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Lunar Transient Phenomena: What Do the Clementine Images Reveal?

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Lunar Transient Phenomena (LTP) have been reported for at least 450 years. The events range from bright flashes, to reddish or bluish glows, to obscurations. Gaseous spectra and photometric measurements of the events have been obtained. Several theories have been offered as explanations for LTP, including residual volcanic activity or outgassing, bombardment by energetic particles, and piezoelectric effects. As the first set of digital multispectral images of the entire Moon, the Clementine data offer a unique opportunity to couple inferences of compositional relationships with lunar geomorphology in the regions of LTP. We have selected 11 regions from which numerous reliable historical reports of LTP exist. Our analysis of the Clementine multispectral images shows that many events occur in regions of bright, spectrally reddish deposits, which may be characteristic of volcanic ejecta. The events may be associated with outgassing of volatiles collected in or beneath mare basalt flows. We find that LTP tend to occur near the edges of maria, in agreement with a suggestion originally made by Cameron (1972. *Icarus* 16, 339–387), and in other regions of crustal weakness. We also find that some of the reported events tend to be in craters with rims of distinctly different (bluer) composition. This compositional difference may result from recent slumping of the rim, accompanied by the appearance of fresher underlying material. In some cases, slumping may be triggered by the release of pockets of volatiles; in turn the slumping events may cause additional pockets of trapped material to be released.

There are four instances in which Clementine multispectral images were acquired both before and after an event that was reported by a terrestrial team of amateur astronomers mobilized to observe the Moon during the mapping phase of Clementine. None of these four sets of images shows clear changes that could be attributed to the reported LTP.

Key Words: **Moon, surface; volcanism.**

I. INTRODUCTION

Lunar transient phenomena (LTP) have been reported for at least 450 years. The events range from bright flashes, to reddish or bluish glows, to fuzzy or foggy patches. Although some events were probably spurious, hundreds of others have been seen by reliable observers. Several gaseous spectra and electronic photometric measurements of events have been obtained by professional astronomers (Kozyrev 1959, Sanduleak and Stock 1965). Interest in LTP has dwindled over the past two decades, even as additional observations continue to be made (e.g., Kolovos *et al.* 1988, 1992, Dollfus 2000). No completely satisfactory explanation for LTP has ever been published, and most lunar geologists and professional astronomers express skepticism about them. Given their persistence, and the potential scientific payoff if they could be shown to be associated with specific types of geologic materials, it is worth closely scrutinizing at least the most worthy of them.

Prior to the exploration of the lunar surface with spacecraft in the 1960s and 1970s, two rival theories existed on the origin of lunar craters: impact and volcanic. It was in the context of this scientific controversy that many of the LTPs were observed. Although most lunar geologists now believe that the vast majority of craters on the Moon were formed by impacts, there are many volcanic features on the Moon, including sinuous rilles and "cobrahead" or dark-haloed craters. Seismic activity (Latham 1971) and emission of radon (Gorenstein *et al.* 1974), a gas that has been associated with terrestrial earthquakes, have both been detected on the Moon (although seismic events can be due to any type of activity, including exogenously produced ones such as impacts and movement due to tidal stresses). It is because of the possible correlation between LTP and current activity on the Moon that the scientific importance of studying these controversial events is so great: they may be evidence for residual volcanic activity on the Moon. The discovery and investigation of any such activity would have significant implications for the thermal structure and composition of the lunar interior. Evidence of current volcanic activity would constrain models of lunar differentiation and thermal evolution.

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Eleven possible causes of LTPs have been compiled by Robinson (1986), which can be summarized in the following categories: (1) Tidal. Greater tidal forces at perigee may cause stressing and fracturing of rocks or even precipitate moonquakes. Concomitant outgassing may occur. (2) Thermal shock. Although the lunar temperature varies by $\sim 45^\circ$ in the 4 h centered around sunrise, the thermal skin depth of the Moon is only $\sim$10 cm. It thus appears unlikely that thermal shock could cause events of the observed scale. However, Cameron's analysis (1972) shows a persistent correlation with the sunrise of a feature. (3) Fields and particle effects. Bombardment by UV radiation, high-energy particles in the solar wind, or interactions with solar magnetic fields have been proposed. The energies involved do not appear to be sufficient to precipitate major events. However, there do appear to be more events at full moon (even if one accounts for observational biases (Cameron 1972)), when the Moon is in the Earth's magnetotail and would thus receive its heaviest bombardment of energetic particles. Based on this correlation, this cause cannot be entirely eliminated. (4) Meteoritic impacts. Although these rare events can account for only a handful of LTP, at least one well-documented medieval (1178) observation of a lunar explosion has been tied to the creation of the crater Giordano Bruno—one of the youngest features on the Moon—and to the Taurid meteor showers (Hartung 1993). (5) Piezoelectric effect. Electromagnetic effects associated with rock fracturing can be released as optical energy. Recent work by Kolovos *et al.* (1988) and Zito (1989) shows that the expected magnitude of this effect is sufficient to cause LTP. Finally, it is important to consider that the events—if they are real—may be simply due to residual volcanism or other geologic activity. They may also represent a combination of phenomena. For example, tidal stress may be the precipitating factor for the fracture of rocks, which in turn causes outgassing and/or the piezoelectric effect. It is also possible that the different types of events have different causes.

Cameron (1972) and Middlehurst (1977) ascribe different importance to the occurrence of LTP at perigee, where tidal forces are greatest. The former believes the effect is only slight and suggests instead that the most significant correlation is the location of the LTP at the edges of maria. If probable volcanic features, including dark-floored and dark-haloed craters, rilles, domes, and ring dikes, are also included, Cameron claims there is a very good correlation between the location of LTP and geologic features indicative of internal activity. In her model, all these features represent areas of weakness from which internal gas can slowly escape. Radon gas has indeed been detected near the edges of maria (Gorenstein *et al.* 1974). It is also true that practically no LTP were observed in the centers of maria.

To our knowledge, no one has published an investigation of these events from space-based images. As the first set of digital, data-based spectral images of the Moon, the Clementine data (primarily the UV/VIS images) represent the best set of observations ever obtained for such a study. Lunar orbiter images, although panchromatic and photographic rather than electronic, are a valuable supplementary data set for observing changes in these areas over time.

The goal of this study is to investigate Clementine images in regions of LTP with current photogeologic techniques to seek specific types of geologic terrains that would indicate active geologic processes on the Moon. The instrument complement on Clementine included instruments suited for both geomorphologic and multispectral (compositional) studies. An ultraviolet and visual/infrared camera (UVVIS) and a near infrared camera (NIR) provided typical resolution of 100 M on the Moon with 12 filters covering the wavelength range between 0.42 and 2.8 μm. With this first multispectral data set of the entire lunar surface, color ratios can be obtained for any region to study compositional inhomogeneities, and to seek out areas of fresh or recently disturbed material. A single-channel, long-wavelength infrared camera (LWIR), sensitive in the 8.0 to 9.5 μm region, provided maps of thermal emission in some cases (its field of view was much smaller than those of the UVVIS or NIR cameras). This instrument can be used to seek areas of anomalous thermal emission that would characterize textural inhomogeneities. A high-resolution camera (HIRES), with resolution about an order of magnitude better than the UVVIS, did not capture images in the regions we have chosen for this initial study. For a more complete description of the Clementine mission and its scientific payload, see Nozette *et al.* (1994).

During the Clementine mission, a group of about 75 amateur astronomers mobilized to carefully observe the Moon while the spacecraft was in lunar orbit, from 19 February to 3 May 1994 (Darling, personal communication, 1996, Cameron *et al.* 1997). For four reports from this group, two of which were observed in the craters Picard and Anaxagoras, a third near Mount Piton, and the fourth at Cobrahead in the Aristarchus plateau, Clementine images were obtained before and after an event. For all four events, no changes in color, geologic landform, or albedo are evident in the before and after pictures. (See detailed discussions below, in Section III.)

II. DATA ANALYSIS

The most extensive investigations of LTP were made by Cameron (1972, 1975, 1978) and Middlehurst *et al.* (1968). Cameron (1972) cataloged 1468 of these events, many of which had associated photographic or photometric records (events were rejected from her catalog if obvious causes could be found for them, such as albedo variegations, atmospheric effects, or the illumination of facets by the setting sun). She classified them into four categories: (1) gaseous, which involved observations of mists and obscurations; (2) reddish colorations; (3) green, blue, or violet colorations; and (4) brightenings. Many events were flashes with short durations. About two-thirds of LTP have been reported in the Aristarchus region, one of the youngest areas of the lunar surface which includes many volcanic features, and where Apollo 15 detected an excess of radon gas (Robinson 1986).

TABLE I
Lunar Transient Phenomena Chosen for Study

Name of feature	Approx. events since 1900	Descriptions
From Cameron and Middlehurst:		
Alphonsus (central peak)	20	Brightenings and red spots; two gas spectra obtained (Kozyrev 1959, Harris 1967, Middlehurst 1968).
Cobrahead (near Aristarchus)	8	Obscurations, as well as red brightenings; two very good locations from Lowell observers (Greenacre 1963).
Aristarchus	hundreds	Reportings often do not give good locations; many recent ones in the E and NE rim and near central peak. Violet and blue glare reported, enhanced spectral regions (Kozyrev 1959). Three events in the Cameron–Darling catalog.
Piton	5	Cloud-like obscurations; no good spectral or photometric events, but easy to localize. Two additional events reported in the Cameron–Darling catalog.
Palus Somni	1	Recent event, well documented (Kolovos *et al.* 1992), but likely a satellite (Maley 1991, Rast 1991).
Plato	20	Blinks; bright spots; UV enhancement (Grainger and Ring 1963).
Ross D	15	Obscurations; bright spots.
Tycho	5	Anomalous luminosities.
Gassendi	15	Bright specks and flashes; reddenings.
Additional regions from the Darling–Cameron catalog (1997):		
Anaxagoras	1	Bright streak from floor to wall and thin dark shadow on floor.
Picard	3	All observations, from April 17–20, 1994, involve darkening.

Another source of candidates for this study is a catalog of events provided to us by the force of amateur astronomers that dedicated many nights to scrutinizing the Moon throughout the Clementine mission (Darling, personal communication, 1996, Cameron *et al.* 1997). Many of their reported LTP occur in the "classical" locations of dozens of previous reports. We refer to their catalog of 144 events as the Cameron–Darling catalog.

After reviewing the 579 events in Middlehurst *et al.* (1968), a subset of Cameron's catalog (Cameron 1972), some recent events, and the Cameron–Darling catalog, we have culled a handful of the most promising locations to analyze for an initial, focused investigation. Our criteria for selecting locations were that at least several events had been reported there by reliable observers since 1900 (the degree of collocation among the events is striking) and that accurate locations had been reported. We also assigned a premium to events for which documented measurements existed, such as photographs or spectra. One event occurring near Palus Somni, which is not an area of cataloged events, was selected because recent photographic evidence for it exists (Kolovos *et al.* 1988). The locations for events that fulfill our criteria for selection are listed in Table I. The craters Aristarchus, Plato, and Alphonsus have been associated with the most LTP. In analyzing the published cataloges, we became aware that some regions tend to exhibit the same type of event. For example, the events in the crater Gassendi all involved bright blinks or flashes, while those near Piton were all described as obscurations.

Clementine images were chosen for each event utilizing the cataloging and archiving capabilities of the Planetary Data System (PDS) Clementine World Wide Web site. For this initial study, we used a fairly small, judiciously chosen set of images that effectively addresses the major scientific goals of studying the geomorphology in the regions of LTP, and of seeking compositional or thermal anomalies. We also sought images obtained before and after the events reported by Cameron *et al.* (1997). Two filters in the UVVIS camera, at 0.42 (the A filter) and 1.0 μm (the E filter), were chosen to maximize the spectral range for compositional studies; the latter filter is located in the Fe absorption band at $\sim$0.95 μm (because of various problems with cross calibration, we considered it unwise to compare filters from different cameras). The geologic analyses were done with images from the UVVIS camera. For each event, we studied both monochromatic images at 0.95 μm and color images created by computing ratios of the A and E filters. The ratio-images pinpoint regions where compositional variegations occur: bluer regions appear brighter on the images. Because Clementine was the first lunar mission to obtain multispectral mapping at high spatial resolution, these indications of compositional changes represent important new information, particularly when placed within the context of geologic features. In several instances, LWIR images existed at the location of the event (the LWIR field of view was only one twenty-fourth that of the UVVIS camera). For the other cases, either LWIR images did not exist or the location of the LTP could not be located accurately enough to place an LWIR image unambiguously at it. The images chosen for study are listed in Table II. The resolution of the images ranges from $\sim$700 M in the early orbits to $\sim$380 M toward the end of the mission.

TABLE II
Images Used in This Study

Event	Images used	Center latitude	Center east longitude	Lunar orbiter
Alphonsus	LLA2758H.037	−13.44	357.11	V 118 M
	LUA2782H.037	−13.01	357.17	IV 108 H2
	LUE2767H.037	−13.15	357.17	
Cobrahead	LLA4272L.318	24.44	310.53	V 204 M
	LUA4293L.318	24.74	310.58	
	LUE4277L.318	24.59	310.59	
	LUA4575L.054	25.50	310.93	V 205 M
	LUE4560L.054	25.28	310.93	
Aristarchus	LLA2968L.186	23.23	312.07	V 197 M
	LUA2964L.186	23.09	312.14	V 198-200 H
	LUE2949L.186	22.95	312.14	
Piton	LUA3365N.300	41.12	359.47	IV 115 H2
	LUE3350N.300	40.60	359.48	
Palus Somni	LUA4189K.152	13.13	43.33	IV 66 H2
	LUE4175K.152	12.95	43.32	
Anaxagoras	LUA4952Q.039	73.19	352.07	IV 128 H2
	LUE4937Q.039	72.51	352.06	
	LUA5023Q.172	73.37	350.05	
	LUE5007Q.172	73.17	350.03	
Picard	LUA2682K.280	15.11	55.55	IV 191 H3
	LUE2667K.280	14.96	55.54	
	LUA4221K.148	15.01	54.31	
	LUE4206K.148	14.83	54.31	
Tycho	LUA1786E.040	−43.33	349.05	V 125 M
	LUE1771E.040	−43.47	349.05	
Plato	LUA4703O.039	50.31	351.69	IV 128 H1
	LUE4688N.039	49.85	351.68	
Gassendi	LUA2652H.050	−18.59	321.64	IV 143 H2
	LUE2673H.050	−18.73	321.64	
Ross D	LUA3996K.159	12.25	24.12	IV 85 H2
	LUE3981K.159	12.07	24.12	

For this initial survey, we did not perform radiometric calibrations for the UVVIS images. We did, however, perform a full radiometric and geometric calibration for the images used in our study of the Cobrahead region on the Aristarchus plateau. Our preliminary analysis (Buratti *et al.* 1996, Calkins *et al.* 1999) showed measurable changes in the spectral reflectance of an area in the Cobrahead subsequent to a report generated by the ground-based team active during the Clementine mission. To confirm our result, we performed a more careful analysis with recently refined calibrations for the Clementine UVVIS camera (Hillier *et al.* 1999). With this new analysis, we find that our initial report is spurious (see discussion below).

The LWIR images were processed with the following steps: (1) The values of "hot" pixels were replaced by the average value of adjacent pixels. (These pixels were caused by a variety of problems, including bad detectors, saturation, and cosmic ray hits.) (2) The resulting image was put through a low-pass filter. (3) The images were corrected for spatial sensitivities by dividing each image by a flatfield image created by co-adding about 750 LWIR images. Finally, the LWIR images were boresighted with the UVVIS images with the pointing information provided to us by the Planetary Data System and the Navigation Subsystem at JPL.

Unfortunately, no HIRES images could be unambiguously located where LTP occurred.

The geologic analysis of each region involved inspection for specific types of volcanic or structural features, including dark-floored and dark-haloed craters, rilles, domes or cones, mantling deposits, pits, fractures, and faults. The boundaries of major geologic units were searched for evidence of local disruption of the crust and regolith due to fracturing and gas release. Gas escaping from fractures may entrain and remove regolith material, resulting in irregular depressions or chains of pits similar to those observed on Phobos, which Thomas *et al.* (1979) suggested were formed by this process. Young mantling deposits can be recognized by a relatively low crater density on their surfaces. We also inspected the LWIR images taken in the same region for anomalies in the thermal signature (lower conductivity representing a mantled region, for example) at the locations of reported LTP.

We did of course look for actual LTP in the images. No such events were found.

III. DISCUSSION OF SPECIFIC EVENTS OR REGIONS

1. *Alphonsus*

Of the many LTP, this one was deemed to be one of the most promising because of a gaseous spectrum obtained near the central peak in 1957 (Kozyrev 1959, D. H. Harris quoted in Middlehurst 1968, Leonardi 1976). The gaseous emission was detected just to the west of the peak, which is the bright patch on the bottom of Fig. 1 (top). Kozeyrev (1959) identified lines in the spectrum with carbon and hydrogen, and he claimed that the observation was consistent with volcanic activity. The Lunar Orbiter image archived in the Regional Planetary Imaging Facility at JPL shows that the central peak is an area of complex faulting and folding, similar to regions of terrestrial impact structures (e.g., Roddy *et al.* 1997). The region shows evidence of volcanic activity, including a chain of (probably volcanic) pits and flows from the crater itself. Furthermore, there are dark haloed craters in the floor of Alphonsus, which may indicate explosive, volatile-rich volcanic activity (Horz *et al.* 1991). The central peak is probably more fractured and porous than the lavas that partly fill the crater, so gases could more easily escape to the surface of the central peak. We note that material from the central peak appears to have partly buried a dark rille to the northeast (Fig. 1 (top)), suggesting slumping of peak material after emplacement of the lavas (this morphology is much clearer in the Lunar Orbiter image, which unfortunately cannot be reproduced here). The LWIR image (Fig. 1 (top)) shows a marked decrease in temperature at the peak, but the change is probably due to shadowing. A color ratio (Fig. 1 (bottom)) shows compositional inhomogeneities in the area of the peak, but there are no color changes in the region where the gaseous emissions were

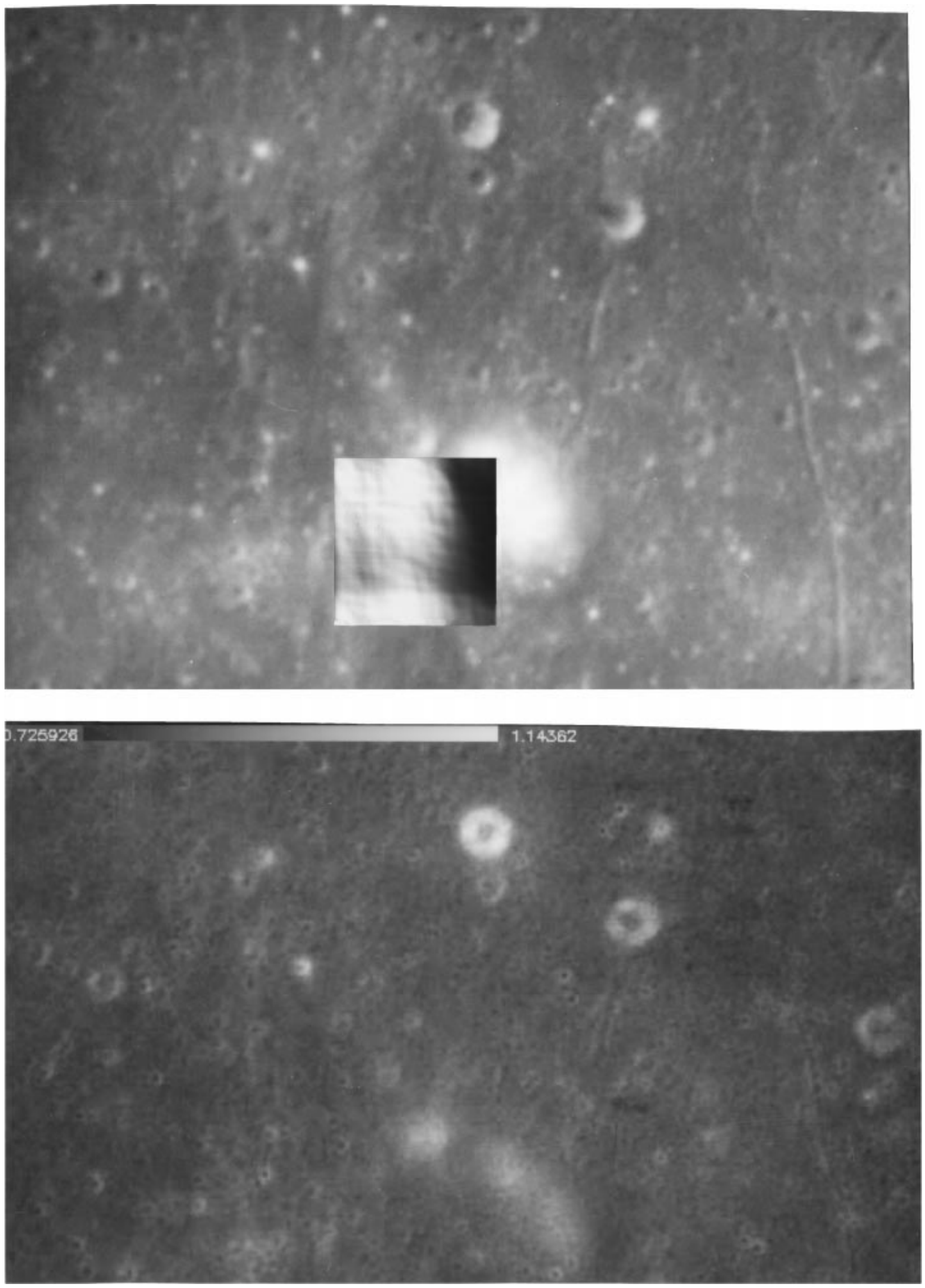

FIG. 1. (top) An E-filter image of the central peak of Alphonsus, with a boresighted LWIR image superimposed. The peak is much darker in the infrared, although this effect is most likely due to lighting effects, as the region contained in the LWIR image is in shadow. The gaseous emissions (Kozyrev 1959) were observed just to the west of the peak. (bottom) A color ratio of the peak shows that the base is measurably bluer than the ambient terrain, but it is redder than the fresh material comprising crater ejecta. (All color ratios are of the A and E filters.)

observed, immediately west (to the left) of the peak. The high-albedo material comprising the peak is bluer than the ambient terrain, but it is much redder than ejecta material from the fresh crater at the top of the image. The existence of bright, reddish material may be an indication that the structure is mantled by fine-grained material such as volcanic ash (see Summary and Conclusions for a detailed discussion of this point). This material is concentrated near the base of the peak, in the area that postdates the rille. The color ratio image provides evidence that residual volcanism could have been present at that location, in an area of crustal weakness.

2. *Cobrahead*

This feature is at the head of Schroter's valley, which is a rille, or collapsed lava tube. It is the largest of several volcanic craters in this area that are sources of the low-viscosity flows that

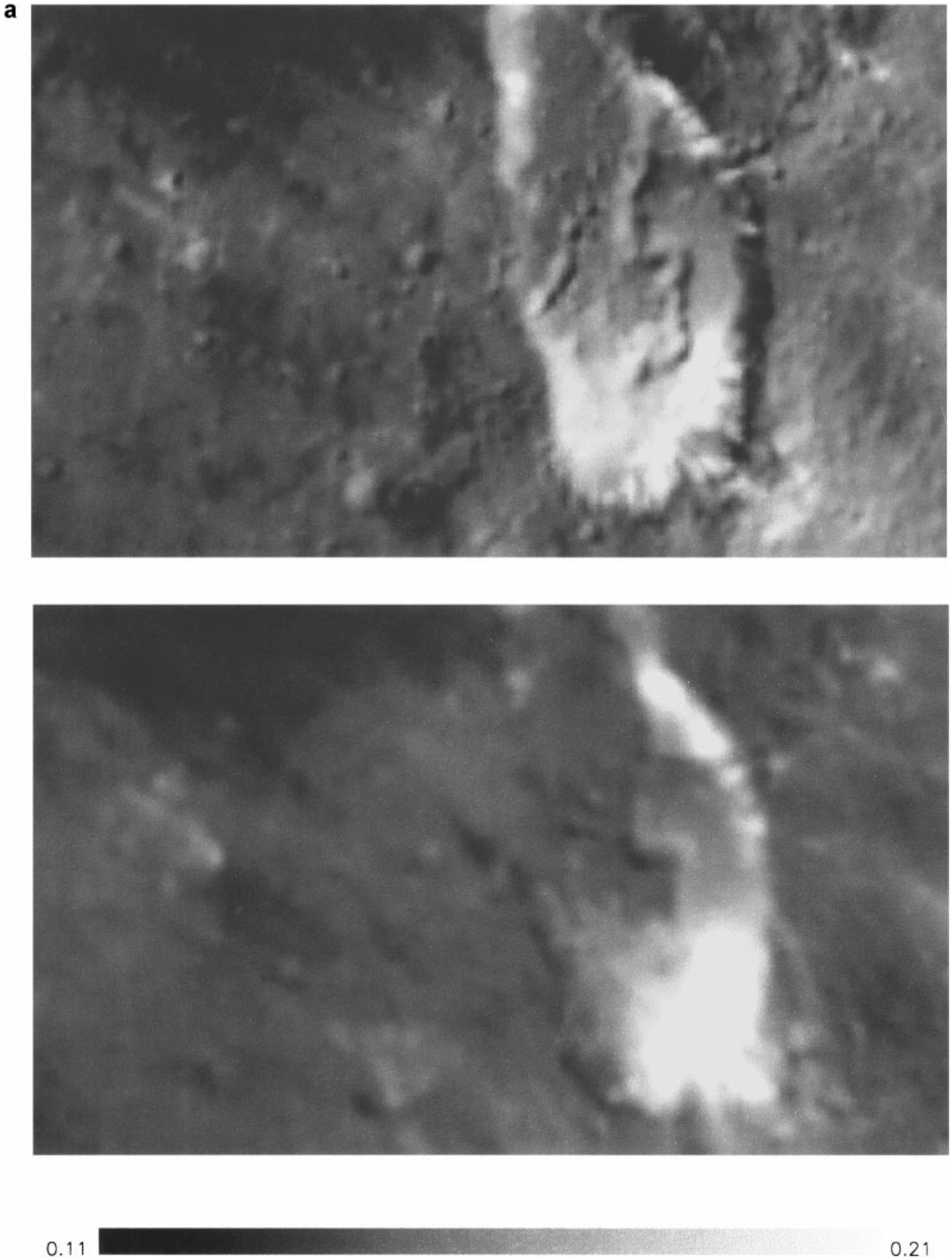

FIG. 2. (a) Fully calibrated E-filter images of the Cobrahead, a classical area of LTP, from orbits 54 (bottom) and 318 (top). The earlier image has been spatially rescaled to correspond to the later image. The later image was obtained 4 days after an event reported by the ground-based team (Cameron *et al.* 1997). (The brighter regions associated with the upper west boundary of Cobrahead on the image obtained prior to the event are due to purely photometric effects; the lighting geometry changed between the two sets of images.) (b) Color ratio images of the corresponding regions. The images show no measurable changes. (c) Scans extracted from the images, corresponding to the lines in Fig. 2b. The scan crosses the western rim of Cobrahead in the spot where we earlier claimed preliminary evidence for a color change subsequent to a report of an LTP. To within our errors, no clear occurred.

apparently formed several rilles in the area. A dark mantling deposit possibly consisting of iron-rich, pyroclastic glass spheres appears to have been deposited by these craters (McEwen *et al.* 1994). As one of the youngest areas on the Moon, the Aristarchus plateau is a region where one would expect to see residual lunar activity, if any existed at all. Two reddish-orange brightenings lasting at least 25 min were reported near Cobrahead by two cautious lunar cartographers, Greenacre and Barr (Greenacre

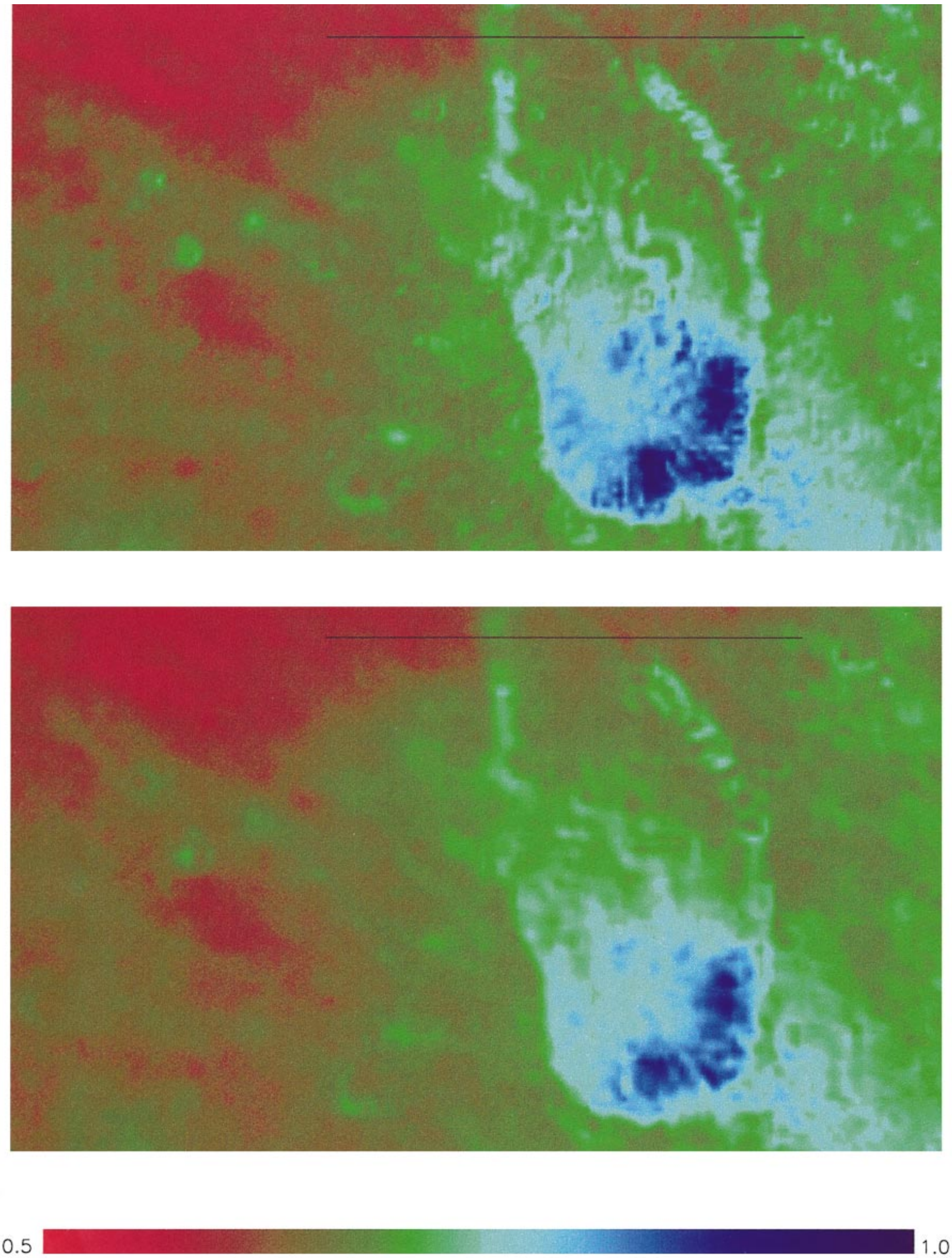

FIG. 2—*Continued*

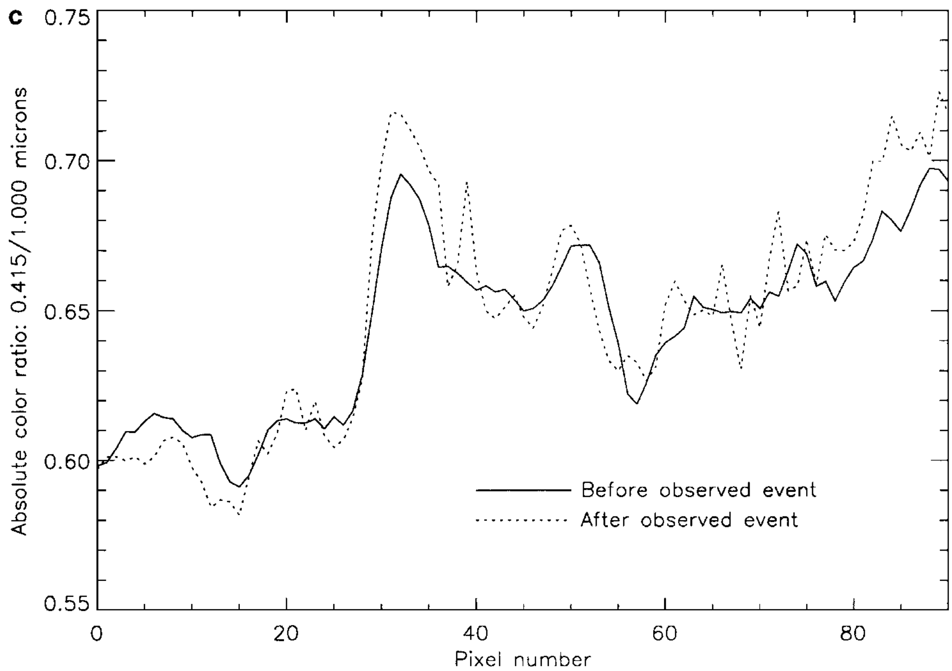

FIG. 2—*Continued*

1963). One of the events was reported just to the west of the high-albedo region at the bottom of the Cobrahead (Fig. 2a). The Clementine spacecraft obtained images of the Cobrahead twice during the mission, once in orbit 54 (bottom of Fig. 2a) and again in orbit 318 at higher resolution (top of Fig. 2a). Figure 2b shows that the high-albedo material near the Cobrahead tends to be blue. A landslide appears on the lower right of the feature, and smaller slumped regions occur all along the feature's edge.

Cobrahead is one of the four regions for which "before and after" Clementine images exist for an event that was reported by the group of ground-based observers. The before and after images were obtained on March 3 and April 27, 1994, while the ground-based LTP was reported on April 23. Our early inspection of the images obtained before and after the LTP observed by the Earth-based astronomers (Cameron *et al.* 1997) showed evidence for a 15% increase in the ratio of the A and E filters for a small area. Because of the importance of this finding, we redid our analysis with calibrated images (Hillier *et al.* 1999), and with the more sophisticated ISIS software package provided by the United States Geological Survey. In our new analysis, which is illustrated in Figs. 2a–2c, no clear changes in color are apparent. Scans extracted from the before (bottom of Fig. 2b) and after (top of Fig. 2b) images in the region of the previously reported change are shown in Fig. 2c. To within our image-to-image errors (estimated at ∼5% for the color images), there is no observable change.

3. *Aristarchus*

Hundreds of reliable observations of LTP have been reported in or near Aristarchus in recent decades. Several events were reported during the Clementine mission itself, including diffuse appearances and one bright glow (Darling, personal communication, 1996, Cameron *et al.* 1997). A gaseous spectrum including emission lines of carbon and hydrogen was observed in the crater by Kozyrev (Kozyrev 1963, Leonardi 1976). Greenacre and Barr observed an "elongated streaked pink" in the southwest interior rim of the crater (Greenacre 1963). Although the event appears near regions of higher albedos, and additional inhomogeneities in the thermal emission are shown in the LWIR image (Fig. 3 (top)), there is nothing in the Clementine or Orbiter images to indicate recent geologic activity. However, the color ratio of the region (Fig. 3 (bottom)) shows that the crater's bright ejecta, depicted so clearly in Fig. 3 (top), are not blue, as fresh ejecta usually are, but they are red or similar in color to the surrounding terrain. This result, which also holds for material surrounding the central peak of Alphonsus, suggests the ejecta consist of fine-grained material, possibly even volcanic ash (see Summary and Conclusions).

4. *Piton*

A classical area of LTP, Mount Piton was observed to undergo changes in brightness by the team of 75 observers active during the Clementine mission. Our inspection of images obtained on March 27 and April 23, 1994, reveals no changes in color or albedo for this region. The mountain is surrounded by Mare Imbrium lavas toward the northern rim. Mare lava may have sealed in gasses, which periodically escape from the perimeter of the mountain (Fig. 4 (top)). Clear compositional variegations appearing in the color ratio map (Fig. 4 (bottom)) suggest possible wasting of material subsequent to outgassing, fracturing, or even the deposition of outgassed material.

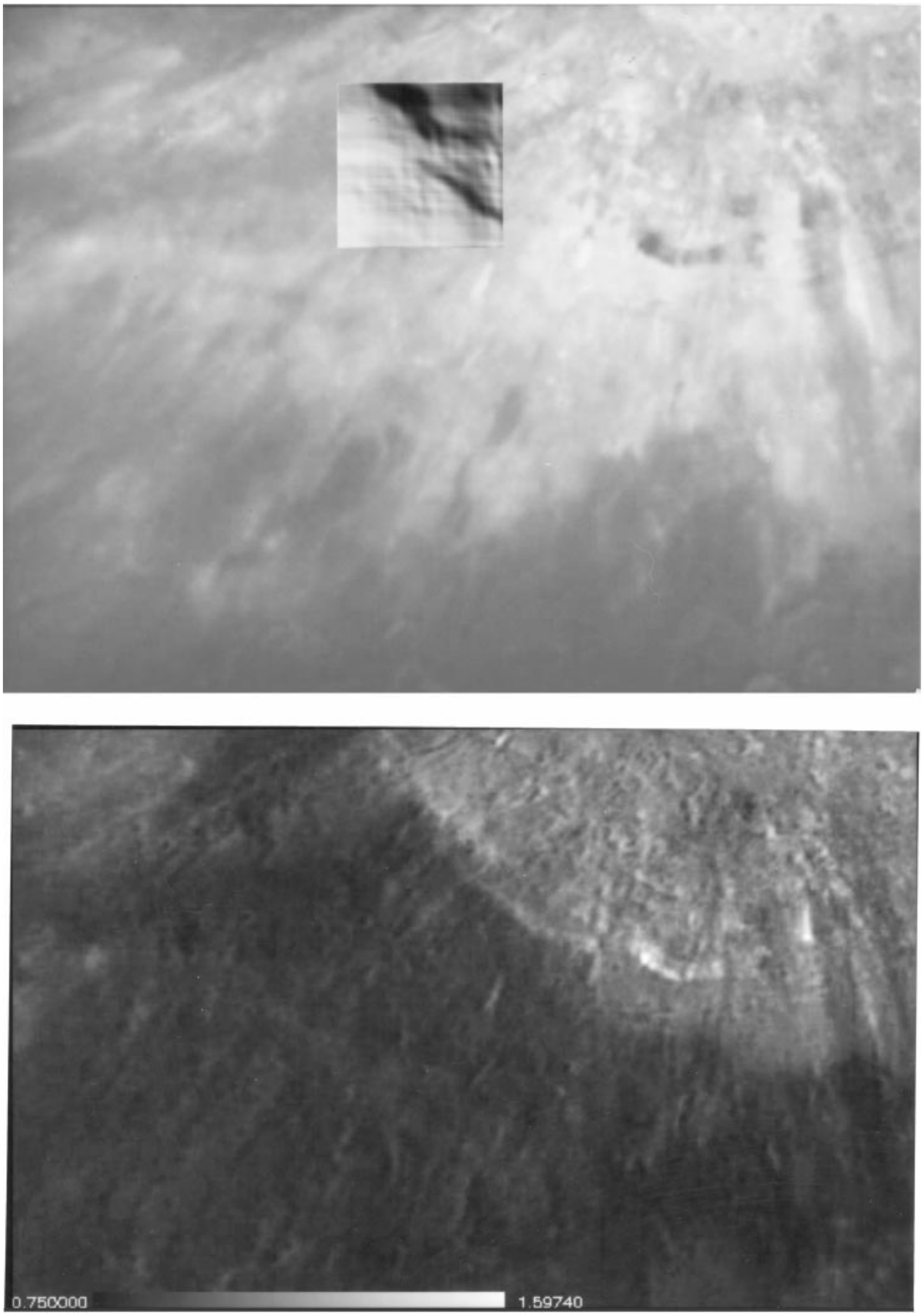

FIG. 3. E-filter (top) and color ratio (bottom) images of Aristarchus.

5. *Palus Somni*

A team of Greek astronomers photographed this recent, well-defined, bright event (Kolovos *et al.* 1988), which occurred near an irregular unnamed crater in Palus Somni. Two subsequent investigators (Maley 1991, Rast 1991) claimed that the event was in fact a glint of sunlight reflected from the Earth-orbiting satellite 1998-042A. Subsequently, Kolovos *et al.* (1992) presented additional evidence that the event occurred just above the lunar surface. Nothing unusual appears in the Clementine image of this area (Fig. 5) or in a color ratio image. A comparison of the Clementine image with a Lunar Orbiter image of the same area shows no changes.

6. *Anaxagoras*

Although this crater was not among the "classical" regions of Lunar Transient Phenomena, a Clementine image was obtained

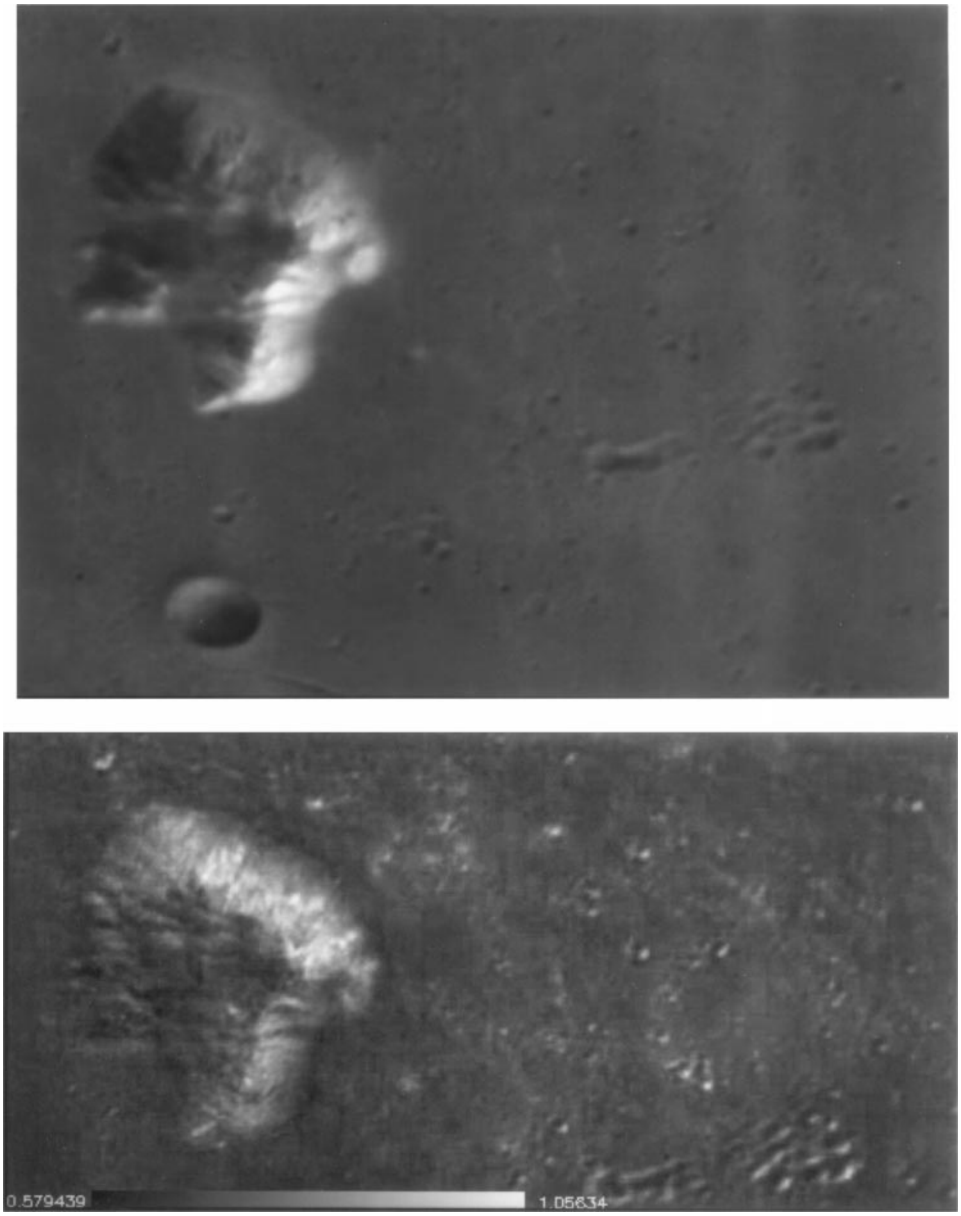

FIG. 4. E-filter (top) and color ratio (bottom) maps of Mount Piton. These images were obtained 10 h and 45 min after a ground-based LTP was observed (Cameron *et al.* 1997).

before and after an event that was reported by the team of ground-based observers (Figs. 6a–6d). They described the event as a "bright streak from floor to wall and thin dark shadow on floor" (Darling, personal communication, 1996). No changes are apparent in the before and after images (Figs. 6a and 6c); the "after" image was obtained on March 28, 1994, about 19 h after the reported LTP. There is an absence of color changes as well (Figs. 6b and 6d). The rim of the crater is similar in color to the surrounding areas. Anaxagoras is a relatively fresh crater with terraced walls; much of the material in the crater is ponded impact melt.

7. Picard

Picard is a relatively young crater near the edge of Mare Crisium. Debris slopes and a bright albedo blanket appear around the rim of the crater. Picard exhibits morphologic similarities to Aristarchus, which has been the source of about a third of historic LTP. As in the case of Aristarchus, the material comprising the bright ejecta blanket is red. The rim of Picard exhibits a well-defined compositional discontinuity with the surrounding area: it is much bluer than the surrounding material, which indicates slumping of material to uncover a fresher, unweathered

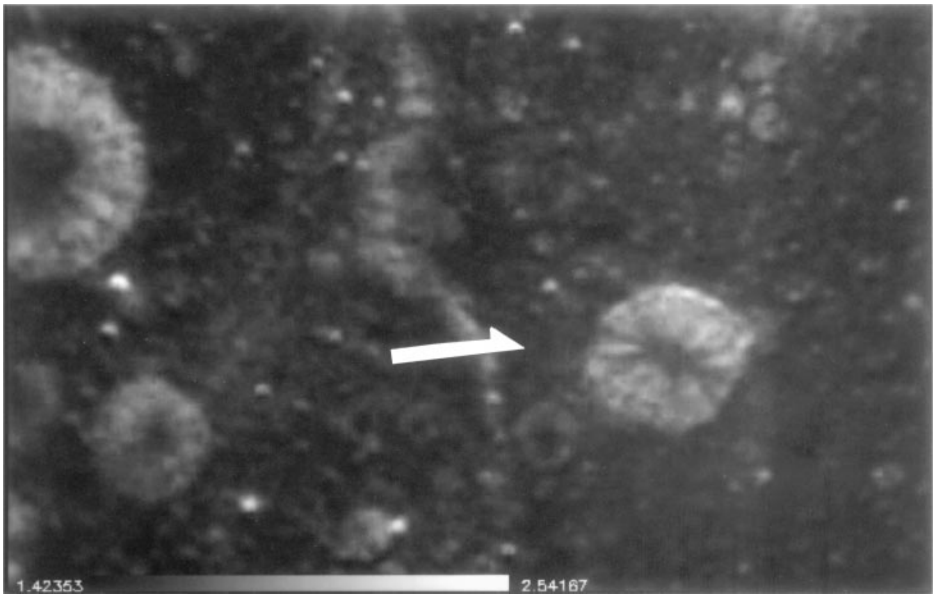

FIG. 5. A Clementine E-filter image of Palus Somni, where a recent photographed event was observed, at the arrow (Kolovos *et al.* 1988, 1992).

substance on the rim. An LTP reported by the ground-based team was sandwiched between two Clementine images. The later image, obtained on April 19, 1994, only 9 h 24 min after the reported event, is shown in Fig. 7c. No changes are evident in the partial portion of the crater that was imaged. The LTP was described as a "wall going dark," and its reliability was deemed to be medium (Cameron *et al.* 1997).

8. *Tycho*

Tycho is a fresh terraced crater similar to Picard and Aristarchus. Most LTP have been observed in the vicinity of the central peak, shown in Fig. 8 (top). The central peak is clearly compositionally distinct from the crater floor, and it is internally heterogeneous (Fig. 8b). The color ratio map also shows a quasi-polygonal grouping of narrow lines composed of bluer and presumably fresher material. This tracery of less-weathered material may indicate the presence of fractures from which outgassing can occur. Bluer regions on the peak suggest the presence of fresh material exposed by slumping.

9. *Ross D*

The relatively blue rim of this crater indicates the presence of fresh material that was denuded by slumping (Fig. 9 (top and bottom)). We note that nearby craters with no reported LTP in their vicinity show similar blue rims.

10. *Plato*

Plato lies near the rim of Mare Imbrium. The crater walls are not distinctly blue like Picard or Ross D (Fig. 10 (top and bottom)). No evidence exists for recent activity in the region of the crater imaged by Clementine.

11. *Gassendi*

Gassendi, like Plato, lies at the boundary of a mare, in this case the edge of Mare Humorum (Fig. 11 (top)). The southeast rim is in fact surrounded by mare material. Gassendi's rim appears even less compositionally distinct from the surrounding region than does that of Plato (Fig. 11 (bottom)). There appear to be regions of weakness along the rim: there is an enhancement of small bright features there. They are not craters, because they are bright and red. They are possibly other examples of the fine-grained material that exists in several of the regions where LTP have been observed (see Summary and Conclusions).

IV. SUMMARY AND CONCLUSIONS

We find no evidence for LTP on any Clementine images. Furthermore, before and after images for four events that occurred during the mission's main mapping phase show no morphological or color changes. An earlier reported change in the Cobrahead region, based on a preliminary analysis (Buratti *et al.* 1996, Calkins *et al.* 1999), is probably spurious.

Analysis of Clementine images in those regions where Lunar Transient Phenomena have historically been reported shows that LTP do not occur randomly on the Moon. They are concentrated near regions of crustal weakness, particularly boundaries of maria. The only features discussed in our study that do not occur near such boundaries are Anaxagoras and Palus Somni. Neither of these regions are areas of historical LTP. We focused on the region of Anaxagoras because the team of ground-based observers informed us of an event that was bound on both sides by Clementine images. Subsequently, however, the team

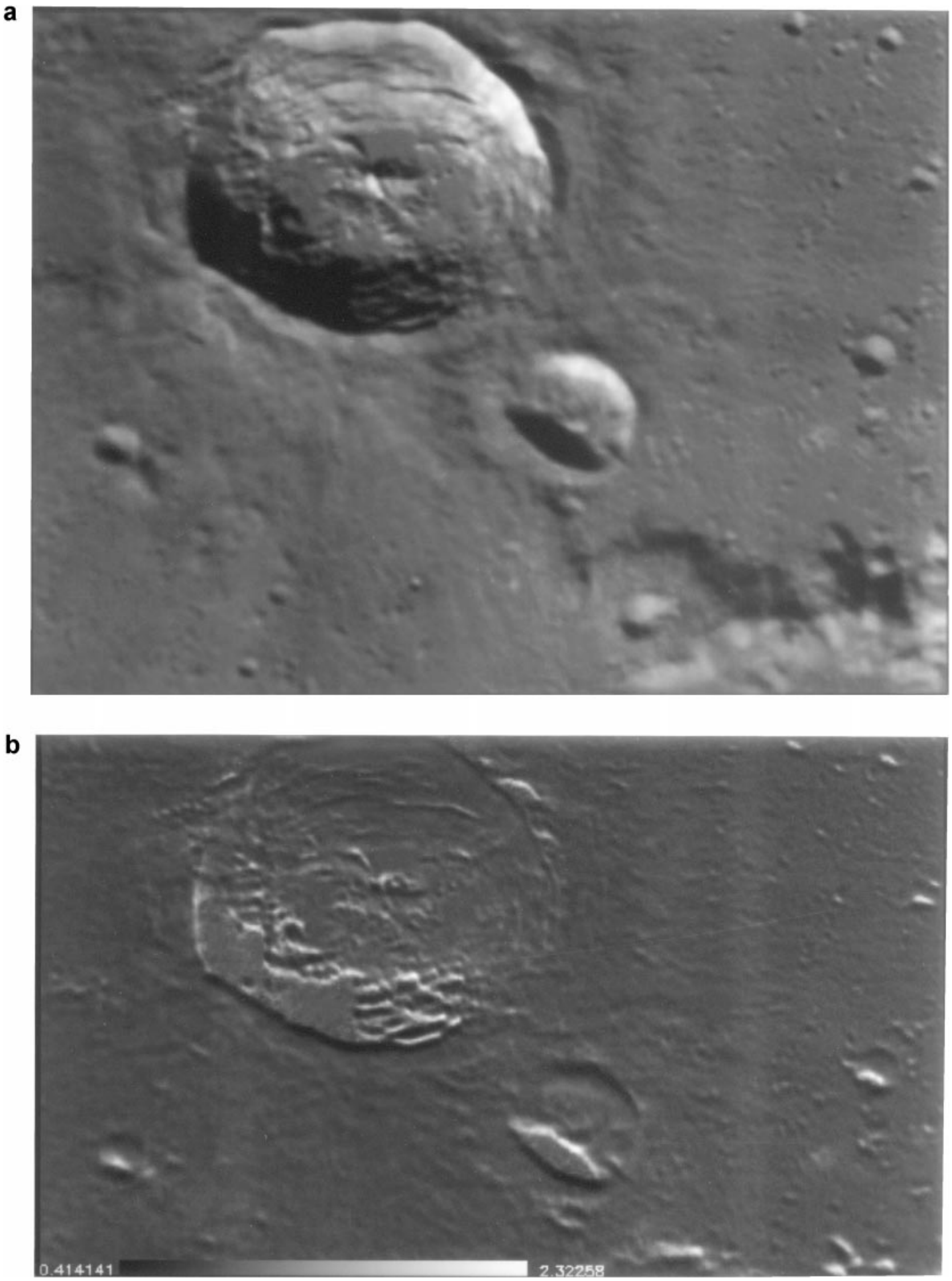

FIG. 6. E-filter (a) and color ratio (b) images of Anaxagoras. A later set of images (c and d) was obtained about 19 h after a reported LTP; no changes are discernible.

downgraded the event to 0 in reliability (on a scale of 0 to 5). The event in Palus Somni was identified as an artificial satellite by two groups. Thus both these regions may not be sources of “true” LTP.

The boundaries of maria may serve as regions of crustal weakness from which gasses escape. This point was originally made by Cameron (1972) and by Gorenstein *et al.* (1974), who observed an enhancement of radon at the boundaries with the

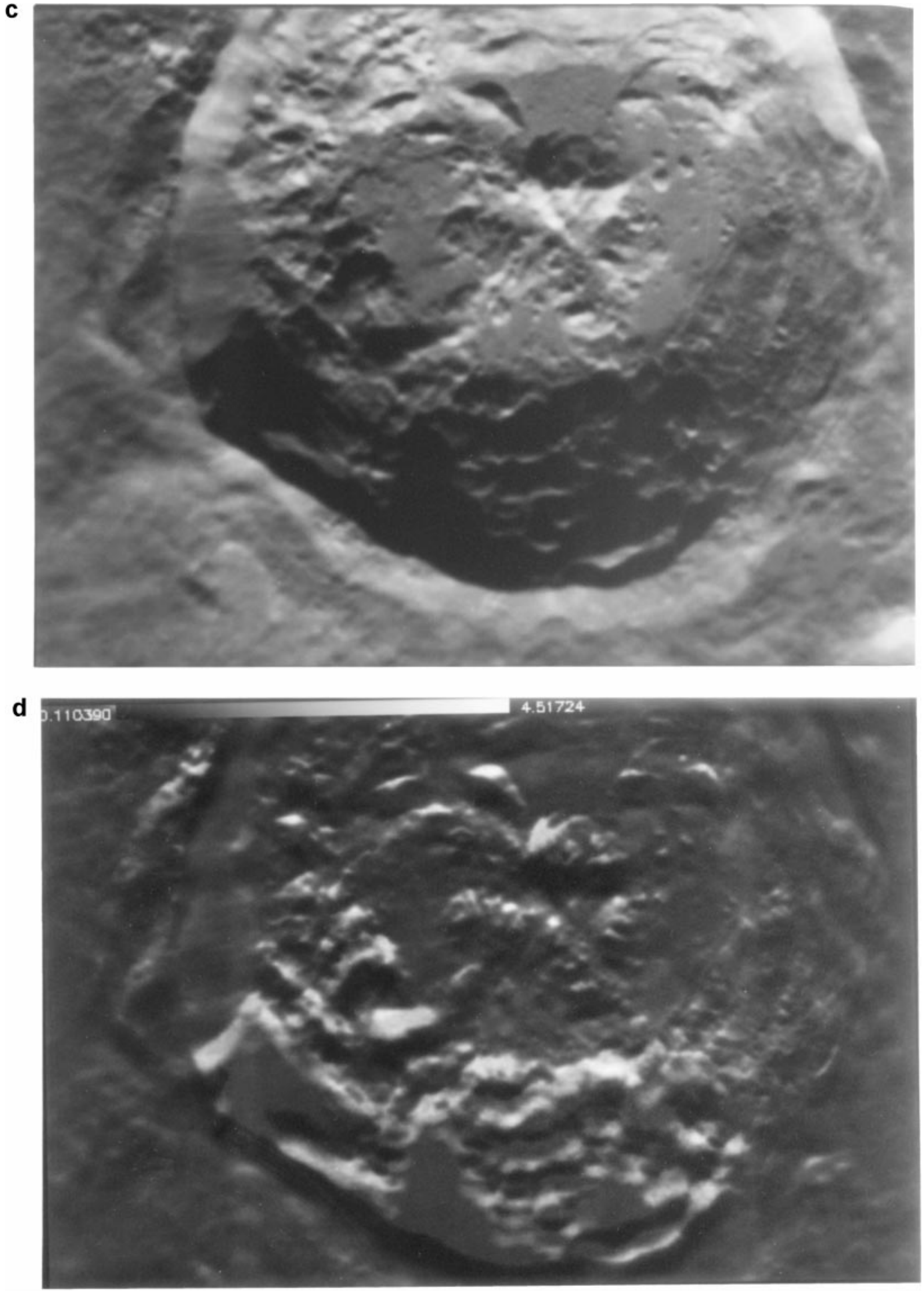

FIG. 6—*Continued*

Apollo alpha-particle spectrometer. In general, LTP are concentrated in regions where radioactive daughter gases are enhanced. A similar argument applies to central peaks in large craters (Alphonsus and Tycho) and to mountain peaks surrounded by maria (Piton): gasses can more easily escape from the fractured rocks in the peaks than from the surrounding basalt. Slumping of material, which was observed on Cobrahead, Picard, Ross D, Tycho, Piton, and Alphonsus, can be catalyzed

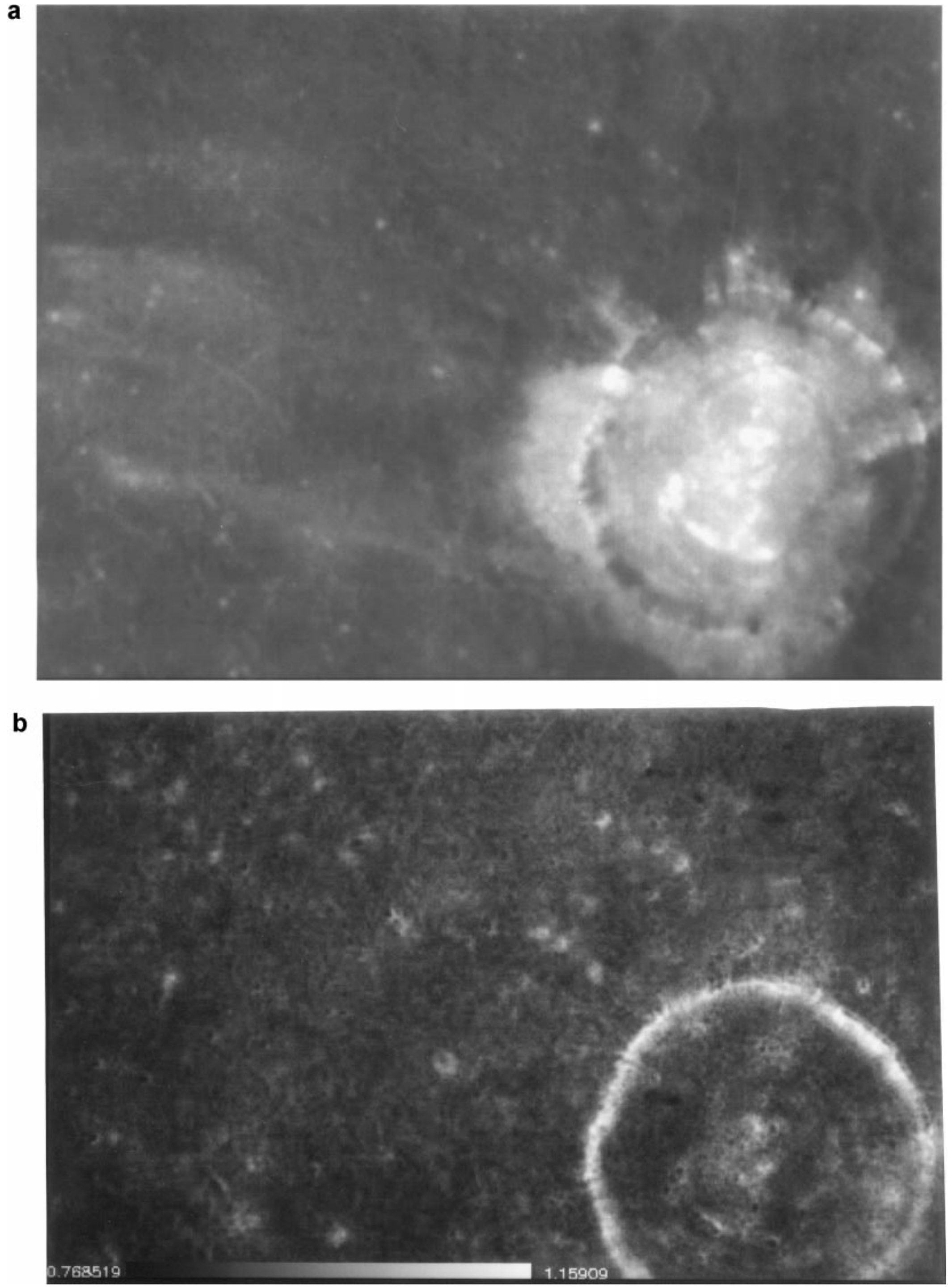

FIG. 7. E-filter (a) and color ratio (b) maps of Picard. A later set of images (c and d) was obtained about 9.5 h after a reported LTP. No changes are apparent, although only part of the crater was imaged.

by outgassing. In turn, slumping can cause the release of additional gasses. Table III summarizes the categories of regions in which LTP occur, as defined by Clementine images.

Blue crater rims seen on Picard and Ross D may have been created by recent slumping of material. The lunar surface is exposed to micrometeoritic bombardment which reddens and darkens it. A disturbance to the soil exposes brighter, bluer underlying material. Gault *et al.* (1974) and Helfenstein and Shepard (1998) show that gardening and mixing of the upper part of the regolith occurs rapidly, so exposed material does not stay optically

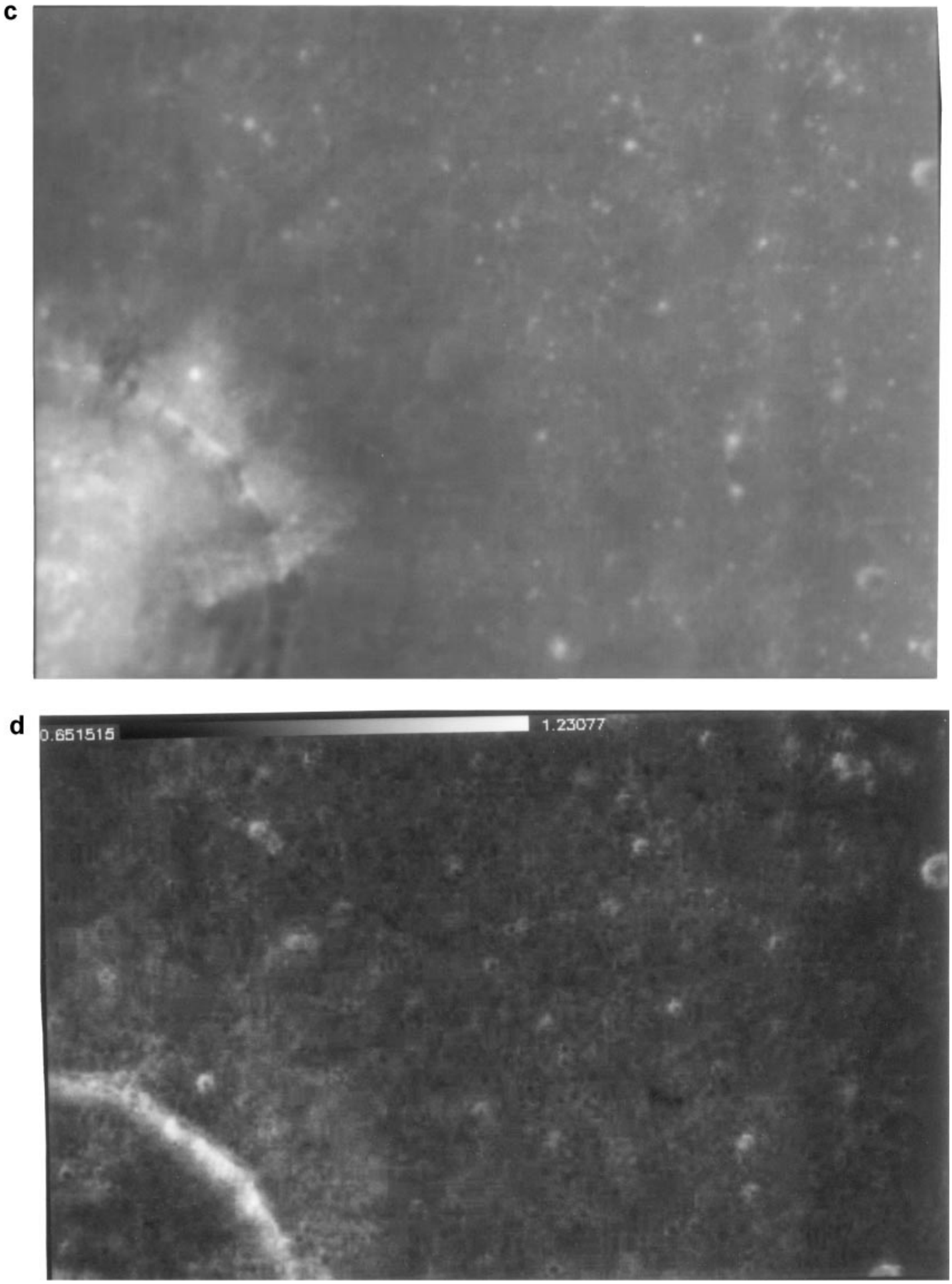

FIG. 7—*Continued*

distinct for long periods of time. These blue areas thus indicate the recent movement of material on the lunar surface.

One important new observation from the Clementine images is that many of the regions of LTP show some evidence for a mantle of fine-grained particles, such as that expected from pyroclastic ash deposits. At least four regions (Alphonsus, Aristarchus, Picard, and Gassendi) contain areas that are bright and red, optical properties consistent with small particles. The

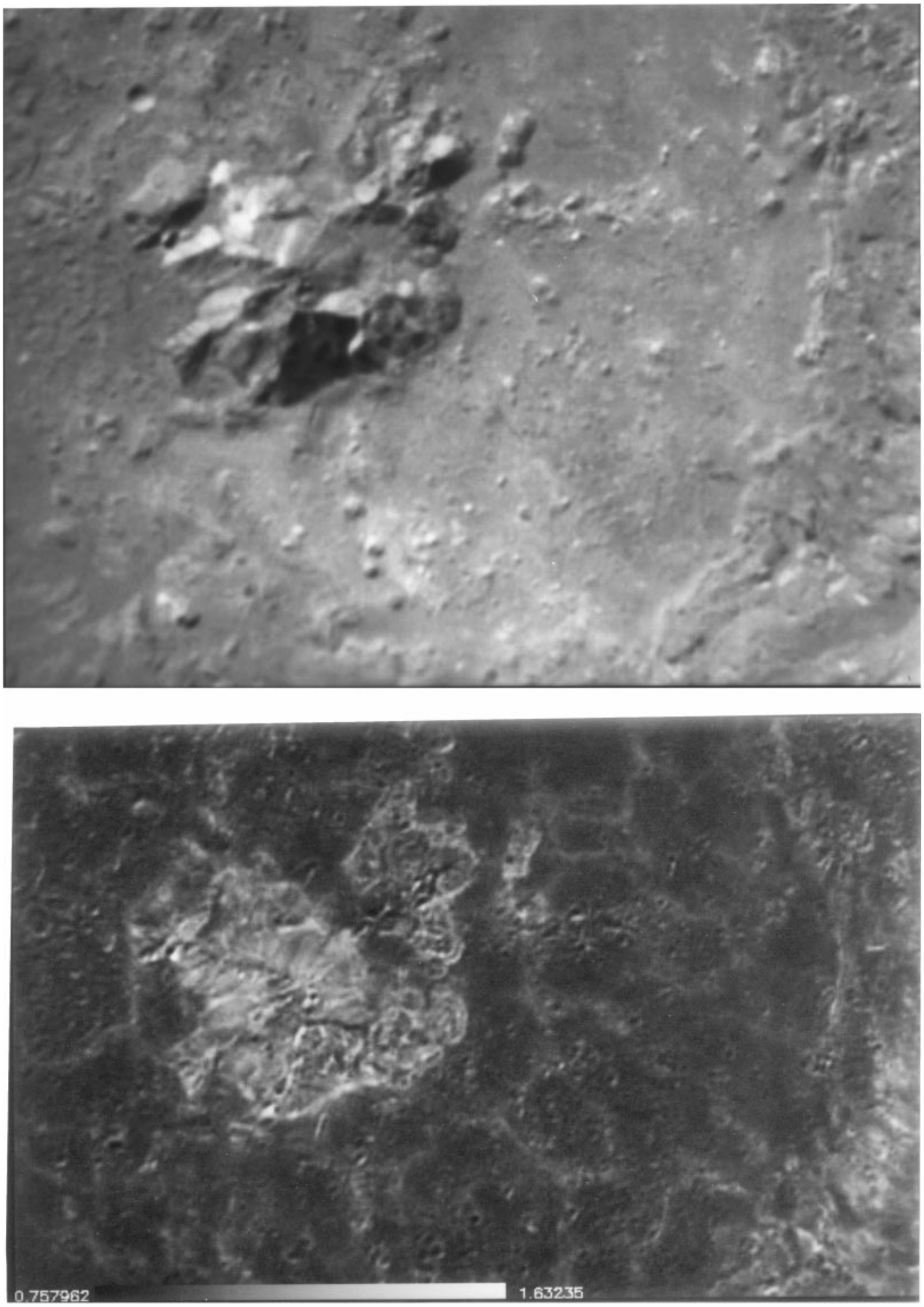

FIG. 8. E-filter (top) and color ratio (bottom) images of Tycho.

higher albedo (when compared with surrounding regions) strongly suggests fine particles, because comminution of particles increases the amount of multiple scattering and thus the albedo. The red color of the material suggests, but does not prove, a volcanic origin. Spectra of pyroclastic glass samples are redder than spectra of mare basalt samples (Gaddis *et al.* 1985, Taylor *et al.* 1991, Figs. 6.18 and 6.20), although Clementine spectra of volcanic deposits show they exhibit a wide range of colors

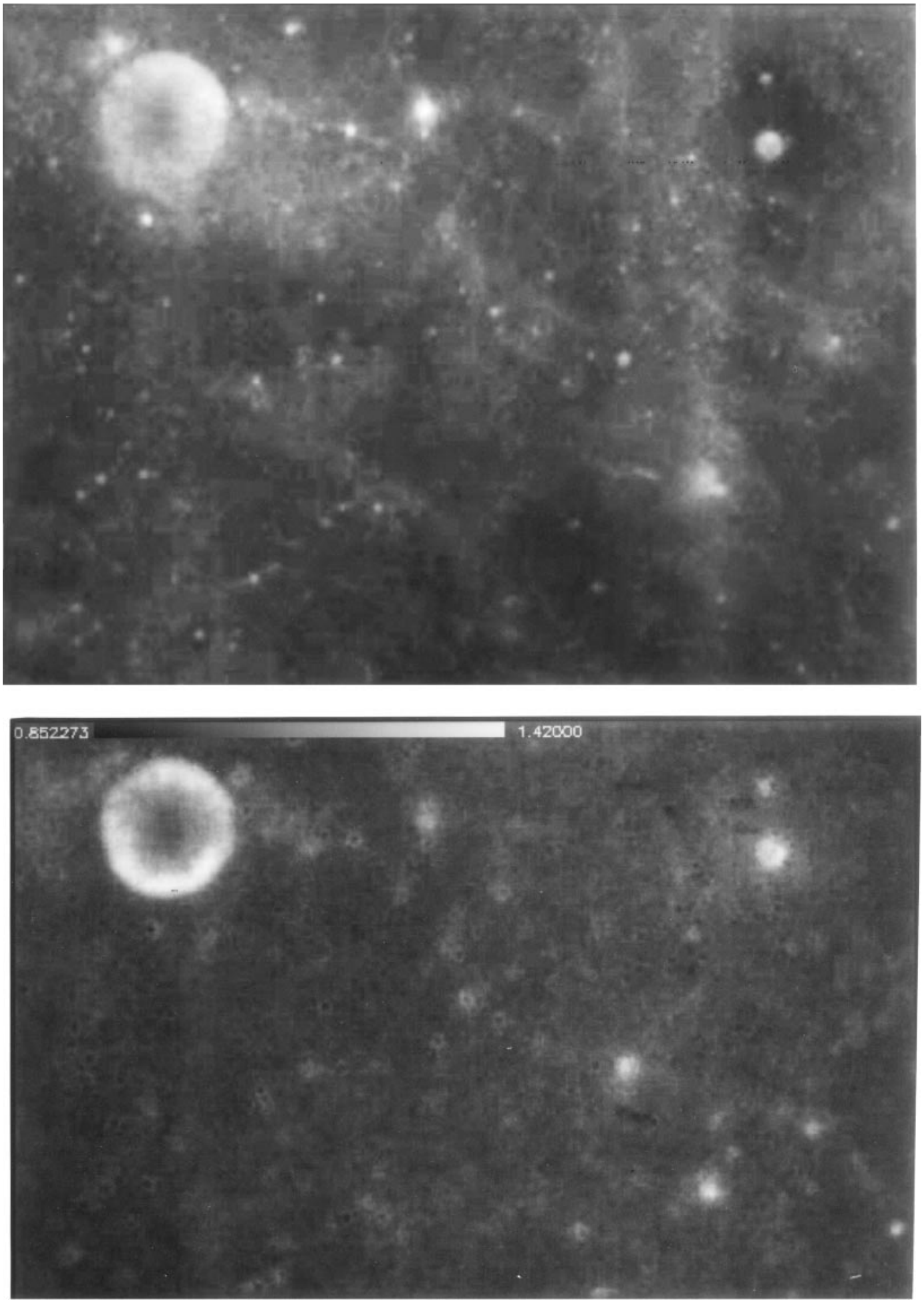

FIG. 9. E-filter (top) and color ratio (bottom) images of Ross D.

(Gaddis *et al.* 2000). Even though these four regions are all undoubtedly impact structures, outgassing of trapped volatiles could occur as an auxiliary process subsequent to the impact.

An LTP recently observed near the central peak of the Langrenus crater has been ascribed to outgassing from a terrain that is heavily fractured and fissured (Dollfus 2000). An increase in albedo and polarization was attributed to light scattering by suspended particles.

The most recently proposed mechanism for LTP, optical pulses caused by electrodynamic effects (Kolovos *et al.* 1988,

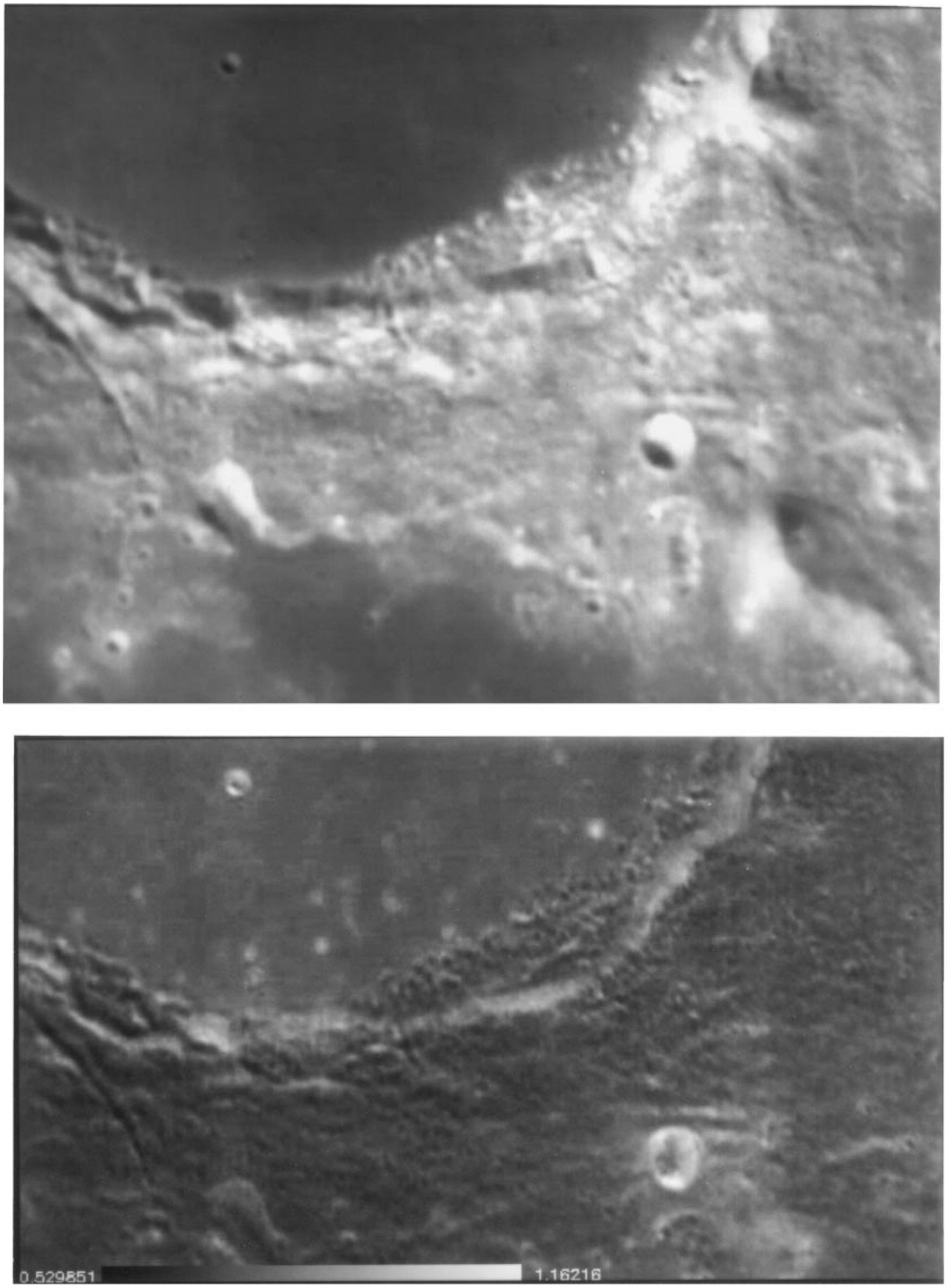

FIG. 10. E-filter (top) and color ratio (bottom) images of Plato.

Zito 1989), is not inconsistent with the mechanisms we discuss. Slumping or cracking at the weak crustal zones could act as a catalyst for electrical phenomena.

Even without the observation of obvious lunar transient events in the Clementine database, reasonable but not compelling evidence, as well as plausible mechanisms, exist for LTP. Although the events occur in certain types of areas, it is easily argued that other similar areas are devoid of LTP. It is important to remember that LTP are due to geologic phenomena, and that they occur on geologic time scales (if they exist). It is quite possible that

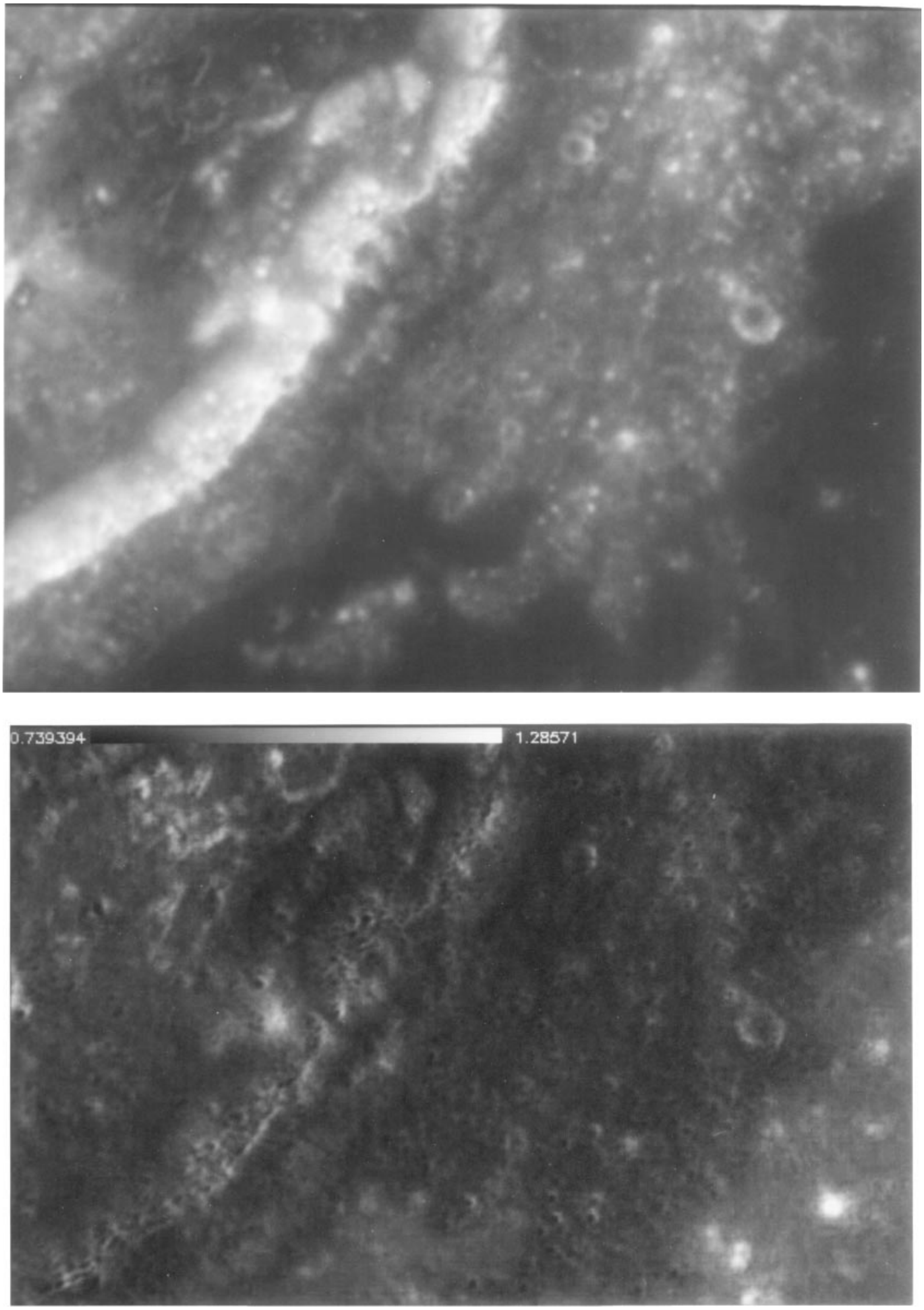

FIG. 11. E-filter (top) and color ratio (bottom) images of Gassendi.

TABLE III
Classification of Regions for LTP

Type of region	Specific locations
Boundaries of maria	All studied, except Anaxagoras and Palus Somni
Young craters: fresh rims; recent slumping; bluer, recently exposed material	Picard, Tycho, Aristarchus, Ross D
Central peaks	Alphonsus, Tycho
Mountains surrounded by maria	Piton
Regions of residual volcanic activity; evidence for pyroclastic deposits	Cobrahead, Aristarchus, Gassendi(?)

LTP just have not occurred in these similar regions during the 100 or so years humankind has been closely scrutinizing the Moon.

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