 1% and 2%. These values are consistent with those exhibited by low TiO_2 mare units elsewhere on the lunar nearside [e.g., *Giguere et al.*, 2000].

[13] In order to further investigate the composition of Buch B ejecta, five point spectra were extracted from calibrated and registered Clementine UV-VIS images (1 km/pixel) [*Robinson et al.*, 1999; *Isbell et al.*, 1999; *Eliason et al.*, 1999] using the techniques described by *Tompkins and Pieters* [1999]. Spectra were obtained for the ejecta deposits associated with fresh impact craters in the southern highlands. These five point spectra exhibit "1 μm" absorption features with centers less than 0.95 μm. The lithologies in those areas for which the spectra were obtained have mafic assemblages dominated by low-Ca pyroxenes. These craters generally expose material dominated by noritic anorthosite or anorthositic norite. The two fresh highland spectra shown in Figure 4 were obtained for immature noritic anorthosite lithologies. Two typical spectra for the exterior deposits of relatively young impact craters in mare regions are shown in Figure 4. These spectra exhibit strong "1 μm" absorption features and the band shapes indicate mafic assemblages dominated by high-Ca clinopyroxene.

[14] Spectra were extracted for different portions of the Buch B dark exterior deposits including the dark ray that extends northwest from the parent crater. Two of these spectra are shown in Figure 4. These spectra have relatively

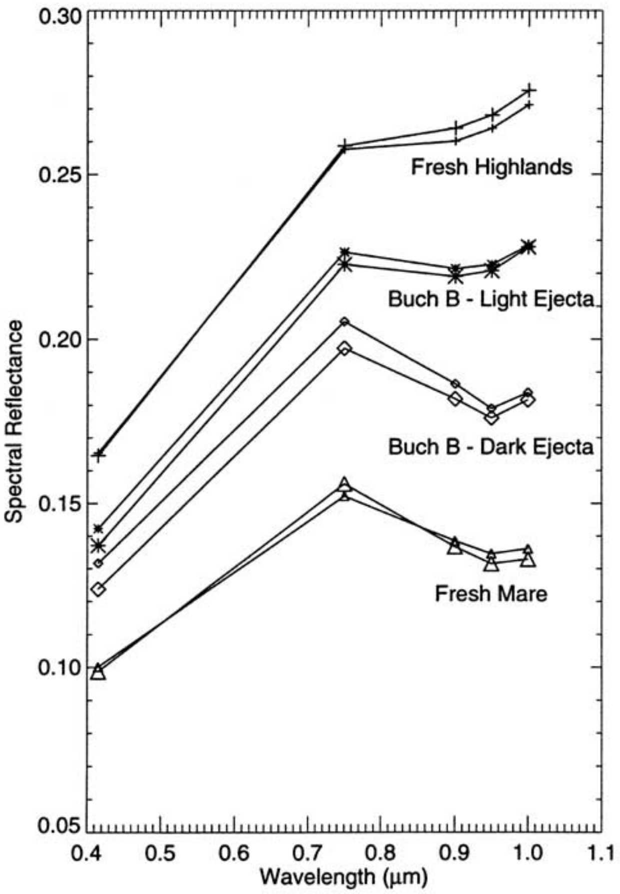

Figure 4. Five point spectra of Buch B ejecta deposits and features in the surrounding area were obtained from Clementine UV-VIS images using the method of *Tompkins and Pieters* [1999]. Pairs of spectra were collected for four areas: fresh highlands (plus), Buch B light ejecta (star), Buch B dark ejecta (diamond), and fresh mare (triangle).

strong "1 µm" absorption bands and have band parameters that suggest the dominance of high-Ca pyroxene. The spectra are very similar to those collected for fresh mare craters and the dark ray segments for which the spectra were obtained are composed of very immature mare basalt or immature mare basalt contaminated with minor amounts of highland debris.

[15] Spectra were also obtained for various portions of the bright Buch B ejecta deposits. Two of these spectra are shown in Figure 4. Although the areas for which these spectra were extracted are dominated by fresh highland material, some have spectral characteristics that suggest that small amounts of mare basalt may be present.

[16] Infrared thermal anomalies of the eclipsed Moon are believed to be related to the thermal conductivity of lunar surface material [*Shorthill and Saari*, 1969]. High values are generally thought to be related to the surface exposure of fresh rocks. *Scott* [1972] noted that the temperature of Buch B was about 22 K higher than its surroundings and suggested that Buch B was the youngest clearly visible Copernican crater in the region. The crater also exhibits enhanced returns in the depolarized 3.8 cm radar images presented by *Zisk et al.* [1974]. This radar anomaly indicates a high abundance of 1–50 cm fragments at or near the surface.

[17] In summary, Buch B is a very young Copernican-age impact crater surrounded by both light and dark ejecta deposits that exhibit a high abundance of immature rock fragments. The dark ejecta is composed of fresh mare-like material but may contain minor amounts of highland debris. The bright ejecta is dominated by fresh highland material but minor amounts of mare-like material may be present in some areas.

[18] It is important to determine the source of the mafic material that was excavated and emplaced by the Buch B impact event. Three possibilities seem most likely: 1) a pre-existing mare pond, 2) a cryptomare deposit, and 3) a buried igneous intrusion of basaltic composition.

[19] Although no mare basalt deposits have been identified in the Maurolycus region, it is at least possible that a mare pond existed in the Buch B pre-impact target site. The target site was centered on the rim crest of Buch C crater and the Buch B impact event excavated both wall and elevated rim material. It seems unlikely that any but the smallest ponds could have accumulated in this topographic setting. The volume of the mare pond material would be far too small to account for the large amount mafic material in the Buch B ejecta deposts.

[20] Ancient mare basalt deposits that have been hidden or obscured by superposed higher albedo material are referred to as cryptomaria [*Head and Wilson*, 1992; *Head et al.*, 1993; *Antonenko et al.*, 1995]. Most represent a record of the earliest (>3.8 Ga) mare volcanism but some are younger (<3.8 Ga) mare deposits with surfaces that have been either covered by or contaminated with highland-rich ejecta from nearby large impact craters. Studies of the Apollo orbital geochemistry data sets and telescopic near-infrared spectra have shown that mafic geochemical anomalies on the lunar surface are commonly associated with light plains deposits that exhibit dark-haloed impact craters which excavated ancient mare basalts [e.g., *Schultz and Spudis*, 1979, 1983; *Hawke and Spudis*, 1980; *Hawke and Bell*, 1981; *Hawke et al.*, 1985; *Blewett et al.*, 1995; *Antonenko et al.*, 1995]. *Schultz and Spudis* [1979] noted that the excavation of either buried mare basalts or mafic igneous intrusions can produce DHCs and described the difficulties in distinguishing between the two possibilities. Subsequent studies of impact DHCs and cryptomaria have concluded that the vast majority of known DHCs excavated buried mare deposits. Still, some DHCs may have excavated mafic intrusions with basaltic compositions.

[21] Buch B doesn't exhibit the characteristics typical of DHCs that have excavated buried mare basalts. It is an isolated DHC and is not located on a light plains deposit. The asymmetry of the dark exterior deposits suggests the nonuniform distribution of the buried mafic unit. Perhaps an igneous intrusion was present in a portion of the Buch B pre-impact target site. Although a cryptomare origin cannot be ruled out, the bulk of the topographic, geologic, and remote-sensing evidence supports an intrusive igneous origin for the mafic unit excavated and emplaced during the Buch B cratering event. *Wilson and Head* [2001] recently presented a new model for lunar dike formation that predicted dike widths which range from 50 to 300 m. These values are very similar to those presented by *Head*

and Wilson [1992]. Perhaps Buch B excavated material from one or more of these giant dikes.

[22] Other albedo anomalies have been identified in the Maurolycus region [e.g., *Scott*, 1972]. *Scott* [1972] noted that dark rays extend locally from Maurolycus A and suggested a volcanic origin for these features. Maurolycus A is an Eratosthenian-aged crater (diameter = 15 km) located largely on the south wall of Maurolycus crater. *Giguere et al.* [1998] and *Hawke et al.* [1998] noted that portions of the ejecta deposits of Barocius M and Maurolycus B appear slightly darker than typical highland surfaces. These workers suggested that FeO enhancements were associated with these craters as well as Maurolycus A [*Giguere et al.*, 1998; *Hawke et al.*, 1998]. These early results were based on studies of low-resolution (35 km/pixel) FeO maps [*Lucey et al.*, 1995]. In some regions, these large pixels included shadowed areas on slopes that face away from the sun. The inclusion of a small shadowed area would have resulted in a higher FeO value for the entire pixel.

[23] In order to further investigate the possible FeO enhancements associated with these three craters, we utilized higher resolution (1 km/pixel and 125 m/pixel) FeO images. Small FeO enhancements are seen in portions of the ejecta deposits associated with these craters. Still, these enhancements do not approach the FeO values (12–14 wt.%) exhibited by the low-albedo exterior deposits of Buch B, and they do fall within the range of FeO abundances (5–9 wt.%) determined for typical highland units in the Maurolycus region. Maurolycus A and the other craters may have excavated mafic material from depth and incorporated this debris into portions of their ejecta deposits. However, the presence of a basaltic component is not required, and it cannot be concluded that either cryptomare or mafic intrusions were present in the target sites of these craters.

4. Conclusions

1. A striking albedo anomaly is associated with Buch B crater which is located in the Maurolycus region. This Copernican-aged crater exhibits a dark halo and dark rays.

2. The results of a morphologic analysis clearly indicated that Buch B is an impact structure. It is not a volcanic vent and is not the product of relatively recent volcanic activity.

3. The high infrared eclipse temperatures and the enhanced 3.8 cm radar returns associated with Buch B indicate a high abundance of fresh rocks and fragments in the 1–50 cm size range. The optical maturity image shows that ejecta deposits of Buch B are immature. No abnormally mature areas are associated with the ejecta deposits. Hence, glassy impact melt plays no role in producing the dark deposits associated with Buch B.

4. There is a good correlation between Buch B low-albedo exterior deposits and areas with high FeO values (12–14 wt.%). These values are only slightly lower than those exhibited by lunar mare basalts (15–18 wt.%). Five point spectra extracted for different portions of the dark deposits are very similar to those collected for fresh mare craters. The dark ejecta is composed of immature mare-like material but may contain minor amounts of highland debris.

5. Buch B excavated either an isolated cryptomare or, more likely, a mafic intrusion of basaltic composition.

6. Maurolycus A, Maurolycus B, and Barocius M may have excavated mafic material from depth and incorporated this material into their ejecta deposits. However, the range of FeO abundances exhibited by these deposits can be explained by known highland rock types in the Maurolycus region.

7. Outside of the Buch B area (and possibly the Barocius M, Maurolycus A, and Maurolycus B areas), there is no evidence that intrusive or extrusive igneous processes played an important role in producing compositional units in the Maurolycus quadrangle and adjacent portions of the southern highlands of the Moon.

[24] **Acknowledgments.** A detailed and thoughtful review by Lisa Gaddis (U.S.G.S., Flagstaff, AZ) substantially improved this paper. This paper is dedicated to the memory of Dr. E. M. Shoemaker who brought the unusual nature of Buch B to our attention. This work was supported by NASA grants NAG5 3635 (B. Ray Hawke, PI), NAG5 3766 (P. Lucey, PI), and NAG5 4212 (K. Keil, PI). This is HIGP publication no. 1196 and SOEST publication no. 5929.

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D. T. Blewett, NovaSol, Inc., 1100 Alakea Plaza, 23rd Floor, Honolulu, HI 96813, USA.

T. A. Giguere, Intergraph Corporation, 2828 Pa‘a Street, Suite 2150, Honolulu, HI 96819, USA.

B. R. Hawke, P. G. Lucey, G. A. Smith, and G. J. Taylor, Hawaii Institute of Geophysics and Planetology, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822, USA. (Hawke@higp.hawaii.edu)

P. D. Spudis, Lunar and Planetary Institute, Houston, TX 77058, USA.