JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. E7, 5069, doi:10.1029/2002JE002013, 2003

Hansteen Alpha: A volcanic construct in the lunar highlands

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Received 19 November 2002; revised 10 April 2003; accepted 29 April 2003; published 5 July 2003.

[1] We have used data from the Clementine and Lunar Prospector spacecraft in conjunction with near-IR reflectance spectra collected with Earth-based telescopes to study the composition and origin of Hansteen Alpha, an arrowhead-shaped highlands feature located on the southern margin of Oceanus Procellarum. Hansteen Alpha is a member of a class of lunar spectral anomalies (Red Spots) that are characterized by a relatively high albedo and a strong absorption in the UV. It has been suggested that at least some of these spectral anomalies were produced by nonmare volcanism. The stratigraphic relationships among the geologic and compositional units in the region show that Hansteen Alpha was emplaced by extrusive igneous processes. The Imbrian-aged craters Hansteen and Billy emplaced relatively FeO- and TiO_2-rich ejecta. Hansteen Alpha exhibits much lower FeO and TiO_2 values. If Hansteen Alpha was present prior to the Billy and Hansteen impact events, it should have been covered with FeO- and TiO_2-rich ejecta because it is located within one crater diameter of the rim crest of each crater. Since it is not, Hansteen Alpha was superposed on these ejecta units. Nonmare volcanism is the only viable process for the formation of Hansteen Alpha. The morphology and surface texture of Hansteen Alpha is similar to many terrestrial features of dacitic and rhyolitic composition formed by extrusions of relatively viscous lavas. Such highly evolved compositions should be very enriched in Th, but Hansteen Alpha exhibits Th abundances of ~6 ppm. Hence Hansteen Alpha is not composed of a highly evolved highlands lithology. *INDEX TERMS:* 8450 Volcanology: Planetary volcanism (5480); 6250 Planetology: Solar System Objects: Moon (1221); 5410 Planetology: Solid Surface Planets: Composition; 1060 Geochemistry: Planetary geochemistry (5405, 5410, 5704, 5709, 6005, 6008); 5464 Planetology: Solid Surface Planets: Remote sensing; *KEYWORDS:* Moon, remote sensing, nonmare volcanism, highlands volcanism, Clementine, spectral anomalies

Citation: Hawke, B. R., D. J. Lawrence, D. T. Blewett, P. G. Lucey, G. A. Smith, P. D. Spudis, and G. J. Taylor, Hansteen Alpha: A volcanic construct in the lunar highlands, *J. Geophys. Res.*, *108*(E7), 5069, doi:10.1029/2002JE002013, 2003.

1. Introduction

[2] Lunar Red Spots make up a very important class of spectral anomalies on the nearside of the Moon. Red Spots are characterized by a relatively high albedo and a strong absorption in the ultraviolet. UV-IR color difference photographs were used by *Whitaker* [1972] to identify and characterize Red Spots on the lunar nearside. The technique of color difference photography involves subtracting a photograph taken at a given wavelength from a second photograph taken at a different wavelength to produce a composite image. *Whitaker* [1972] suggested that these anomalously red areas may have compositions that are substantially different from those of typical highlands. The identified red areas included Hansteen Alpha, Darney Chi, Darney Tau, Mons La Hire, the Helmet, the southern portion of Montes Riphaeus, the Gruithuisen domes, and an area surrounding the anomalous craters Lassel K, G, and C. Red Spots are concentrated on the western portion of the lunar nearside. These spectral anomalies also appear in digital vidicon multispectral images [*McCord et al.*, 1976].

[3] *Wood and Head* [1975] conducted a detailed study of Red Spots and determined that these spectral anomalies exhibit a wide range of morphologies. These include domes, smooth plains units, rugged highlands terrain, and impact-related features. They found that Red Spots are located in a variety of geological settings and are frequently found in clusters. Many Red Spots are embayed by younger mare units, suggesting that they may have originally covered a greater portion of the lunar surface.

[4] In the immediate post-Apollo era, several workers presented evidence that at least some Red Spots were produced by highlands (i.e., nonmare) volcanism and suggested a connection with KREEP basalts (Medium-K Fra Mauro basalt {MKFMB}) or even more evolved highlands

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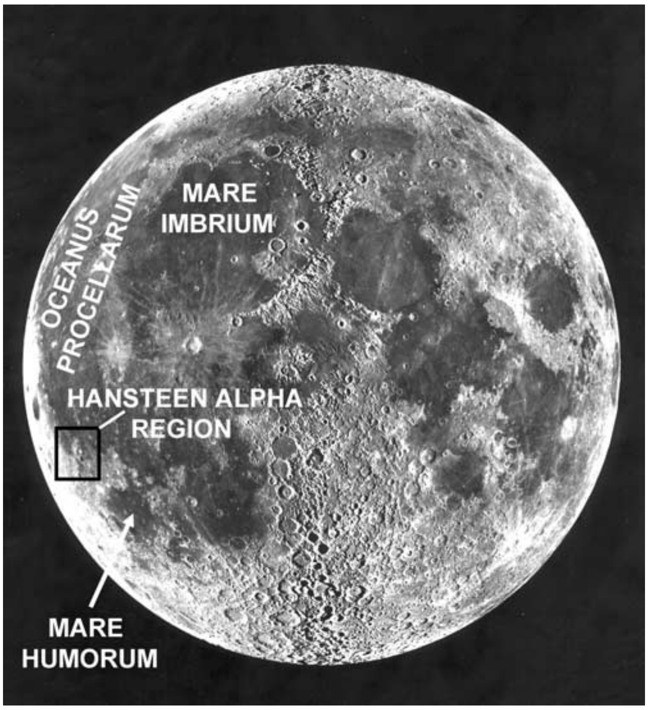

Figure 1. Full-disk image of the Moon showing the location of the Hansteen Alpha region. The base photograph is a pseudo-full Moon mosaic produced by Lick Observatory.

compositions (e.g., High-K Fra Mauro Basalt {HKFMB}, dacite, rhyolite). Largely on the basis of Apollo X-ray fluorescence and gamma-ray spectrometry data, *Malin* [1974] suggested that Red Spots are the surface manifestations of KREEP basalts ("Apollo 14/KREEP/norite material") emplaced before the period of mare volcanism. *Wood and Head* [1975] suggested that some red material may have been involved in post-Imbrium extrusive volcanic activity prior to the emplacement of the major maria. *Head and McCord* [1978] presented geologic and spectral reflectance evidence that the Gruithuisen and Mairan domes represent morphologically and spectrally distinct nonmare extrusive volcanic features of Imbrian age.

[5] More recently, major controversies have been associated with highlands volcanism, the origin of KREEP, and the nature of Red Spots. Many highlands units that were originally thought to have been formed by volcanic processes [e.g., *Wilhelms and McCauley*, 1971] have been reinterpreted to be of non-volcanic origin [e.g., *Wilhelms*, 1987]. *Bruno et al.* [1991] described spectral differences that indicated that Red Spots do not have a single mineralogic composition and suggested that Red Spots have multiple origins. While most workers consider Mons La Hire to be a portion of the inner ring that formed during the Imbrium impact event, some have suggested that Mons La Hire is a volcanic construct, possibly formed by the extrusion of magma that had risen along a basin-related fault [e.g., *Raitala et al.*, 1999]. Finally, *Chevrel et al.* [1999] have recently presented additional spectral data which support the likely volcanic origin of the Gruithuisen domes.

[6] It is important to establish the reality of highlands volcanism as well as the composition of lithologic units emplaced by this process. The existence of ancient highlands volcanism has major implications for lunar thermal history and crustal evolution. The study of Red Spots of possible volcanic origin can provide crucial information for understanding the early Moon. Hence we have been using remote sensing data to determine the composition of selected Red Spots and to investigate the relationship between Red Spots and KREEP basalts and other evolved highlands compositions [*Hawke et al.*, 2001, 2002]. The purpose of this paper is to present our results for Hansteen Alpha (Figures 1 and 2), which we have determined to be a volcanic construct with highlands affinities.

2. Method

[7] Both Earth-based and spacecraft remote sensing data were used to investigate the chemistry and mineralogy of lunar Red Spots. Chief among these were Clementine UVVIS images and Lunar Prospector orbital geochemistry data.

[8] The U.S. Geological Survey's Astrogeology Program in Flagstaff, Arizona has completed and published on CD-ROM a Clementine five-color digital image model (DIM) for the Moon [*Isbell et al.*, 1999; *Eliason et al.*, 1999; *Robinson et al.*, 1999]. Data from this DIM were mosaicked to produce an image cube in orthographic projection centered on Hansteen Alpha, at 100m/pixel spatial resolution (Figure 3a). This calibrated image cube was utilized for the production of a number of other data products, including FeO, TiO_2, and optical maturity maps (Figures 3b, 4a, and 4b) prepared using the algorithms of *Lucey et al.* [2000a, 2000b]. The method developed by *Lucey et al.* [1995] for determining FeO abundances relies on 750 nm reflectance and 950/750 nm ratio images to measure the spectral effects of ferrous iron in major lunar minerals such as olivine and pyroxene. This technique controls for the optical effects of submicroscopic metallic iron that is

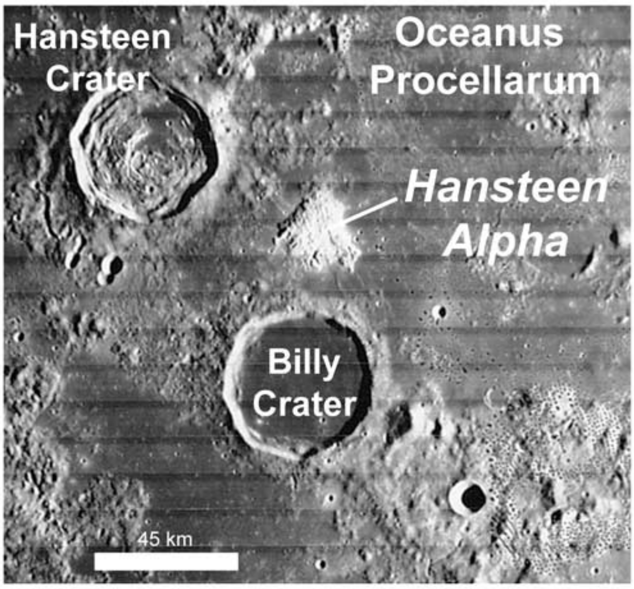

Figure 2. Portion of Lunar Orbiter IV Frame 149-H2 showing the morphologies of features in the Hansteen Alpha region. Billy crater is 45 km in diameter. North is toward the top.

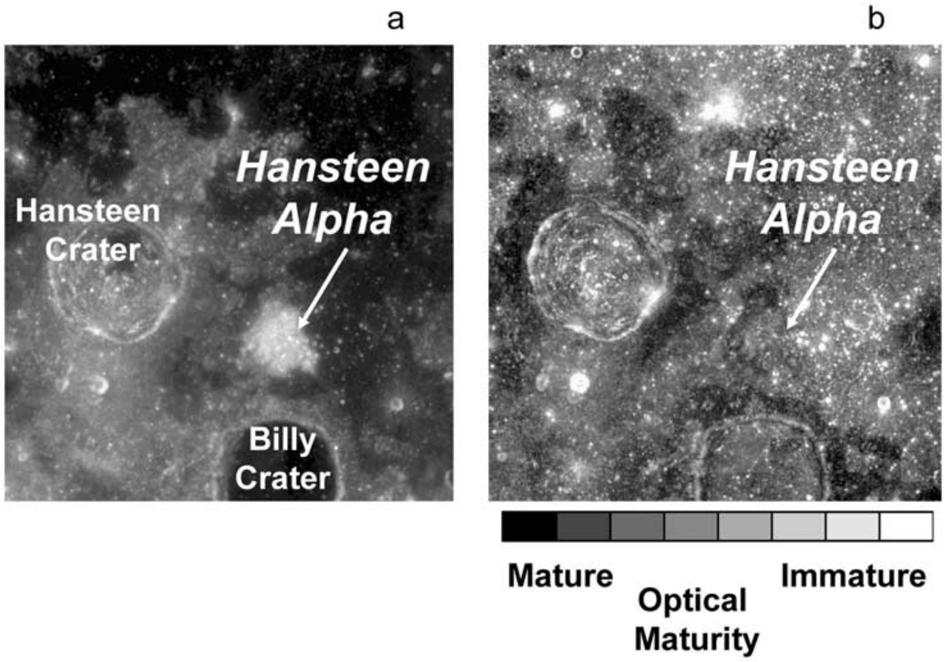

Figure 3. (a) Clementine 750 nm albedo image of the Hansteen Alpha region. (b) Optical maturity parameter image produced for the area shown in (a). Brighter tones indicate lower maturity (fresher material).

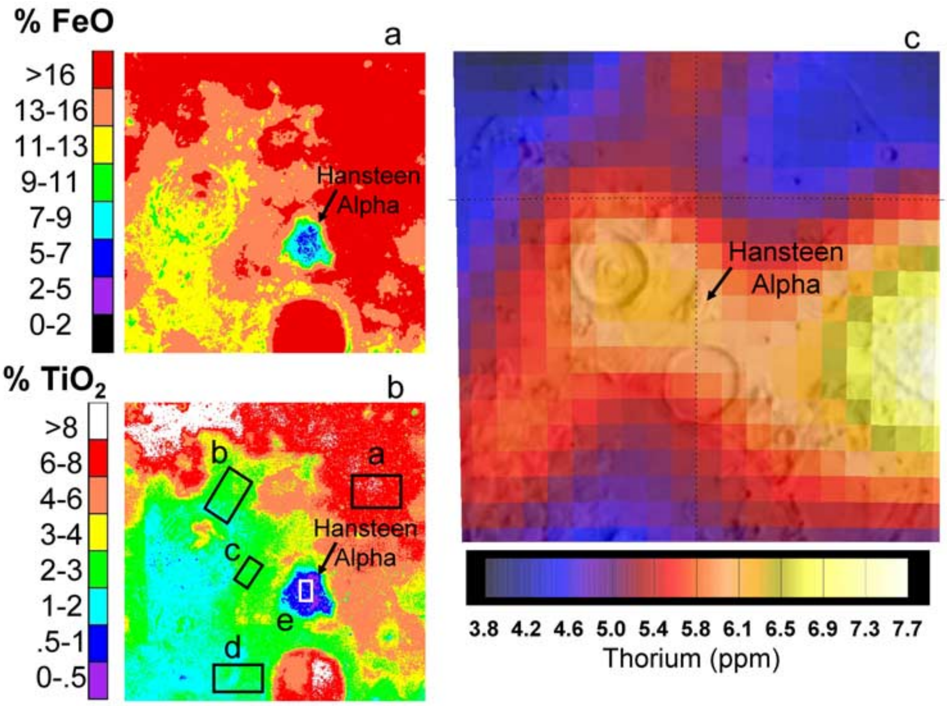

Figure 4. (a) FeO map derived from Clementine UVVIS imaging. This image is for the same area as the 750 nm image shown in Figure 3a. (b) TiO_2 map derived from Clementine UVVIS imaging. The area is the same as that shown in Figure 3a. The boxes indicate the five areas for which the average abundances of FeO, TiO_2, and Th were obtained (Table 1). (c) Smoothed thorium abundances in the Hansteen Alpha region. The raw $0.5^\circ \times 0.5^\circ$ Th data have been smoothed by a two-dimensional, equal-area Gaussian function with a 32 km HWHM. The map boundaries range from longitude 45° W to 55° W and from latitude 7° S to 17° S. The color-coded Th image was merged with a shaded-relief map.

produced as rocks are exposed to micrometeorite bombardment and solar wind implantation at the lunar surface.

[9] The method used by *Lucey et al.* [1998, 2000a] to estimate the TiO_2 content of the lunar surface utilizes a parameter derived from 750 nm reflectance and 415/750 nm ratio images. The mapping from the color-albedo parameter to wt.% TiO_2 is based on an understanding of the spectral effects of the Ti-rich opaque mineral ilmenite as a component of a mineral mixture comprising the lunar regolith at the locations sampled by the Apollo and Luna missions [*Blewett et al.*, 1997; *Lucey et al.*, 1998, 2000a; *Blewett and Hawke*, 2001]. As sampled, the lunar regolith consists of a relatively restricted suite of minerals and compositions (high – Ca plagioclase feldspar, Fe-bearing ortho- and clinopyroxenes, minor Fe- bearing olivine, minor ilmenite and other opaques, agglutinitic glass). *Blewett and Hawke* [2001] noted that it is possible that there exist on the Moon locations dominated by lithologies that are rare in the sample collection, or lithologies and mineral chemistries which have not been sampled. They also noted that the presence of unusual minerals or mineral chemistries could affect the color of some materials to the extent that they do not fit in UV ratio-reflectance space as expected. Hence the color-albedo parameter measured for such materials would violate the assumptions of the opaque mineral – Ti model.

[10] The Lunar Prospector spacecraft carried a gamma-ray spectrometer to measure the natural radioactivity of the lunar surface. Th abundance maps were produced for both high-altitude (lower spatial resolution) and low-altitude (higher spatial resolution) portions of the mission [*Lawrence et al.*, 1998, 1999, 2000]. For this study, we extracted the section of the recent global low-altitude ($2° \times 2°$, corresponding to ~60km/pixel) Th map that covers the southern Oceanus Procellarum-Mare Cognitum region. The data were color-coded and merged with a shaded-relief image to aid in the identification of major surface features.

[11] *Lawrence et al.* [2002] have recently presented a method for the production of Th maps with high pixel resolution and optimized spatial resolution. For the Hansteen Alpha region, a Th map with $0.5° \times 0.5°$ sized pixels was produced by smoothing raw $0.5° \times 0.5°$ thorium data with a two-dimensional equal-area Gaussian function having a half-width, half-maximum of 32 km. The color-coded Th image was merged with a shaded-relief map and has an intrinsic spatial resolution of ~45 km (Figure 4c).

[12] It should be noted that the Th data sets used in this study are those presented by *Lawrence et al.* [2000, 2002]. Efforts are underway to develop forward modeling techniques (D. J. Lawrence et al., Small-area thorium features on the lunar surface, submitted manuscript, 2003) (hereinafter referred to as Lawrence et al., submitted manuscript, 2003) as well as spatial deconvolution algorithms that can substantially improve our understanding of the thorium spatial distribution. For example, Lawrence and co-workers have used a smoothed Th map and an improved understanding of the GRS response function to provide better constraints on the surface Th abundance of the Compton/Belkovich thorium enhancement (Lawrence et al., submitted manuscript, 2003). Application of the techniques currently under development should result in an improved understanding of the Th abundances of the geologic units in the Hansteen Alpha region.

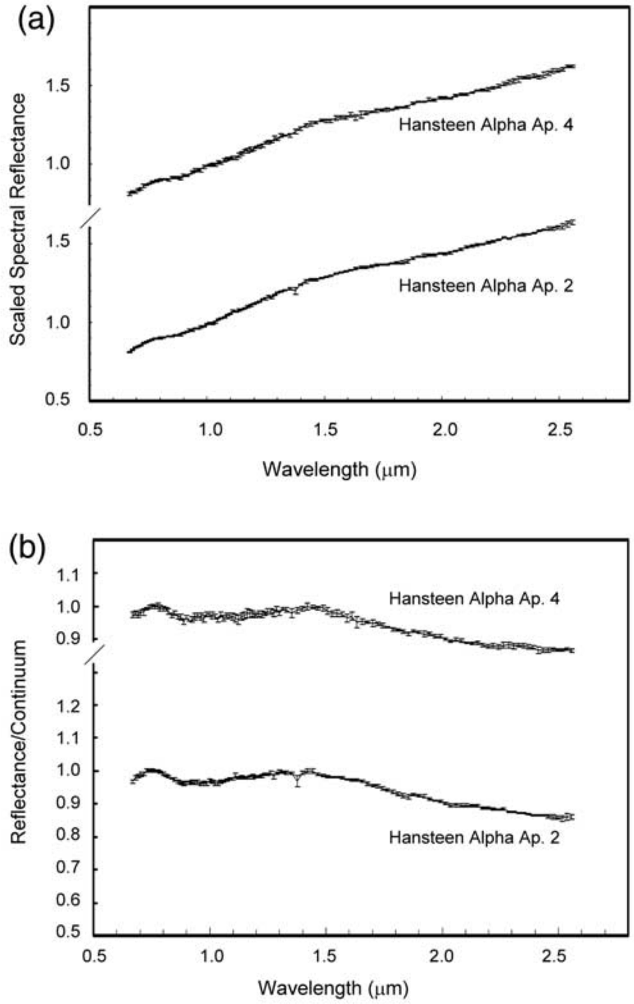

Figure 5. (a) Near-infrared reflectance spectra relative to the Sun for two portions of Hansteen Alpha. The spectra are scaled to 1.0 at 1.02 μm. (b) Continuum-removed versions of the Hansteen Alpha spectra in (a).

[13] Near-infrared (near-IR) reflectance spectra were obtained for Hansteen Alpha with a University of Hawaii 2.2 meter telescope at Mauna Kea Observatory using the Planetary Geosciences InSb circular-filter spectrometer. The telescope configuration and the size of the spectrometer aperture determine the diameter of the area of the lunar surface for which a spectrum was obtained. Two spectra were collected for Hansteen Alpha (Figure 5). One spectrum (aperture 4) was obtained for a relatively large spot (diameter = ~16 km) centered on Hansteen Alpha. The other spectrum (aperture 2) was collected for a much smaller area (diameter = ~8 km) that was also centered on Hansteen Alpha. Standard observing techniques and data reduction procedures were employed [*McCord et al.*, 1981].

3. Results and Discussion

3.1. Geologic Setting and Morphology

[14] Hansteen Alpha is an arrowhead-shaped highlands feature located on the southern margin of Oceanus Procel-

Table 1. Average Abundances of FeO, TiO_2, and Th for Five Areas in the Hansteen Alpha Region[a]

	A Mare Unit	B Hansteen Ejecta 1	C Hansteen Ejecta 2	D Billy Ejecta	E Hansteen Alpha	Apollo 15 KREEP Basalt	Granite and Felsite	Quartz Monzodiorite	Apollo 15 Group C LKFM
FeO%	18.1 ± 0.3	13.6 ± 0.5	13.8 ± 0.5	12.7 ± 0.5	6.9 ± 0.5	9.8 ± 0.3	7.7 ± 3.9	14.2 ± 1.2	8.1 ± 0.9
TiO_2%	6.7 ± 0.8	2.5 ± 0.5	2.4 ± 0.3	2.0 ± 0.3	0.5 ± 0.1	2.0 ± 0.2	1.0 ± 0.5	2.5 ± 0.5	0.9 ± 0.2
Th, ppm	5.1	5.9	6.3	5.7	6.1	11.0 ± 0.8	36.0 ± 13.0	40.0 ± 12.0	5.7 ± 0.6

[a]The areas for which the averages were obtained are shown in Figure 4b. The listed uncertainties are one standard deviation. The average concentrations of FeO, TiO_2, and Th in selected highly evolved lunar igneous rocks and Apollo 15 Group C LKFM are listed for comparison [*Korotev*, 1998].

larum just north of the crater Billy (Figures 1 and 2). The distinctive shape of Hansteen Alpha has resulted in many workers referring to it simply as the "Arrowhead." The feature is a rough textured triangular mound that is ~ 25 km on a side (Figure 2) and it exhibits a relatively high albedo (Figure 3a). *Wood and Head* [1975] noted that the Arrowhead appeared distinctive in its surface texture, color and albedo from nearby highlands and is embayed by adjacent mare units.

[15] *McCauley* [1973] described Hansteen Alpha as being made up of steep-sided, bulbous, very bright dome materials that exhibit hackly surfaces. He also described several small, linear, smooth-walled depressions at the crests of gentle individual topographic highs. These linear depressions were interpreted to be probable volcanic vents [*McCauley*, 1973].

3.2. Clementine UVVIS Data Products

[16] A Clementine UVVIS image cube was used to produce a number of products including FeO, TiO_2, and maturity maps, for the Hansteen Alpha region (Figures 3a, 3b, 4a, and 4b). A 750 nm reflectance image of the region is shown in Figure 3a. High reflectance values are exhibited by Hansteen Alpha as well as impact crater walls. Low values are associated with mare deposits. Intermediate reflectance values are exhibited by highland units such as those associated with the ejecta of Hansteen and Billy craters.

[17] It has been informally suggested that Hansteen Alpha and similar features are bright because they are extremely young and their surfaces have not reached optical maturity. These surfaces could have been formed by the recent emplacement of volcanic material or by the formation of numerous primary or secondary impact craters [e.g., *Scott and Eggleton*, 1973]. An optical maturity map of the Hansteen Alpha region is shown in Figure 3b. This image shows that Hansteen Alpha, with the exception of a few small impact craters, is fully mature. Its high albedo is not due to extreme immaturity, therefore it must result from a compositional difference with adjacent terrain.

[18] Maps showing the distribution of FeO and TiO_2 in the Hansteen Alpha region are presented in Figure 4. Mare units in this region generally exhibit FeO abundances >16% and TiO_2 values range between 4% and 8%. Average values for the mare area outlined in Figure 4b (Box A) are given in Table 1. Lower FeO and TiO_2 values are seen near highland/mare boundaries and are probably due to contamination of mare surfaces by highlands debris emplaced by lateral transport or vertical mixing by impact.

[19] In sharp contrast, much lower FeO and TiO_2 values are exhibited by Hansteen Alpha. FeO values range from 5% to 9% with slightly higher values occurring near the highland/mare contact. Most of Hansteen Alpha exhibits <1.0% TiO_2 and certain areas near the center of the feature have <0.5% TiO_2. The core portion of Hansteen Alpha (Figure 4b, Box E) has an average FeO value of 6.9% and an average TiO_2 value of 0.5%. Since this core region has suffered the least amount of contamination by surrounding mare units, its composition may most closely approximate that of the underlying lithology.

[20] The other highlands units in the Hansteen Alpha region are dominated by deposits associated with Hansteen (diameter = 46 km) and Billy (diameter = 45 km) craters (Figures 2 and 3a). For Hansteen, these include continuous ejecta deposits, wall material, and unflooded portions of the crater floor. For Billy, the highlands deposits are limited to ejecta and wall material since the entire floor is covered by mare basalt. The highlands units associated with Hansteen and Billy craters exhibit FeO values that generally range between 10% and 14% and TiO_2 abundances of 1–3%. The average FeO and TiO_2 values for two portions of the Hansteen ejecta deposit and one area on the Billy ejecta deposit (Figure 4b, Boxes B, C, and D) are listed in Table 1. Both Hansteen and Billy excavated and emplaced relatively FeO-and TiO_2-rich material (FeO = 11–14%, TiO_2 = 2–3%). Note that these values are much higher than those exhibited by the central portion of Hansteen Alpha (FeO = 6.9%, TiO_2 = 0.5%).

[21] Both Billy and Hansteen are Imbrian-aged impact structures [*Wilhelms and McCauley*, 1971]. Billy crater is older than Hansteen crater which has been determined to be of Late Imbrian age [*Wilhelms*, 1987]. The Late Imbrian Epoch began immediately after the Orientale impact which was estimated by *Wilhelms* [1987] from superposed crater frequencies to have occurred at 3.8 Ga.

[22] Hansteen Alpha is located within one crater diameter of the rim crests of both Hansteen and Billy (Figure 2). If Hansteen Alpha was present prior to the Billy and Hansteen impact events, it should have been covered by FeO- and TiO_2-rich ejecta from both craters. Since it is not, Hansteen Alpha was formed after these Imbrian-aged craters. The evidence indicates that Hansteen Alpha was superposed on Billy and Hansteen ejecta by an episode of highlands volcanism that occurred after 3.8 Ga.

3.3. Lunar Prospector Thorium Data

[23] The low altitude ($2° \times 2°$) global Th map presented by *Lawrence et al.* [2000] was used to investigate Th abundances associated with Red Spots in the southern Oceanus Procellarum-Mare Cognitum region. No Th enhancements were found to be associated with the Helmet, Darney Chi, Darney Tau, and the southern Riphaeus Moun-

tains. These Red Spots exhibit Th abundances similar to those of the surrounding terrain [*Hawke et al.*, 2001, 2002]. However, the 2° × 2° pixel that contains Hansteen Alpha does exhibit a minor Th enhancement (<1 ppm) relative to the surrounding region (5–6 ppm). A 0.5° × 0.5° Th map (Figure 4c) was used to further investigate the distribution of Th in the vicinity of the Arrowhead. This high resolution Th map indicates that Th abundances range from ~4.5 ppm to ~8 ppm in the Hansteen Alpha region. Figure 4c shows no unusually high or low Th values associated with the Arrowhead. The most reasonable interpretation of the Th data is that Hansteen Alpha exhibits a Th value of ~6 ppm. Slightly higher values (6.0–6.5 ppm) are associated with the eastern portion of Hansteen crater and its adjacent ejecta deposits. Even higher Th values (7.0–8.0 ppm) are exhibited by highlands units ~100 km east of the Arrowhead. On the basis of these findings, it does not appear that Hansteen Alpha is composed of highly evolved highlands lithologies that are extremely rich in Th (Table 1).

[24] It has been proposed that the Th concentrations observed in the lunar highlands are largely controlled by the distribution of the Th-rich Imbrium ejecta [e.g., *Mezger et al.*, 1973; *Evenson et al.*, 1974] (see discussion by *Haskin* [1998]). This is unlikely in the Hansteen Alpha region. As discussed above, Hansteen and Billy craters have excavated relatively Th-rich material (5–6.5 ppm). The maximum depth of excavation of these craters was probably ~4.5 km. *Marshall* [1963] estimated that Imbrium ejecta in the region ranged from a few meters to almost 500 m in thickness. Hence these craters would have penetrated any Imbrium ejecta present in their target sites and excavated subjacent material.

[25] *Jolliff et al.* [2000] have defined the Procellarum KREEP Terrane (PKT) which is characterized by elevated Th abundances. The Hansteen Alpha region is located in the southern portion of the PKT (Figure 1). Since Billy and Hansteen excavated material from the upper 4.5 km of the crust, enhanced Th must be a property of the upper crust in the southern portion of the Procellarum KREEP Terrane. The elevated Th values in this region cannot be due solely to the presence of Th-rich Imbrium ejecta.

3.4. Earth-Based Reflectance Spectra

[26] *Head and McCord* [1978] presented relative reflectance spectra (0.3–1.1 μm) of seven Red Spots including Hansteen Alpha. They noted that each of these Red Spots exhibits a high albedo and has a spectrum with a strong ultraviolet absorption which is responsible for the red color. These characteristic Red Spot spectra differ from the usual spectra of mature highlands regions in this spectral range (UV-VIS) only in the strong ultraviolet absorption and no known mare spectra are similar to Red Spot spectra [*McCord et al.*, 1972; *Head and McCord*, 1978]. Finally, *Head and McCord* [1978] noted that the specific compositional property causing the ultraviolet absorption in the Red Spot spectra is unknown.

[27] High-resolution reflectance spectra (0.39–0.82 μm) for Hansteen Alpha and seven other Red Spots were presented by *Bruno et al.* [1991]. They described a violet/UV absorption of approximately 4% in the Hansteen Alpha spectrum and noted that the spectrum begins to drop off toward the UV at ~0.47 μm. *Bruno et al.* [1991] documented differences among the spectra of the various Red Spots which implies that they are not identical compositionally. They noted that this variation among Red Spots admits the possibility of multiple origins for Red Spots.

[28] Two near-infrared reflectance spectra (0.6–2.5 μm) were collected for Hansteen Alpha (Figure 5). A relatively large aperture (Ap. 4) was used to obtain a spectrum for an area approximately 16 km in diameter that was centered on Hansteen Alpha. Aperture 2 was used to collect a spectrum for a smaller spot (diameter = 8 km). Both near-IR spectra relative to the Sun are shown in Figure 5a. The spectra are scaled to 1.0 at 1.02 μm. The continuum-removed versions of the Hansteen Alpha spectra are shown in Figure 5b.

[29] The near-IR continuum slope (Δ reflectance/$\Delta\lambda$) is measured by fitting a straight line tangent to points on the spectrum on either side of the "1 μm" band, typically near 0.7 and 1.5 μm. Both composition and maturity control the near-IR continuum slope, higher-FeO and more-mature surfaces exhibiting spectra with steeper continuum slopes. The Hansteen Alpha spectra have continuum slopes of 0.550 and 0.564. These values are well within the range of those exhibited by mature highlands surfaces [*Pieters*, 1986; *Blewett and Hawke*, 2001].

[30] In order to extract mineralogical information, an analysis of the mafic mineral absorption bands near 1 μm was conducted [*McCord et al.*, 1981; *Lucey et al.*, 1986]. Of principal interest for determining mineralogy are the position of the band minimum and the band depth. Orthopyroxene (low-Ca pyroxene) is characterized by band minima shortward of 0.95 μm. High-Ca pyroxene produces bands with minima at wavelengths >0.95 μm [*Adams*, 1974]. Surfaces with a greater abundance of pyroxene or with higher-Fe pyroxenes will have deeper absorption bands. Fe-bearing olivines will produce spectra with broader absorption features centered beyond 1.0 μm. Both of the Hansteen Alpha spectra have relatively shallow (3.7%–4.1%) "1 μm" bands centered shortward of 0.95 μm. The lithology in the area for which the spectra were collected is dominated by non-mafic minerals. The mafic assemblage is dominated by low-Ca pyroxene. No olivine was detected in the areas for which the spectra were collected.

3.5. Implications of the Composition of Hansteen Alpha

[31] The morphology of Hansteen Alpha suggests derivation from a viscous, presumably silicic lava. This implies an evolved magma, such as KREEP basalt, quartz monzodiorite, and granitic lithologies. However, the low Th concentration of Hansteen Alpha (6.1 ppm) clearly rules out the possibility that it is related to evolved lunar rocks in the Apollo sample collection, which contain 2 to 6 times as much Th (Table 1). It appears that Hansteen Alpha is composed of an unsampled rock type. One possibility is that it is similar to KREEP basalt, but from a magma that contained about half as much Th as KREEP basalt in the Apollo collection. KREEP basalt magmas could have formed in several ways, but two are most favored (see *Shearer and Floss* [2000] for a review of the petrogenesis of lunar rocks). They could have formed by partial melting of magma ocean cumulates and then assimilated KREEP. Alternatively, KREEP basalts might have formed by partial melting of magma ocean cumulates or primitive lunar

mantle that had been hybridized. In either case, it is reasonable to expect variations in trace elements concentrations but relatively uniform major element concentrations. However, this would not explain the FeO and TiO_2 contents of Hansteen Alpha. Furthermore, samples of KREEP basalt are not enriched in silica, so would probably not erupt as highly viscous flows unless they had cooled significantly and contained abundant phenocrysts. A well-studied surface occurrence of KREEP basalt, the Apennine Bench Formation, suggests that the lavas were fairly fluid [*Spudis*, 1978; *Hawke and Head*, 1978]. Formation of Hansteen Alpha from a Th-poor form of KREEP basalt seems improbable.

[32] LKFM impact melts might represent magmas, although no pristine (endogenous igneous rock) sample has been reported. Nevertheless, if such magma existed at depth in the Moon, it might have erupted. A LKFM sample with the appropriate Th concentration is given in Table 1. Although Th is similar to that in Hansteen Alpha, FeO and TiO_2 are significantly higher. LKFM, like KREEP basalt, is not enriched in silica, hence not viscous enough to form thick flows like those of Hansteen Alpha. Thus a volcanic variety of LKFM is not a viable candidate for the composition of Hansteen Alpha.

[33] Hansteen Alpha might be composed of an exceptionally aluminous magma. Converting its FeO concentration to Al_2O_3 by using the well-known inverse correlation between Fe and Al in lunar rocks, gives an Al_2O_3 content of about 21 wt%. Perhaps the high Al content led to a viscous magma. However, a magma with this high Al content would almost certainly lie off a cotectic, implying a high percentage of melting of plagioclase-rich rock. In turn, this implies a high temperature, hence a low viscosity. Nevertheless, it seems reasonable to suppose that Hansteen Alpha formed by eruption of a magma rich in Al, moderately rich in Th, and low in Fe and Ti. More compositional data are clearly needed to determine the concentrations of other elements, especially of Si, Mg, and Ca. The high viscosity suggested by the morphology of Hansteen Alpha suggests that Si is high and Mg relatively low.

4. Summary and Conclusions

[34] 1. The stratigraphic relationships among the geologic and compositional units in the Hansteen Alpha region demonstrate that the Arrowhead was emplaced by extrusive igneous processes. The Imbrian-aged craters Billy and Hansteen emplaced relatively FeO- and TiO_2-rich ejecta. The Arrowhead exhibits much lower FeO and TiO_2 values (Table 1). If the Arrowhead was present prior to the formation of Billy and Hansteen craters, it should have been covered with FeO- and TiO_2-rich ejecta since it is within one crater diameter of the rim crest of each crater. Since it is not, Hansteen Alpha was emplaced on top of the FeO-rich ejecta deposits. Nonmare volcanism is the only viable process for the formation of Hansteen Alpha.

[35] 2. The morphology and surface texture of Hansteen Alpha is similar to many terrestrial features of dacitic and rhyolitic composition formed by extrusions of relatively viscous lavas at low rates. Such highly evolved highlands compositions should be very enriched in Th (Table 1). Since Hansteen Alpha exhibits Th abundances of $\sim$6 ppm, we conclude that this feature is not dominated by a highly evolved highlands lithology. The precise nature of magma that formed Hansteen Alpha is difficult to determine. Available chemical data and inferences from morphology suggests that it was rich in Al and Si, moderately rich in Th, and low in Fe, Mg, and Ti. This does not correspond to any known lunar rock type. The application of improved techniques currently under development to the Th data obtained for the Hansteen Alpha region should result in a better understanding of the Th concentrations of units in the area.

[36] 3. Billy and Hansteen craters excavated and emplaced relatively Th-rich material derived from depths of up to 4.5 km. The upper crust in this portion of the Procellarum KREEP Terrane is composed of Th-rich material. Th-rich Imbrium ejecta cannot be entirely responsible for the Th distribution pattern observed in the southern portion of the Procellarum KREEP Terrane.

[37] 4. Prior to the Apollo missions to the Moon, large portions of the lunar highlands were interpreted to be of volcanic origin [e.g., *Wilhelms and McCauley*, 1971]. In the immediate post-Apollo era, most of the units previously thought to be of extrusive igneous origin were reinterpreted as the products of impact processes [e.g., *Wilhelms*, 1987]. Many of the light plains deposits that were once considered to be of highlands volcanic origin have now been demonstrated to be cryptomaria [e.g., *Schultz and Spudis*, 1979, 1983; *Hawke and Spudis*, 1980; *Hawke and Bell*, 1981; *Bell and Hawke*, 1984; *Head et al.*, 1993; *Blewett et al.*, 1995; *Antonenko et al.*, 1995]. Still, a few strong candidates for nonmare volcanism exist. These include the Gruithuisen domes [*Head and McCord*, 1978; *Chevrel et al.*, 1999] and the Apennine Bench Formation [*Hackman*, 1966; *Hawke and Head*, 1978; *Spudis*, 1978; *Spudis et al.*, 1988; *Blewett and Hawke*, 2001]. On the basis of the data presented here, Hansteen Alpha must now be considered to be an extremely strong candidate for a highlands volcanic construct.

[38] **Acknowledgments.** This work was made possible by NASA grants NAG5-3635 (B.R. Hawke, P.I.), NAG5-3766 (P.G. Lucey, P.I.), and NAG5-11591 (K. Keil, P. I.). Thanks are due to the U.H. Telescope Scheduling Committee for providing the observing time needed to collect the spectra presented in this paper. Helpful comments were provided by Barbara Bruno. A very constructive review of this paper was provided by Mark Robinson. This is HIGP publication number 1271 and SOEST contribution 6128.

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