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NASA CR-147553

FINAL REPORT

Contract NAS 9-12564

National Aeronautics and Space Administration

Johnson Spacecraft Center

Houston, Texas

Volcanology and Morphology

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March 20, 1976

MAY 1976
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(NASA-CR-147553) VOLCANOLOGY AND MORPHOLOGY Final Report (Woods Hole Oceanographic Institution) 53 p HC $4.50 CSCL 03B

N76-23123

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INTRODUCTION

During the last several months of 1975 discussions were begun with scientists and NASA personnel in Washington and Houston as to the possibilities of extending the termination date of this grant beyond the date of the Lunar Science Conference, in order to allow the principal investigator the opportunity to attend that conference. A small amount of money was retained to cover salary and travel for this purpose. As there appeared to be no mechanism for such an extension, the grant terminated as originally scheduled on December 31, 1975, with this money still unspent.

This report thus summarizes work completed to December 31, 1975 and concludes with some suggestions for future work, based on this experience. One publication is still in preparation and will be submitted for inclusion in the Proceedings of the Seventh Lunar Science Conference.

Published papers produced in the course of this project include two contributions to the Apollo 17 Preliminary Science Reports and three journal articles. A fourth publication is in preparation. Copies of these papers and of an abstract of the fourth paper are included as part of this report.

Certain tasks outlined in the original proposal had to be modified or abandoned either because no adequate photo coverage was obtained, or because technical difficulties were encountered. Specifically, proposed studies of volcanic features in the Marius Hills region were not carried out because this area was not included in the Apollo photo coverage. Our plans to produce detailed contour maps of lunar volcanic features proved impractical because the stereo reference level in lunar metric photos is distinctly spherical, and this problem cannot be resolved with simple equipment as in the case of terrestrial air photos. Fortunately, the excellent quality of the 1/250,000 scale lunar contour maps eliminated much of the need to perform this work.

Original plans to relate the photo studies closely to data fromother orbital science experiments had to be modified or abandoned, mainly because these data either became available too late in the program or because their resolution is much poorer than that in the photos. The most successful interaction has been withthe lunar gravity research through interactions with C. Bowin at Woods Hole. Even here, there have been limitations, due to initial delays in receipt of gravity data and numerical problems which had to be resolved to process the data. Also, most of the gravity studies have proved feasible only over the maria, and thus have not been incorporated into our studies of smaller impact craters.

WORK COMPLETED

Maria Basins - Excellent Apollo 15 photo coverage of the southern parts of Serenitatis and Imbrium was used for a study of the morphology and distribution of wrinkle ridges, a feature which has been widely attributed to lava extrusion along fractures. It was shown (Bryan, 1973) that many of these ridges appear to be of tectonic origin, deforming pre-existing lava fill in the maria. A relatively small amount of subsidence of the mare lava fill could result in the degree of compression required to form these ridges, and this interpretation was compatible with existing interpretations of the lunar gravity data.

An initial interpretation of volcanic and structural features along the south margin of Serenitatis (Bryan and Adams, 1973) included a discussion of the Dawes basalt cinder cones. These are the most convincing volcanic cones encountered in studies of mare volcanism. This initial study also called attention to some details of structural evolution in and around mare basins which have been more fully developed in a later paper (Bryan et al., 1976).

Large craters - Based on existing photo coverage and quality of photos, three large craters were selected for detailed study. Volcanic and structural features in crater Aitken (Bryan and Adams, 1973, 1974) were outlined and it was shown that a sequence of post-impact volcanic events can explain most of the morphologic details. Evidence of compressional deformation was documented both within Aitken and in the adjacent highlands. Subsequent study of crater Goclenius (Bryan et al., 1975) showed a close relationship between morphology of the impact crater and the trends of both external and internal linear grabens which tend to parallel directions of the lunar grid. This relation was further supported by a study of linear trends in the walls of crater Tsiolkovsky (Bryan et al., 1976).

Small craters - Small craters of possible volcanic origin have been discussed in connection with other volcanic features of maria and large craters as noted above. Possible cinder cones were noted associated with the Dawes basalt and in the floor of craters Aitken and Goclenius. Small pit craters were also noted within the floors of these larger craters, and were interpreted as collapse features due to lava drain-back. Pits or fissures of likely volcanic origin associated with wrinkle ridges appear to be the exception rather than the rule.

Linear features - Throughout the course of this study we have been impressed by the tendency of linear structural elements to approximate one of the principal directions of the so-called "lunar grid". Although a predominance of northwest and northeast-trending linear features has been noted by many other workers, the reality of this grid and its origin remain controversial. During this past year, our studies have emphasized the geometry and fine-scale morphology of these structural lineaments. Specifically, we have noted several details not emphasized by earlier work:

1. The consistency of linear orientations over most of the lunar surface is most easily explained if the lineaments are related to a spiral grid pattern. This may imply a torsional mechanism for producing the grid.

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2. The pattern is very old, and tends to be rejuvenated or etched out by a variety of processes, including flow of lava, large and small impact events, and compressional deformation.

3. Even where a major linear feature such as a wrinkle ridge or sinuous rille curves or has a gross trend apparently unrelated to the grid, it may be made up of small elements which do parallel the grid direction.

Our previous and concurrent work on linear sea-floor structures, and a review of recent literature on terrestrial structural geology, shows that certain analogies may exist between tectonic evolution on the Earth and Moon. We develop this idea in our latest paper (Bryan et al., 1976) and suggest that, while terrestrial structure is complicated by sea-floor spreading, directions of spreading may be controlled by an ancient terrestrial grid pattern.

Quantitative morphology - Several attempts were made to produce or to obtain detailed contour maps of specific small features. Discussions with NASA photogrametric personnel at Houston and Geological Survey personnel at Menlo Park indicate that obtaining and utilizing proper elevation control points is not an easy matter even for qualified experts. The Geological Survey attempted detailed contouring of a small cone in Aitkin, which was completed too late to be included in the published paper. The contour map proved very difficult to use as it could not be related directly to photo imagery. A different attempt to produce a contour map of part of the floor of Goclenius had to be abandoned, because of excessive distortion in the photo image.

Our own equipment has proved useful for making point determinations of elevation differences, which are often sufficient for general estimates of height, slope, or volume. Detailed contouring has not proved practical. Overall, the 1/250,000 contoured ortho-photo maps satisfy most needs for a contoured photo product. These maps proved useful during the past year for study of lunar structure trends, but most arrived too late to be applied to the earlier published papers.

Transient events - Original proposals to compare Orbiter and Apollo photos of the same area to find evidence of possible short-term changes associated with volcanism or other processes appear ambitious, if not naive, in retrospect. While there is much overlap between Apollo 15 and 17 photo coverage, and between Apollo and Orbiter coverage, there is rarely sufficient consistency in sun angle or photo quality. It was not possible to obtain any significant results as a result of such comparisons due to these inconsistencies.

Future work - The usefulness of Apollo photos could be enhanced if there were more supporting data from other orbital experiments. To date, only the gravity data seems to have been summarized in a substantial number of journal publications. Knowledge of shallow structure, as deduced from the lunar sounder experiments, or compositional variation deduced from x-ray fluorescence, could provide valuable constraints on geologic models deduced from photo studies.

Much additional morphologic study of photos, in the absence of such constraints, would appear to be of limited value. The partial redundancy in Apollo photo coverage, combined with the poor quality of photos taken at high sun angles, also puts severe limits on the areas suitable for study. Photos obtained in polar orbit at 20-30 degree sun angles would greatly expand the possibilities for further profitable photogeologic studies of the Moon. The altitude and scale of the Apollo metric photos appears most suitable for this purpose.

More detailed comparative studies of Earth and Moon, perhaps utilizing Apollo and ERTS photos, may prove profitable. The apparent limitation of lunar volcanism mainly to the mare-filling episodes 3.5 to 2.5 b.y. ago, and the continuing prominent role of volcanism on Earth, are intriguing contrasts. Similarly, the possibility of a common mode of origin of ancient lunar and terrestrial tectonic grids merits study.

Originally I suggested that a catalog of lunar volcanic features would be a possible product to be included in the final report. Recent discussions with Dr. James Head suggest that such a contribution might be an appropriate input for a new project headed by him which would be a comparative study of basaltic volcanism on the terrestrial planets. I have agreed to participate on his research team. If it seems appropriate, additional support for this work would be sought

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under the Lunar Synthesis Program. My current work on submarine and circum-oceanic volcanism is also a source of material for this project. At present, the Apollo and Orbiter photography assembled under the "Volcanology and Morphology" grant is being retained as reference material for these comparative studies.

ACKNOWLEDGEMENTS

Mary-Linda Adams and Peter Jezek worked as research assistants on this project and contributed substantially to the ideas expressed in the publications. C.O. Bowin provided much discussion on interpretation of lunar geophysics and geological data. I am especially grateful to Nat Hardee, D. Kinsler, and Joe Dixon for much assistance in obtaining lunar photo products and for arranging contacts with appropriate technical personnel in the NASA organization, and to Henry Moore for arranging the contouring of Aitken and Goclenius photos by the Geological Survey.

PUBLICATIONS

Copies of published papers, and an abstract of the last paper presented at the Seventh Lunar Science Conference, are attached.

Wrinkle-ridges as deformed surface crust on ponded mare lava*

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GEOCHIMICA ET COSMOCHIMICA ACTA

Journal of The Geochemical Society and The Meteoritical Society

SUPPLEMENT 4

PROCEEDINGS OF THE FOURTH LUNAR SCIENCE CONFERENCE

Houston, Texas, March 5-8, 1973

Sponsored by

The NASA Johnson Space Center

and

The Lunar Science Institute

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Proceedings of the Fourth Lunar Science Conference
(Supplement 4, *Geochimica et Cosmochimica Acta*)
Vol. 1, pp. 93–106

Wrinkle-ridges as deformed surface crust on ponded mare lava*

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Abstract—Wrinkle-ridges in Mare Imbrium developed as low swells concurrently with the inpouring of the most recent lava flows, as shown by ponding and deflection of the flows. Deformation completed after consolidation of the lava deformed the flows by sharp wrinkling along the crest of the swells. Monoclinal down-faulting of the mare basin is also indicated. An early, dark mare fill is downwarped toward the center of Mare Serenitatis, and tensional deformation associated with the downwarp extends into adjacent highlands. Later compressional deformation produced a wrinkle ridge along the east margin of Serenitatis which locally is thrust over highland material. A younger light-colored central fill shows both radial and concentric compressional patterns of wrinkle ridges; wrinkle-ridge morphology is controlled in part by pre-existing joint blocks. This pattern, or an alternate pattern of en-echelon concentric ridges, can be explained by isostatic subsidence of the spherical surface shell represented by mare lava fill. This collapse could take the form of central sagging (model 1) or uniform surface collapse along vertical marginal ring faults (model 2). Model 2 collapse is shown to be the most effective source of crustal shortening.

Introduction

Wrinkle-ridges have been recognized for many years in telescopic photos and in the more recent Ranger and Orbiter photography of the lunar surface. Consistency of orientation of some ridge systems, especially in Procellarum, has led some authors to attribute these ridges to global deformation related to the lunar tectonic grid (Fielder and Kiang, 1962; Strom, 1964). Recognizing a consistent en-echelon arrangement of ridges in the northern part of Procellarum, Tjia (1970) suggested regional strike-slip deformation as a major mechanism for forming them. Colton *et al.* (1972) found similar en-echelon patterns in southern Oceanus Procellarum which are consistent with this interpretation. However, in the same area they recognized a variety of swells and ridges, some of which appeared to reflect sagging of mare crust over buried ridges, and others which could be partly volcanic extrusives. Volcanic origins for mare ridges have been popular with many authors. The Flamsteed Ring (O'Keefe *et al.*, 1967) is one of the best known examples of a possible extrusive ring dike. Morphologically, it is not really equivalent to the wrinkle ridges discussed in this paper, which consist of a broad curvilinear swell topped by a narrow, steep-sided, sinuous, braided, or irregular zig-zag ridge. This is the typical "wrinkle-ridge" or "mare ridge" as described by Strom (1972), who also favored a combination of regional deformation and volcanic extrusions to explain them. A predominantly volcanic or volcanic-intrusive origin for mare ridges seems to be very generally accepted and is usually the

*Contribution No. 3095 of the Woods Hole Oceanographic Institution.

explanation given in summary treatments of lunar geology. Thus Lowman, (1972, p. 139) referring to mare ridges, domes, and rilles, states, "The first two are clearly post-mare volcanic features of some sort. . . ." Guest (1971, p. 130) suggests that mare ridges may be the source of large lava flows, and attributes variations in detailed morphology to viscous extrusions or shallow intrusions along fissures.

As many wrinkle ridges are intimately associated with mare basins and are concentric or radial to the basin centers, it is reasonable to suspect a genetic relation between mare basins and the formation of at least some wrinkle ridges. Baldwin (1968) interpreted wrinkle ridges as compression features, and graben-like rilles on the margins of Mare Imbrium as tensional fractures, both produced by subsidence and compaction effects in a lava-filled basin. O'Keefe (1968) also called attention to morphologic features such as inward tilting of mare fill and the Mare Humorum ring fault, which suggested subsidence of a basin in response to lava fill. He also noted the need to derive the dense mare fills from sources either at great depth or well outside the basins, in order to satisfy the gravity data. Phillips *et al.* (1972) showed that Orbiter and Apollo 15 gravity data are best modeled by assuming the maria represent thin fillings of basalt which taper toward the margins of the basin. They considered several hypotheses to explain the wrinkle ridges in Serenitatis and Crisium. They favored the view that the ridges are a tectonic expression of the load imposed on the lunar crust by the mascon, although they did not develop this concept in detail. Study of ridge morphology in Apollo metric photographs over parts of Mare Serenitatis and Mare Imbrium strongly supports the model proposed by Phillips *et al.* (1972), and in particular provides new evidence for the relative time of formation of the wrinkle ridges, and for their essentially compressional origin.

Ridges in Mare Imbrium

The relation between lava flows and wrinkle ridges is well displayed along the south side of Mare Imbrium, especially in the vicinity of Mons La Hire. The Imbrian lava flows are shown by the Apollo 15 metric photographs to have originated well to the south near Euler (Schaber, 1973). They flowed north into the Imbrium Basin across the area covered by the Apollo 15 orbits. The north obliques AS15-1554 and AS15-1555 illustrate these flows especially well, and show them crossing marginal wrinkle ridges and extending well out toward the center of Mare Imbrium.

The flow boundaries are irregularly scalloped and lobed, as in typical terrestrial pahoe-hoe flows, but their gross trend is approximately perpendicular to the wrinkle ridges. Within the flow boundaries more subdued central feeder channels may be seen, and locally there are levees, flow ridges, and "kipukas" which define the original course of the flows. A low north-facing scarp extending west from Mons La Hire is crossed by a flow which spread slightly east along the base of the scarp, then diverged around a kipuka and continued well out into Mare Imbrium (Fig. 1). The flow is crumpled and deformed but undeflected by a prominent

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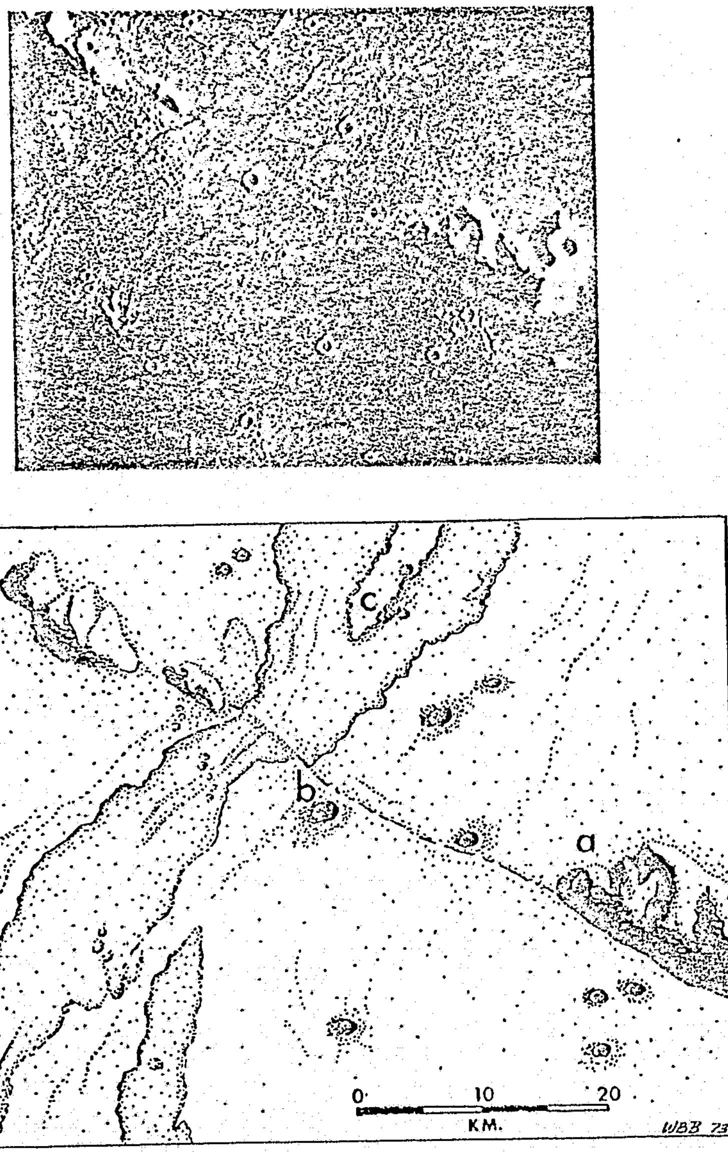

Fig. 1. A lava flow crossing low scarp west of Mons La Hire (a), south side of Mare Imbrium. The flow originates to the southwest (lower left). Note that the flow narrows where it crosses the scarp (b), then spreads a short distance southeast along the base of the scarp, then spreads and diverges around a kipuka (c). Apollo metric photo AS15–1840.

wrinkle ridge and similarly is warped but undeflected by several low, linear swells parallel to the wrinkle ridge farther out in the mare.

East of La Hire, the scarp continues as a low monoclinal warp, again with the basin side down. Another prominent flow which originates southwest of crater Lambert crosses this monocline but is apparently undeflected by it. A short distance to the north, however, this same flow crosses another monoclinal warp topped by a prominent wrinkle ridge. The flow boundaries and its central channel are warped and deformed, but undeflected, by the wrinkle ridge, but at the base of the monocline the flow ponded, backing up along a line parallel to the ridge and forming a delta-like lobe extending northeast into the mare (Fig. 2). The flow eventually broke out on the northern edge of the lava delta and crossed the position of a second prominent wrinkle ridge. It ultimately terminated well out in the mare. There is no evidence that any of these flows originated on the wrinkle ridges, as advocated by Strom (1972).

These observations have important implications for the time of formation of wrinkle ridges and marginal faulting relative to the time of filling of the Imbrium Basin, and by analogy, of the other mare basins. The surface of Mare Imbrium was evidently already subsiding at the same time that large flows were still entering it from a source outside the central basin. This subsidence produced fault scarps and monoclinal folds which caused minor deflection and ponding of flows, and continued with more intense compressional deformation after the flows solidified. Post-mare impact events are distributed indiscriminately over flows and wrinkle ridges; and craters are undeformed by the same ridges that deformed the flow features. Thus, these ridges began to form while the basin was still filling with lava, and the most intense deformation was completed after the lava ceased flowing but before the majority of the post-mare impact events took place.

Ridges in Mare Serenitatis

On the east and south side of Serenitatis (stereo pairs AS15-0394, AS15-0395), the dark "continental shelf" is almost level near the highland contact, but is monoclinally warped into a gentle slope toward the mare basin. A prominent wrinkle ridge runs slightly east of north from a point west of Littrow and the Taurus Mountains, to the highland front near the north edge of the photograph (Fig. 3). At this point, the wrinkle ridge terminates, but the mare floor has been thrust up and over the base of the highland front. This over-thrust closely follows the base of the highland slope, suggesting that it is a shallow, surficial feature localized by the topographic discontinuity. If the up-turned edge of the mare crust originated at the break in slope, the amount of overthrusting is about 0.5 km. Near the southern terminus of this same ridge, there is some evidence of deformation of adjacent small impact craters. Faulting and slumping of regolith material into these craters may account for the apparent flow of material from ridges into craters (Strom, 1972, Fig. 1).

The well-known graben-like rilles on the shelf cross highlands and shelf alike without interruption, except where they are locally inundated by younger mare

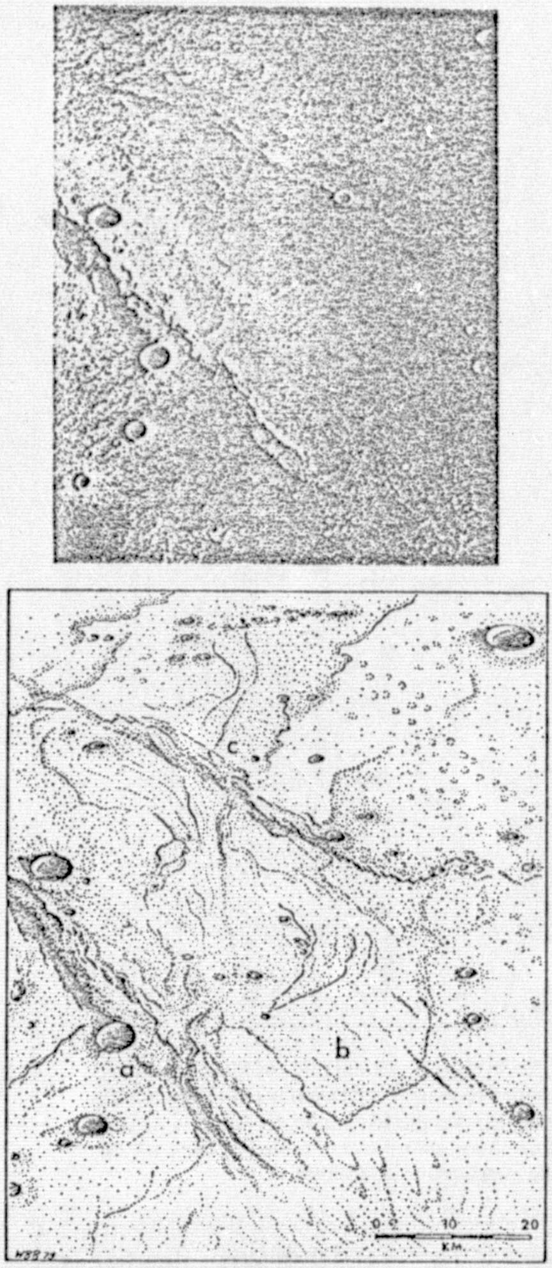

Fig. 2. Oblique view of lava flows and wrinkle ridges on the south side of Mare Imbrium east of Mons La Hire, looking north. A flow originating to the southwest (lower left) crossed the position of a prominent ridge (a), and ponded on the northern (mare) side of the ridge, forming a broad delta (b). The lava broke through the north side of the delta and can be traced across another ridge (c). Note intense crumpling of lava crust on crest of ridges. Apollo Metric photo AS15-1554.

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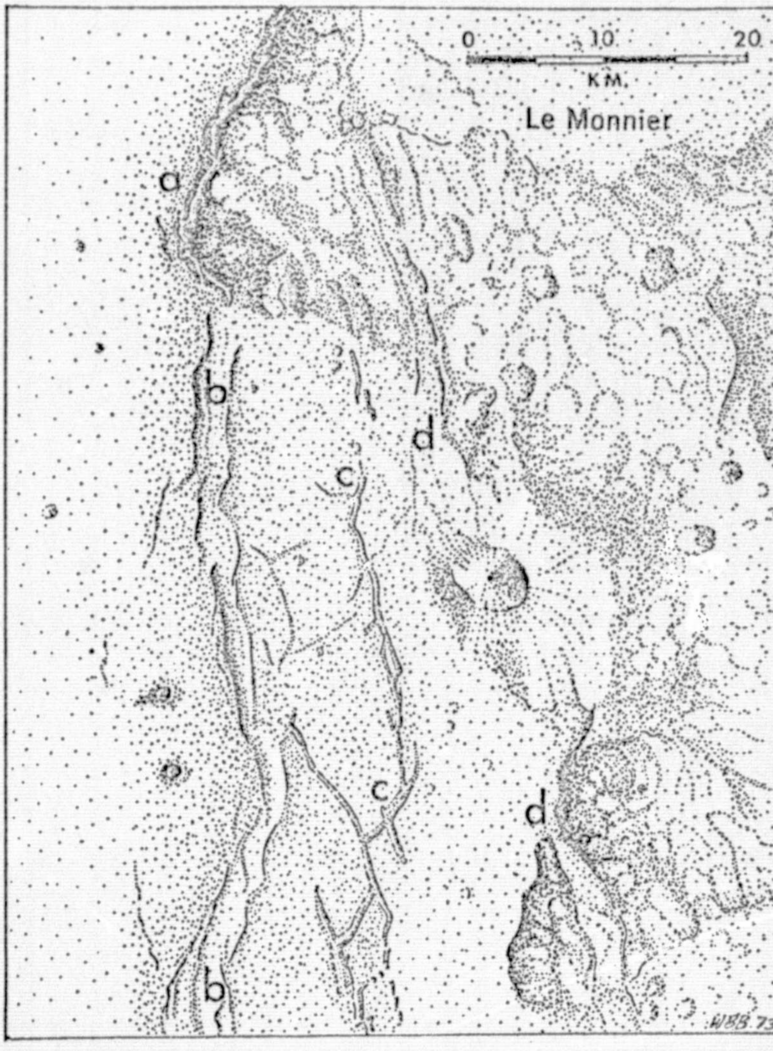

Fig. 3. Mare crust thrust over base of highland slope on the east side of Mare Serenitatis (a). The thrust fault merges to the south with a prominent wrinkle ridge developed in the marginal dark border fill (b). Note tensional (?) fractures in dark fill between the wrinkle ridge and highlands (c), and graben faults in highland which are buried by the dark fill. Sketched from Apollo metric photo AS15-0395.

basalt. A set of angular fractures confined to an area between the highlands and the wrinkle ridge also suggests an episode of tensional deformation affecting only the mare shelf basalt, possibly when it was a thin crust covering still-molten ponded lava. Howard *et al.* (1973) estimated extension of the Serenitatis margin of 0.1 km in a traverse of 37 km, based on measured displacement in the graben faults. They attribute this extension to sagging of the early mare fill toward the center of the basin.

Along the south side of Mare Serenitatis, Apollo 17 metric photography reveals additional details of the mare filling and deformation. Metric photo AS17-0451 shows well-defined wrinkle ridges within the basin, running both parallel and perpendicular to the margin (Fig. 4). The perpendicular ridges terminate approximately at the boundary between the central light fill and the darker border fill, although in low angle lighting they can be seen to extend as low welts across part of the dark margin. Detailed study of the "wrinkles" on the crest of the concentric ridges under 6X stereo observation shows that deformation follows a saw-toothed pattern resulting from tilting and rotation of angular blocks, which apparently have failed along a pre-existing joint set (Bryan and Adams, 1973). The presence of these angular blocks clearly indicates a deformational origin; the rounded, lobate forms of lava domes is not evident in these ridges. There is no indication of linear arrays of craters or other vent-like features along the crests of the ridges, nor is there evidence of graben-like tensional faults on their crests such as were described by Colton *et al.* (1972) in Procellarum.

These concentric and radial ridges divide the crust into roughly trapezoidal blocks around the mare border. This pattern is well-developed on the west and northern sides of Serenitatis as is clearly shown in earth-based telescopic photographs and Orbiter photography. Metric photo AS17-0447 shows that the graben faults which parallel the southern margin of Serenitatis are inundated by a younger lava flow which appears to originate outside the basin and feeds the central, lighter fill (Bryan and Adams, 1973). Other evidence for the existence of at least five flow units in Serenitatis is provided by color contrasts within the central

Fig. 4. Wrinkle ridges in Mare Serenitatis near the southern margin of light central fill are arranged both radial to, and concentric with, the center of the basin. Note graben-like rilles in dark fill and zig-zag pattern in ridge near left margin produced by offsets along angular joint blocks. The dark fill slopes toward the center of the mare. Apollo metric photo AS17-0449.

mare unit (Thompson *et al.*, 1973). These features again provide clear evidence of an early period of marginal deformation which involved tensional extension of the early dark mare fill and highlands as well as basin subsidence. This deformation was partly covered by later mare basalt, indicating that it was coincident with filling of the basin. The latest event was intense compressional deformation that formed wrinkle ridges slightly inward from the margins. Compressional stress was directed both perpendicular to the margin and parallel to it, as indicated by the radial and concentric ridge patterns. Most post-mare impact craters on the wrinkle ridges are undeformed, indicating that the compression occurred soon after the filling of the basin.

Models for Mare Filling and Deformation

The morphological relations discussed above suggest that wrinkle ridges represent the final episode in a series of deformational events that accompany the filling of a mare basin. It is not evident whether the lava was completely solidified at the time of deformation of the crust, or whether the crust was still underlain by liquid lava when it was deformed. However, the weight of evidence suggests that the mare basins were filled relatively slowly by interdigitating, overlapping lava flows, over an extended period of time. This filling by individual thin sheets is indicated for at least the later stages of mare filling by the layering observed in the walls of craters or rilles (for example, Hadley Rille), by morphological evidence for individual lava flows, as in the Imbrium Basin, or by morphological contrasts, albedo contrasts, and color boundaries between flows, as in Mare Serenitatis. Direct evidence for the existence of underlying liquid lava might be provided by the presence of features resembling lava "squeeze-outs" along fractures associated with deformed surface crust. Such features are rarely observed and are not positively identifiable as lava. Certainly, the major part of the mare wrinkle-ridge structures in Mare Imbrium and Mare Serenitatis do not show "squeeze-out" morphology but consist of deformed, pre-existing mare surface crust, as indicated by deformation of lava channels and flow boundaries and displacement along joint surfaces. The restriction of wrinkle-ridge deformation to mare lava probably is primarily due to localization of deformational stress within the mare, and does not necessarily imply that the mare crust is decoupled from the underlying basement by a liquid layer.

That wrinkle ridge deformation results from compression is shown by the intense crumpling along the crests of the ridges, as well as by their overall arch-like form, and by local evidence of overthrusting. Evidence of tensional deformation, such as graben-like faults along the crests of ridges, is not observed. The absence of tensional deformation seems to rule out the possibility that the ridges are formed by arcuate, shallow intrusions of magma, which would arch and stretch the crust. Construction of these ridges by extrusion of viscous lava domes is also not supported by observations. The wrinkle ridges do not show the characteristic morphology of terrestrial lava dome ridges such as those described by Bryan (1966). The bulbous dome morphology and characteristic steep flow fronts are not evident in the wrinkle ridges.

Compressional deformation which formed the wrinkle ridges was directed both perpendicular to mare margins, forming concentric ridges, and parallel to the margins, forming radial ridges. This stress distribution implies shrinkage of the mare basin, such that the surface decreased both in diameter and circumference. On a circular plane surface, of course, these dimensional changes must necessarily be related. On a spherical surface they need not be. An en-echelon pattern of mare ridges is evident in Orbiter photography of the western part of Imbrium and this arrangement also is evident on a smaller scale in many mare ridge complexes. This en-echelon arrangement immediately suggests a strike-slip component in the deforming stress, but may in fact represent simply an alternative response in which a single ridge develops under combined radial and tangential compressional stress (Fig. 5, a and b).

It is difficult to generalize on the total amount of crustal shortening represented by compressional wrinkle ridges because even a single ridge varies greatly in size and intensity of deformation along its length. However, some order of magnitude figures can be given. A major ridge may have a maximum width of 10 km at the base of the arch, with the crestal ridge complex averaging 2–4 km in width. Maximum elevations would be about 500 m for the arch and 200 m for the crestal ridge. The amount of crustal shortening implied by these figures is about 0.1 km for the arch, and about 0.05 km for the crestal ridge, a total of about 0.15 km. Intense crumpling, overturning, and thrusting could, of course, make these figures misleadingly low; but on the other hand most ridges are smaller than this. In particular, where multiple ridges are present, the individual units are relatively smaller. Gentle warping and undulation of mare surfaces may also contribute in subtle ways to crustal shortening which will be difficult to evaluate until detailed topographic maps become available. Overall, it would appear that crustal shortening sufficient to produce each of the ridges observed would be in the range of 0.1–0.2 km. If this shortening is symmetrically disposed on either side of a mare basin, total crustal shortening in the range of 0.5–1.0 km could produce one or two lines of ridges on each side of the mare basin.

Crustal shortening of this magnitude can be produced by collapse of the mare surface on the order of a few kilometers. This arises from the fact that the diameters of the maria are large relative to the spherical diameter of the moon. Collapse can take one of two forms, although in practice there is undoubtedly a combination of the two effects. The first form, which for convenience in later discussion may be called model 1 collapse, is the central sagging implied by the marginal tensional faults and the inward-sloping dark margin of Serenitatis. The second form of collapse, model 2, is uniform vertical subsidence of the mare surface which is displaced relative to bordering highlands along vertical marginal ring faults. For purposes of discussion it is convenient to visualize subsidence along distinct fault planes, although in practice a broader zone of faulting or monoclinal warping would be equally effective. Direct morphological evidence of marginal ring faults is rarely observed. Figure 6 summarizes the geometric parameters required to describe these forms of collapse. Model 1 collapse implies a change in spherical surface diameter in which $D_0 \rightarrow d_0$. The planar surface diameter d_0 represents the minimum diameter which can be attained; central collapse

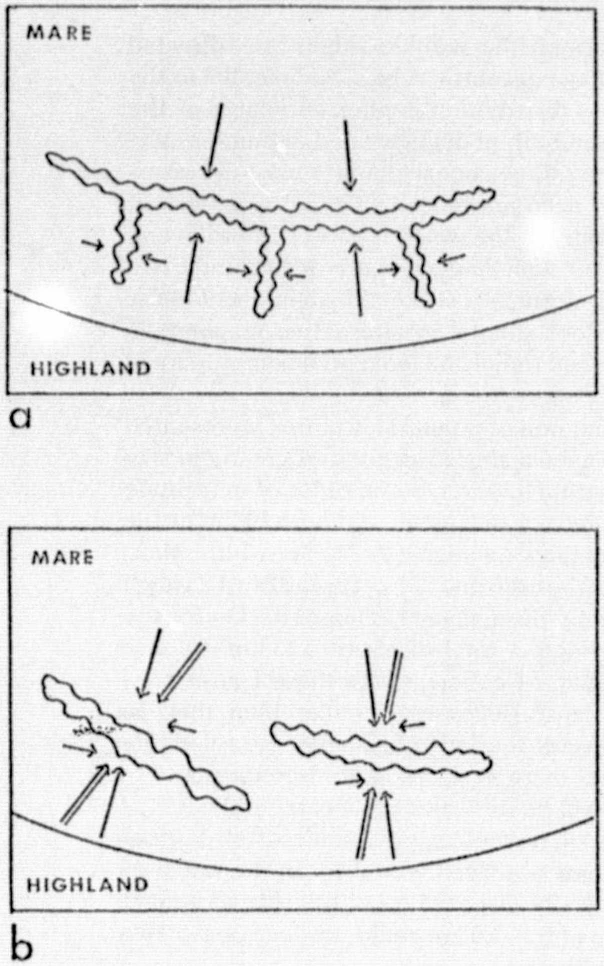

Fig. 5. Alternate responses to combined radial and tangential compression. Arrows represent direction and magnitude of stresses. (a) Direct response producing concentric and radial ridge patterns. (b) En-echelon pattern produced by the resultant vector (double arrow) of the two stress directions.

greater than C_c must lead to increase in surface diameter and consequent extension. Model 2 collapse implies a change in spherical surface diameter in which $D_0 \rightarrow D_c$ with uniform vertical collapse ΔR, and there is the possibility of further central sagging (model 1 collapse) in which $D_c \rightarrow d_c$. The maximum crustal shortening possible is therefore represented by a combination of the two models with $D_0 \rightarrow d_c$.

Order-of-magnitude figures for crustal shortening due to collapse in Mare Imbrium and Mare Serenitatis may readily be obtained, assuming dips of marginal

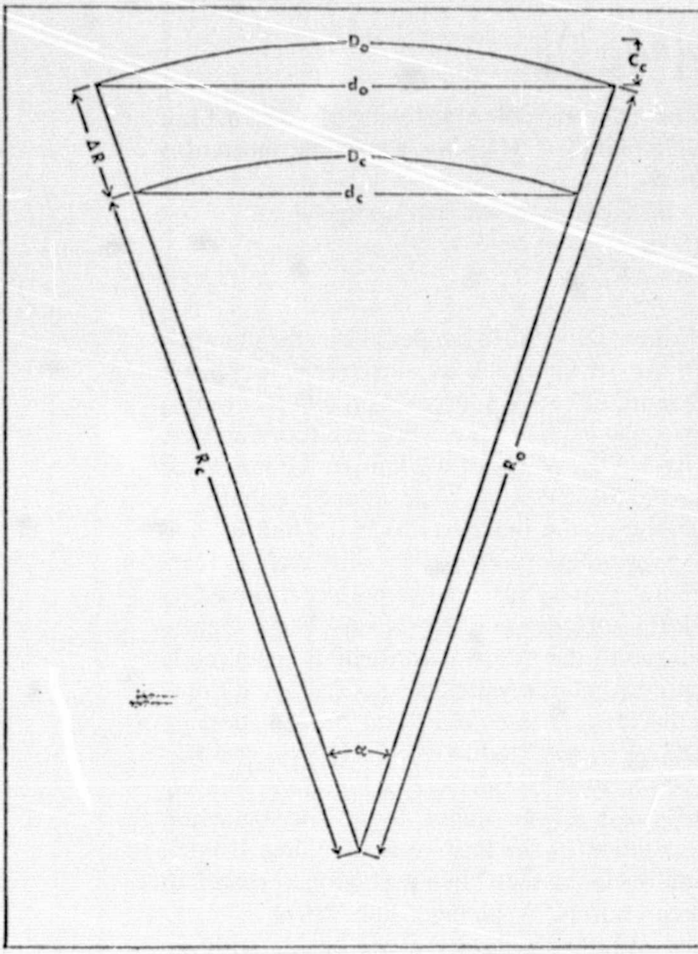

Fig. 6. Geometric parameters for mare collapse models. D_0 = original spherical surface diameter. d_0 = planar surface diameter. R_0 = original spherical radius. D_c = planar diameter of collapsed surface. R_c = spherical radius of collapsed surface. $\Delta R = R_c - R_0$. α = angle subtended by perpendiculars to lunar surface at mare margins. C_c = the vertical component of central collapse.

ring faults approximate local vertical. The apex angle, α, of the inverted cone defined by these faults may be derived from the relations in Fig. 6, as we have

$$\alpha = \frac{D_0}{2\pi R_0} \times 360$$

The effective D_0 will be the spherical diameter of that portion of the mare basin deduced to be involved in subsidence. Taking R_0 as 1740 km, and D_0 as 668.1 km for Imbrium and 546.6 km for Serenitatis gives α Imbrium = 22°, and α

Serenitatis = 18°, adjusted to the nearest degree and 0.1 kilometer. Then,

$$d_0 = 2\left[R_0\left(\sin\frac{\alpha}{2}\right)\right]$$

giving d_0 Imbrium = 664.0 km, or a maximum possible shortening of some 4.1 km due to central collapse; and giving d_0 Serenitatis = 544.3 km, a possible shortening of about 2.3 km due to central collapse.

For crustal shortening due to model 2 collapse we may compute

$$\Delta D_0 = \Delta R \frac{\alpha\pi}{180}$$

It is immediately evident that for Imbrium, $D_0 = -0.38$ km per kilometer of subsidence, and for Serenitatis, $D_0 = -0.31$ km per kilometer of subsidence. It appears that model 2 collapse would be a far more effective source of crustal shortening than model 1 collapse. Model 2 collapse also implies a reduction in circumference, which will be approximately given by $\pi\Delta D_0$, or about 1.2 km per kilometer of collapse for Imbrium and about 1.0 km per kilometer of collapse for Serenitatis.

Subsidence which accompanies filling of the mare basins is implied by evidence cited previously. In practice, severe departures of the mare surface from the equipotential, approximately spherical gravity surface should be prevented by lava fillings which are coincident with the subsidence of the basins. Each successive layer of lava will be accommodated to the deformation which has already taken place, and will record only that deformation which results from additional subsidence following deposition of the lava. It is evident that deformation initiated on older lava may continue and be transmitted to overlying, younger material, as shown by the Imbrium lava flows. Wrinkle ridges once initiated probably tend to remain as preferred zones of stress release unless there is a significant change in the stress pattern during evolution of the basin and its filling. It must also be stressed that subsidence and deformation may have been greater than that inferred here, the evidence having been buried by younger lava flows.

These deformational models apply only to the larger maria basins with associated mascons. The intensity of deformation would be expected to decrease both as the diameter and depth of filling decrease. Small lava-filled basins would be expected to show little or no wrinkle ridge deformation, a relation that is qualitatively supported by Orbiter and Apollo photography. However, many well-developed systems of wrinkle ridges appear in broad areas of presumably shallow mare-type lava cover, as in Procellarum. These regions are not associated with mascons, and deformation may reflect effects other than subsidence-induced compression. Some of these ridge and rille complexes in southern Procellarum recently have been discussed by Young (1972) and by Colton *et al.* (1972). The rectilinear pattern evident in some of these ridge systems may define fundamental zones of weakness in the lunar crust with deformation triggered by tidal forces or other mechanisms no longer operative on the moon. It is possible, then, that these same effects also operated on the deep maria basins and are superimposed on the effects of subsidence compression. It is possible that mare subsidence is only one aspect of a more general moon-wide surface compaction and shrinkage which may represent the last stages of internal recrystallization and consolidation of accreted material.

Marginal tensional deformation which produced the graben rille systems marginal to Mare Serenitatis are probably associateed with a model 1 type of collapse. Although the ultimate effect of model 1 collapse should be compressional deformation concentrated near the mare center, tensional deformation above the marginal hinge line could be expected, especially if the effective hinge line is at a depth of several kilometers. Older grabens are evident in the highlands but are buried under mare fill, while the younger grabens pass uninterrupted from older mare surface into adjacent highlands. This suggests a relatively long period of central sagging of the basin. Continuing impact events must have developed regolith on the uppermost mare flows, and the graben rilles probably represent tensional adjustment of relatively thin regolith to arching of underlying bedrock. Gravity sliding on the inward sloping margins could also contribute to this tensional deformation, and might contribute to crustal shortening associated with wrinkle ridges. Model 1 collapse alone would not be expected to produce significant tangential compression at mare margins, although inward gravity sliding of marginal mare crust implies a reduction in circumference, with the possibility of some tangential compressive stress.

Summary

Morphological relationships suggest that mare wrinkle ridges are formed by localized compression of a relatively thin crust which is effectively decoupled from underlying topography and structure. Since the deformation took place shortly after the mare filling was completed, it is possible that this thin crust was underlain by still-liquid lava. Certainly the thin edges of the mare fill solidified completely and suffered tensional deformation along with the highland basement, which presumably was being warped downward under the increasing weight of mare fill. In Serenitatis, the very earliest episodes of central collapse with marginal tensional faulting took place before filling was complete. The earliest collapse was essentially of the model 1 type, while the later collapse was of the model 2 type. In Mare Imbrium, the initial zones of weakness represented by monoclinal flexures also localized the subsequent compressional failure. These monoclinal flexures imply collapse predominantly of the model 2 type.

The interpretations outlined above have important implications for further gravity modeling of mare fill, as well as for the origin of the mare basins. There is no need to postulate shallow, buried highland-type basement beneath the wrinkle ridges. Nor is there any reason to believe that these ridges represent feeder dikes which may tap deep-seated magma chambers beneath the basins. In fact the available evidence suggests that the source of much, if not all, the mare fill lies outside the basins. It is possible that the basins were enlarged contemporaneously with the inpouring of basaltic magma, due to isostatic adjustment to the load, and may now be much wider and deeper than the depressions in which lava was originally ponded.

Acknowledgments—This research was supported by NASA grant NAS9-12564. C. O. Bowin and J. C. Beckerle provided much helpful discussion during the investigation of mare features and reviewed a preliminary version of the manuscript.

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Proceedings of the Fifth Lunar Conference
(Supplement 5, Geochimica et Cosmochimica Acta)
Vol. 1 pp. 25-34 (1974)
Printed in the United States of America

An interpretation of volcanic and structural features of crater Aitken*

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Abstract—Crater Aitken is one of the few farside lunar craters which shows evidence of mare-type volcanism. In general aspect it resembles the larger crater Tsiolkovsky, apparently having been excavated by impact and later flooded by a dark, mare-type fill. Ventlike features considered to be of volcanic origin are common in this fill; they include irregular, trench-like pits and both clustered and individual subcircular cones 6–8 km in diameter. These cones tend to fall into one of two categories: breached cones showing an internal "high lava mark" and a lower hummocky central fill; and closed cones with an internal "high lava mark" and a lower smooth or gently undulating central fill. Sinuous ridges associated in part with these cones are considered to be surface expressions of late-stage faulting in loose regolith rather than lava flows. These ridges deform impact craters but are rarely deformed by younger impacts, indicating their relatively recent origin. The ridges can be traced from the mare fill into the walls of Aitken, and similar ridges are observed in highland craters near Aitken. The ridges are oriented predominantly north–south and probably result from faulting due to east–west compression. Eruptive activity within Aitken probably commenced with an explosive cone-building stage, followed by lava eruptions from cones and fissures, and ended with drain-back restricted to the relatively deep lava ponded in the vents.

INTRODUCTION

CRATER AITKEN is located at 17°S and 173°E, east of Tsiolkovsky on the lunar farside. Several sets of Apollo 17 metric and panoramic photographs at favorable sun angles were taken on orbits which passed almost directly over the crater. Like Tsiolkovsky, Aitken appears to have been excavated by a moderately large impact event, and the floor of the crater was later flooded by a dark mare-type fill (Fig. 1). The probable impact origin and the principal volcanic features as seen in metric photography were discussed briefly by El Baz (1973) and by Bryan and Adams (1973). In this paper we report more detailed observations from study of panoramic photography which suggest that there has been significant late-stage compressional deformation of the crater and adjacent highlands. We have presented an admittedly speculative interpretation of eruptive activity and drain-back events within Aitken, which leads to the conclusion that hummocky topography within certain cones represents collapsed lava rather than extrusive domes.

AITKEN CRATER FLOOR

The albedo and cratering of the dark fill in Aitken resembles the surface of the nearside maria. Craters are sharply defined and are generally less than 2 km in

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*Contribution No. 3216 of the Woods Hole Oceanographic Institution.

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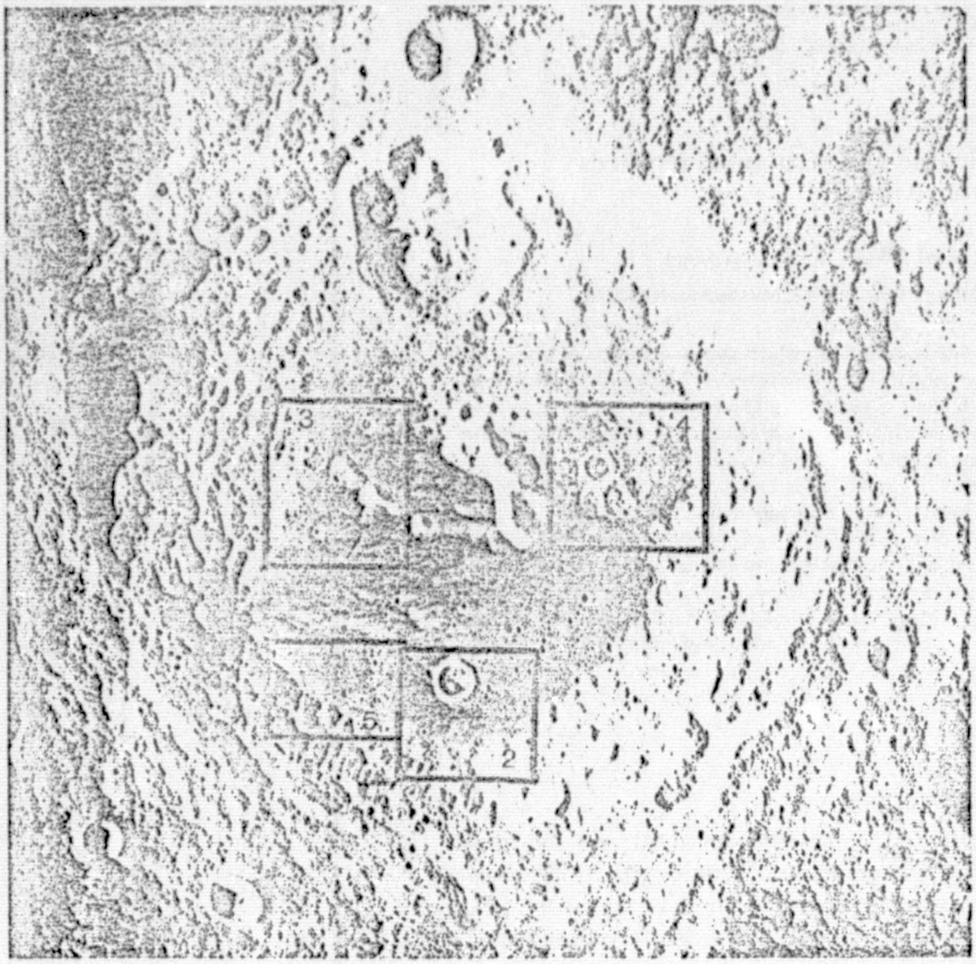

Fig. 1. General view of crater Aitken. Note hummocky chaotic floor, terraced inner walls, and raised central peak, features suggestive of impact origin. Numbered areas represent detailed figures from panoramic photography. AS17-M481

diameter; most are much smaller than that. The floor along the north side of Aitken (Fig. 1) not covered by the dark fill is more heavily cratered and includes larger impact events. There is more evidence of degradation of older craters, indicating that this surface may be distinctly older than the dark fill.

The most conspicuous craters on the Aitken dark fill are about 6–8 km in diameter. Several craters contain a distinctive hummocky central fill. The conspicuous crater near the south margin of the floor (Fig. 2) is almost perfectly circular in plan and is unbreached. Within the crater there is a conspicuous "high lava mark" (arrows). The level of this mark is about at the level of the surrounding fill, as indicated by stereoscopic parallax measurements. No comparable mark is evident on the outer walls of the crater, or along the margin of the dark fill where it

Fig. 2. Circular crater in mare fill near south side of Aitken floor. Crater is unbreached and shows an internal, but no external, "high lava mark" (arrows). Note general absence of impact cratering on the raised crater rim, and the drowned "ghost" crater (G) suggesting a very shallow fill along the south margin of Aitken. There is no "high lava mark" on the Aitken wall. AS17-P1917

meets the Aitken Crater wall. The varying illumination angle within the crater shows a difference in albedo and a distinct break in slope at this high lava mark. The lower central fill has an undulating surface slightly modified by small impact events.

Craters on the northwest side of the Aitken floor (Fig. 3) are more irregular in outline. They contain the same internal "high lava mark" and the floors are smooth or slightly undulating and pitted by minor impacts. Again, there is no indication of "high lava marks" on the outer walls of the craters or along the margin of the Aitken fill. Here, as can also be seen in Figs. 2 and 5, buried ghost craters in the old floor show through the dark fill. This indicates the very shallow depth of fill over most of the Aitken floor, and the lack of any detectable topographic boundary on the margin of the dark fill suggests that it was very fluid

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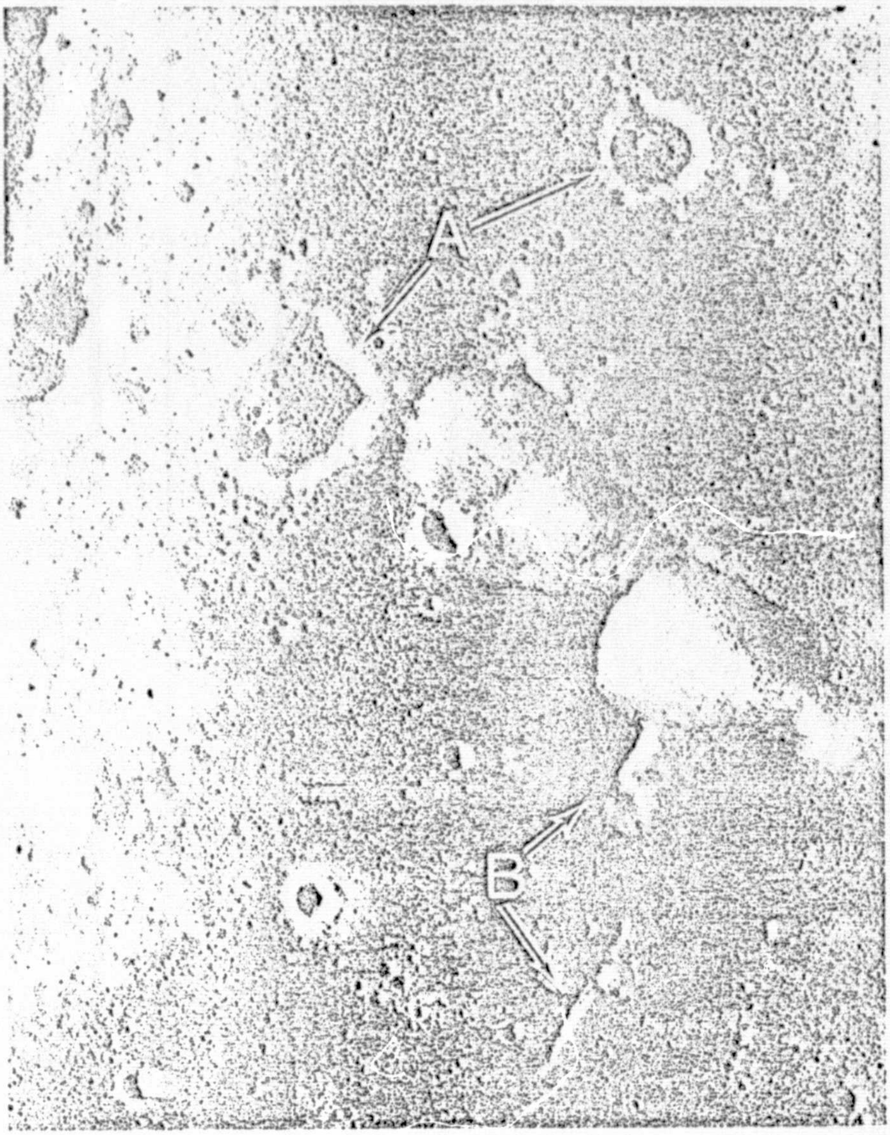

Fig. 3. Irregular craters on the northwest floor of Aitken (A), showing internal "high lava mark" and undulating central fill. Riftlike depressions (B) probably were formed by drain-back into fissure vents. AS17-P1919

and spread out virtually to a "feather edge" without forming an appreciable marginal scarp.

To the south (Fig. 3) there are two lizard-shaped depressions, which may represent the locus of drain-back into an underlying fissure. Although the northern depression terminated against one of the hills protruding through the fill, there is no evidence to suggest this hill is a volcanic cone. El Baz (1973) suggested that these hills might represent part of an incipient igneous ring complex, but it seems more likely that they represent post-impact rebound of the central portion of the floor. The volcanic fissure may follow a line of weakness related to this rebound.

The cluster of five craters in the northeast part of the floor (Fig. 4) displays the "high lava marks" and the smooth to undulating central fill described previously. The nesting of these craters, without overlap or interference between them of material forming their walls, suggests that they were formed essentially simultaneously, a relation that is easiest to understand if they are volcanic craters which were active together over a period of time. The northernmost crater (A) is nearly circular in plan, is completely enclosed, and shows a faint "high lava mark" and a relatively smooth central fill, resembling in these respects the craters on the south and northwest sides of the floor. Three other craters (B, C, D) are breached or partly flooded. They show distinct internal "high lava marks"; that in (B), Fig. 4, can be traced around to the breach in the crater wall, where it merges with the surface of the marelike fill outside the crater. The breached craters all have a distinctive hummocky central fill, which appears to consist of a cluster of domes. The highest parts of these domes extend up to or just below the level of the internal "high lava mark." A fifth crater (E) is a conical pit with a deeper dome-like central fill and also a suggestion of an internal "high lava mark." As in the other examples discussed, there are no external "high lava marks," and ghost craters (F) indicate that the external mare fill is very shallow.

Recent Deformation

Fine-scale sinuous ridges and scarps are associated with margins of the dark Aitken fill on the southwest and northeast sides of the floor (Figs. 4 and 5). Those at C in Fig. 4 appear, on casual examination to be related to a breach in the wall of the adjacent crater and thus might be lava flow margins. However, closer inspection shows that these ridges are not symmetrically disposed with respect to the breach, as they should be for a flow extending from the breach. The scarps instead run diagonally across the breach, and one extends up and over the rim of the cone. Both scarps face westerly; thus they are not boundaries of a flow surface elevated between them. Similar ridges associated with a partly drowned crater (A, Fig. 5) on the southwest side of Aitken extend from the dark fill into the lower slopes of the enclosing walls of Aitken (B, Fig. 5).

Similar relations can be observed on the fill margin and lower walls on the eastern side of Aitken (H, Fig. 4). In this case, the scarps face east, run along the margin of the fill, and continue up into the lighter colored crater wall material. Locally, these scarps run through impact craters but there is no tendency for material related to the scarps to pond in craters; rather, the scarp offsets and deforms the craters. These scarps can be traced in the crater wall for a distance of over 80 km along a line running approximately NNE–SSW. We believe these scarps represent recent compressional deformation, as described by Howard and Muehlberger (1973), because they do not show the proper geometric relation to

Fig. 4. Crater cluster on the northeast side of Aitken floor. Unbreached northern crater (A) shows a faint "high lava mark" and smooth inner floor. Breached craters (B, C, D) show hummocky inner floors and "high lava marks." Conical crater (E) shows small domelike fill and faint suggestion of a high lava mark. Ghost craters (F) imply a very thin external fill. Sinuous ridges (G) are low scarps which can be traced across the breached opening of crater (B) and into (E). Similar scarps (H) run along the margin of the dark fill and into the walls of Aitken. Composite of AS17-P1915 and AS17-P1918

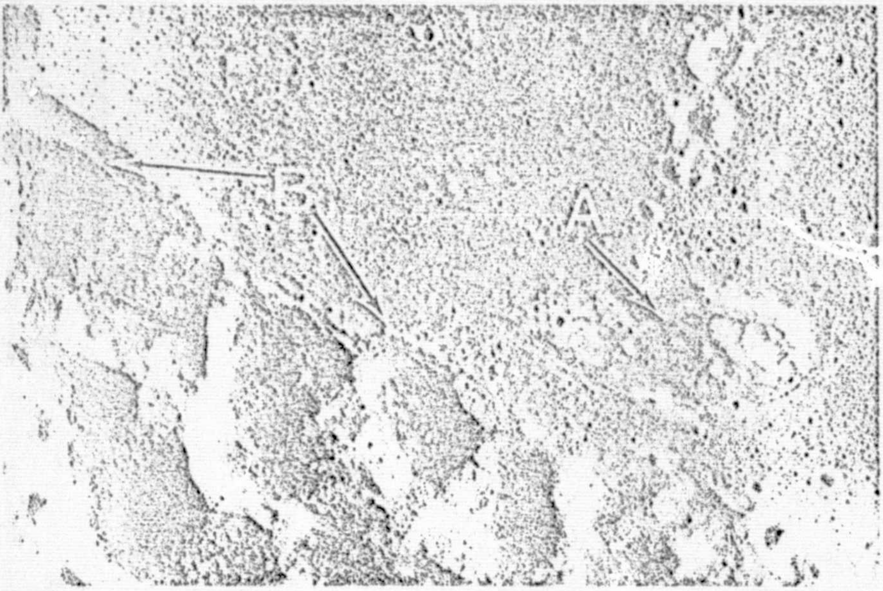

Fig. 5. Partly drowned crater with internal "high lava mark" and hummocky central fill (A), and scarp due to thrust-faulting (B) on the southwest edge of Aitken floor. AS17-P1919

possible vents; they traverse material of varied albedo and texture; they extend into the walls of Aitken Crater, and they deform impact craters but are not formed by impact.

Similar deformation is present in the highlands outside Aitken Crater. A crater about 80 km NE of Aitken (Fig. 6) is traversed by scarps which run across the floor and up the walls. These scarps may represent faults related to a set of imbricate thrust sheets. Again, the deformation appears younger than most impact events, but there is evidence of some impact following the deformation (A, Fig. 6). El Baz (1973) interpreted these scarps as possible margins of impact blankets originating from Aitken. We do not believe these scarps are related to impact blankets because they appear very young, and deform preexisting craters. As El Baz noted, if these are flow fronts, they imply flow from the west rather than from the south–southwest, which is the direction radial from Aitken.

Volcanic Events in Aitken

If the circular craters and crater clusters in Aitken are of volcanic origin, it should be possible to account for the variety of features observed in terms of some logical sequence of volcanic episodes. It is necessary to account for the following observations:

(1) There are at least three types of possible vents—circular cones with smooth floors, breached cones with hummocky floors, and irregular depressed rifts.

Fig. 6. Fault scarps in a highland crater northeast of Aitken. Note the impact crater (A) which postdates deformation. AS17-P1676

(2) Most of the cones show an apparent "high lava mark" which is near the level of the external mare-type fill.

(3) "High lava marks" do not appear on the inner walls of Aitken Crater or on the outer flanks of the cones within the dark fill.

(4) Existence of "ghost" craters over most of the floor, and especially near the cones, suggests that the mare-type fill is very thin.

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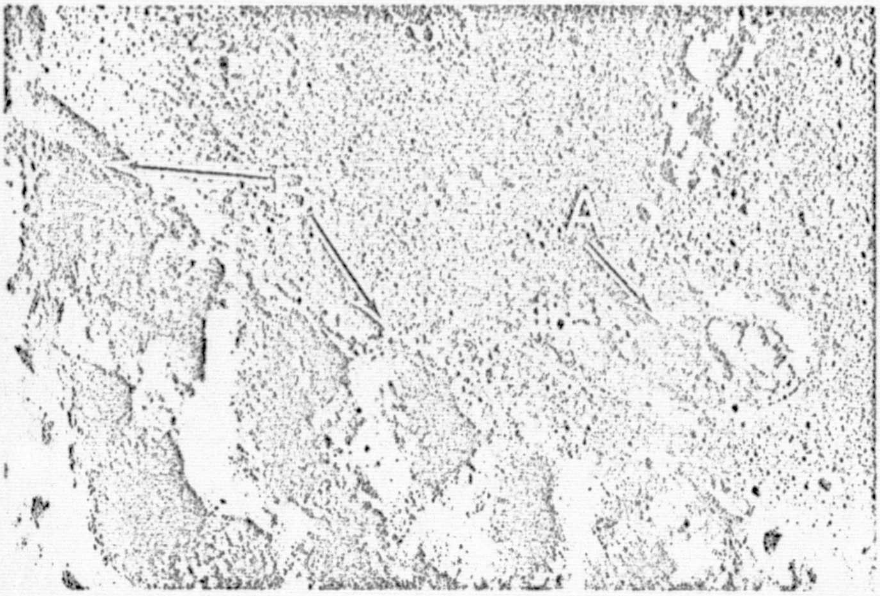

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Our interpretation of volcanic events in Aitken rests heavily on the recognition of supposed "high lava marks" within certain craters. We wish to emphasize that similar features have been observed in Apollo photography of many other areas of the moon, and are not restricted to Aitken. Although we believe that many of these features are indeed related to changing lava levels, the varied circumstances in which they occur demands that each case be interpreted individually. Recently, we have examined modern examples of "high lava marks" in the vicinity of Kilauea volcano, Hawaii, and these also appear in a variety of circumstances. Those appearing in pit craters due to vertical rise and fall of lava tend to be continuous and of uniform upper elevation, while those associated with margins of large lava flows tend to be discontinuous and of varying elevation, reflecting temporary blocking or ponding of the flow. Many of these "high lava marks" initially consist of distinct horizontal terraces which tend to collapse with time, so that their lower slopes develop a series of coalescing talus fans which may tend to bury marginal portions of the adjacent flow. Close examination of some of the Aitken cones suggests development of talus at the base of the inner walls below the "high lava marks."

We believe the following outline of volcanic events can explain the morphological features observed in Aitken.

The first activity consisted of explosive eruptions which built cinder cones on the northeast, south, and northwest sides of the Aitken crater floor. Subsequently, certain cones became sites of lava eruption; their walls were breached, and they supplied fluid lava which flooded the crater floor. At this time the fissure vents on the west side of the floor may have become active. Those cones which were not lava suppliers may have continued to erupt explosively. As the fill reached its present level, explosive eruptions ceased. New lava welled up in the cones which previously had been sites of explosive activity, and equilibrated with the level outside the cone. These cones were not breached because the lava pressure was equalized on both sides of the wall of the cone. The final event was withdrawal of lava in the craters to its present level. The newest lava in the previously explosive cones had the thinnest crust and thus subsided evenly. The older lava in the breached cones had a thicker crust which collapsed unevenly, giving the pronounced hummocky surface observed in these cones. There was no appreciable drain-back from the main Aitken lava lake into these vents, because the thick crust blocked the breach in each of the cones; only the relatively deep ponded lava within the cones was capable of significant drain-back. Probably most of the Aitken fill was built up by thin overlapping flow sheets, each of which was nearly crystallized before being buried by the next. This also would prevent drain-back into the vents. The irregular depressions may have been formed by collapse of the solid crust into a void left by drain-back of a small amount of lava in the underlying fissures.

Although we believe this interpretation is plausible when compared with volcanic events observed at terrestrial volcanoes, the scale of the phenomena is almost an order of magnitude greater. This scale problem has been noted by Hodges (1973). The 6–8 km diameter of the Aitken cones with their ponded lava is impressive by terrestrial standards. The Diamond Head tuff cone, for example, is about 1 km in diameter; the caldera of Kilauea is about 3 km rim-to-rim; the Halemaumau pit crater and other Hawaiian pit craters which show many of the drain-back features described in the Aitken craters, are .5 km or less in diameter. McGetchin and Head (1973) have shown that the relatively large scale of lunar cinder cones may be related to the lower gravity field of the moon.

CONCLUSIONS

The dark fill in Aitken probably originated in eruptions from breached cones and fissures widely distributed over the floor. A reasonable series of volcanic events can be postulated which adequately accounts for the "high lava marks" within these craters as described by El Baz (1973). Flowlike features associated with these cones, and also observed in the Aitken walls and adjacent highlands, appear to represent surface traces of reverse faults, as described by Howard and Muehlberger (1973). We believe the bunlike features enclosed within certain breached craters in Aitken represent irregular collapse of thick lava crust, rather than viscous extrusions.

Acknowledgments—This research was supported by NASA grant NAS9-12564. We would like to thank C. O. Bowin, R. D. Ballard, Carle Pieters, and R. A. Young for critical comments on the manuscript.

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Proc. Lunar Sci. Conf. 6th (1975), p. 2563–2569.
Printed in the United States of America

Volcanic and tectonic evolution of crater Goclenius, western Mare Fecunditatis*

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Abstract—Crater Goclenius was probably formed by impact at about the beginning of the period of volcanic activity that flooded Mare Fecunditatis. The shape of the crater was influenced by preexisting fractures which conform to the lunar grid system, and was further enlarged and shaped by tectonic subsidence preceding and accompanying volcanic activity within the crater. Evidence for this volcanism includes a dark, mare-type fill on the crater floor; dark halo craters; and rilles, pits, and craters which show evidence of structural control. This volcanism probably coincided with the period of flooding of Mare Fecunditatis. Subsidence of the basalt-filled mare basin caused tensional stresses on the margin which produced graben subsidence along the fracture set tangent to the margin of the basin.

INTRODUCTION

CRATER GOCLENIUS is one of a number of craters on the lunar nearside which are characterized by an internal dark, fractured floor. Most of these craters lie well outside the photo coverage obtained on the Apollo missions. Goclenius was included in an excellent oblique photo taken on Apollo 8 (Fig. 1) and is just within the southern limit of the Apollo 16 metric and panoramic photo coverage. Goclenius appears unusual in that the pattern of the crater walls and of the internal fracturing in the floor are parallel to, and in some cases continuous with, external tectonic lineaments which correspond to the so-called "lunar grid." Many small craters within the floor also are localized by, or aligned parallel to, the principal fracture trends. Impact, volcanism, and tectonic events apparently have all played a role in the evolution of Goclenius. In this paper we attempt to evaluate the relative roles of these processes and their sequence of occurrence.

Goclenius is located at 10°S, 45°E near the point of convergence of a prominent set of rimae, of which the central member, Rima Goclenius II, is the most prominent. Rima Goclenius II can be traced into the crater and across its floor. Baldwin (1971) was able to document the graben-like form of the rima and to estimate the amount of subsidence of its floor. These relations have been confirmed by our stereoscopic observations using Apollo 16 metric photography. Kopecky (1972) briefly mentioned Goclenius as a possible lunar analog to the central intrusive complexes of Scotland.

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Fig. 1. Oblique view looking southwest across Goclenius. Rima Goclenius II and minor parallel grabens can be seen at right. Note rectilinear form of the crater, which is reflected in terraces on the crater walls, AS8-2225-E.

Form and Regional Relations of Goclenius

The close relationship between the location and outline of Goclenius and the location and orientation of the rimae is indicated in Fig. 2, an outline sketch traced from Apollo 16 metric photography. The relatively straight inner northeastern wall of Goclenius coincides with the southeasterly extension of the outermost pair of rimae which parallel Rima Goclenius II (5F to 4G in Fig. 2). The relatively straight inner southwestern wall of Goclenius follows the southeasterly extension of the faint rima running from Gutenberg to Goclenius. This latter lineament (Rima Gutenberg) converges on Rima Goclenius II near the southernmost part of the Goclenius floor, which also is a major point of intersection of minor rimae within the crater floor. Step-like terraces on the northwestern wall of Goclenius also are linear and nearly perpendicular to Rima Goclenius II. This relationship is most clearly portrayed in Fig. 1, in which the low-angle lighting brings out the linear, step-like terracing on this wall (to the right in the figure) and on the southwestern wall (far wall in the figure) and emphasizes the abrupt angle between these trends. The southern wall swings around the southeastern extremity of the crater in a

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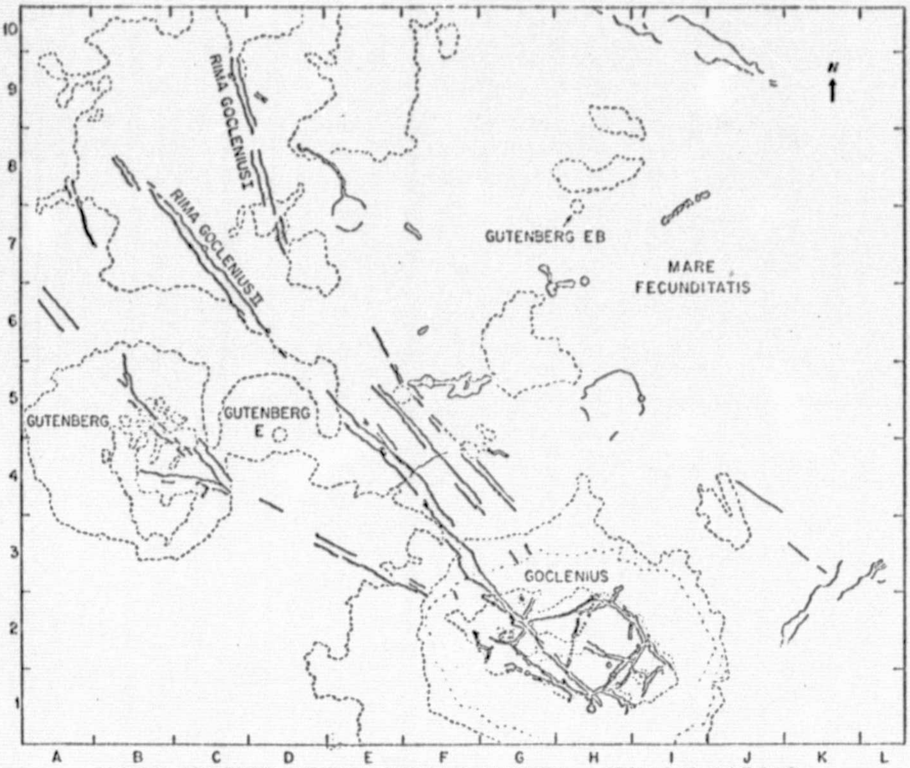

Fig. 2. Sketch map of major craters and linear features in western Mare Fecunditatis. Heavy solid lines = trace of scarps and margins of rilles: light solid lines = traces of minor lineaments and craters; dashed line = boundary between mare-type and highland type surface; dot–dash line = crest of rim deposits around Goclenius. Based on metric photos AS16-0417 and AS16-0418.

relatively sharp curve, giving Goclenius overall the form of a distorted ellipse, measuring about 63 km along its major axis, and 44 km along its minor axis.

The trends of Rimae Goclenius I, Goclenius II, and Gutenberg range between 306° and 340°, thus approximating one of the prominent trend directions of the lunar grid systems as outlined by Fielder (1963) and others. The general 40°–50° trend of the north wall of Goclenius approximates the second prominent direction of the lunar grid, although there are no major lineaments outside the crater in this direction. However, both directions are represented by minor lineaments in Mare Fecunditatis east and north of Gutenberg EB (8I, 10I, Fig. 2), and immediately east of Goclenius (3K, Fig. 2).

Goclenius is surrounded by a low, hummocky rim not unlike that associated with other subdued craters of similar size generally thought to be of impact origin. The rim facies are broadest north and south of the crater and are almost absent at the northwest and southeast extremities of the crater. An irregular elongate, hummocky hill projects through the dark fill in the south-central part of the crater floor, and resembles hills which also have been attributed to rebound of the floor in craters of impact origin.

The Inner Floor of Goclenius

The relatively smooth, dark inner floor of Goclenius is very similar in albedo and density of cratering to the surface of Mare Fecunditatis. In the stereoscopic image it is clear that the dark floor is domed upward in the center of the crater, although the overall elevation is distinctly below that of the surrounding mare surface. As in the case of the dark fill in Aitken (Bryan and Adams, 1974), the boundary of this fill is not distinct but appears to "soak" into the base of the crater walls and central hill.

The dark floor is traversed by a set of rille-like fractures and elongated pits in a kite-shaped pattern that approximately parallels the outline of the crater walls (Figs. 3 and 4). The most prominent of these rilles is a graben-like extension of Rima Goclenius II. It traverses the northwestern crater rim (8A, Fig. 3), the dark fill, and the central hill, narrowing and terminating at a complex group of pits and intersecting rilles on the south edge of the floor (12, Fig. 3).

Dark halo craters are located at the northwestern margin of the floor (1, 2, Fig. 3). Three small craters in the same area (3, Fig. 3) appear to have slightly built-up rims. Another area of higher albedo (4, Fig. 3) shows an unusually high concentration of pits and hummocks. Bounding rilles give this area a subcircular outline, more evident in photos than in Fig. 3, suggestive of an underlying partly buried crater 8–9 km in diameter, about the size of inner craters with hummocky floors reported in Aitken (Bryan and Adams, 1974). Other craters have a low albedo similar to that of the fill, are located either on or close to rille intersections, follow lines parallel to rilles, or lie on projected trends of rilles (5, 6, 7, and 8, Fig. 3). Rather complex relations appear along the northeast margin of the floor. The rille marking the approximate boundary of the floor has been uplifted on its inner side, and outward-dipping layering can be detected in the stereo image of the outer wall of the rille. Pits along the margin of the floor (9, Fig. 3) also closely follow the trend of this rille. The outer crater at 10, Fig. 3 lies within the wall material and has a subdued, built-up rim, while the inner crater on the edge of the dark floor is very bright and sharp, and appears very fresh. At 11, Fig. 3, mounds of high-albedo fill cover part of the rille extending from 10 to 12; craters on this fill are located along the trend of the rille. Pits and short rille segments extend into the base of the wall deposits (12, Fig. 3) on the southern edge of the floor. There is no evidence of extensions of Rimae Goclenius II and Gutenberg into the south rim beyond this point. Cusp-like margins along the rille at 13, Fig. 3, are suggestive of a line of pits localized along the rille.

Discussion

The manner in which Goclenius conforms in shape and dimensions to the trends and distribution of the rimae; the dark mare-like fill on its floor; and the apparent structural control on the location of many craters and rilles on its floor;

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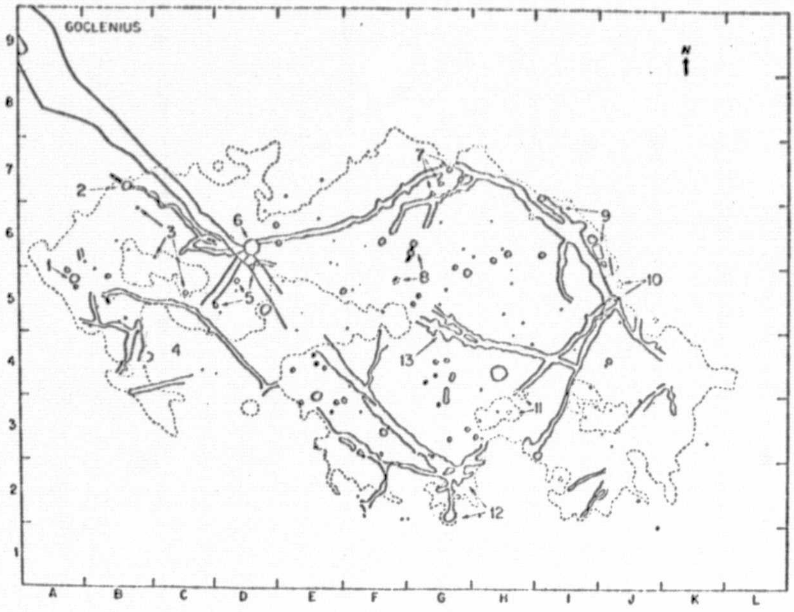

Fig. 3. Sketch map of features on the floor of Goclenius. Compare to Fig. 4 for details. Dashed line = boundary between dark fill and rim material or central peaks. Numbered features are discussed in text.

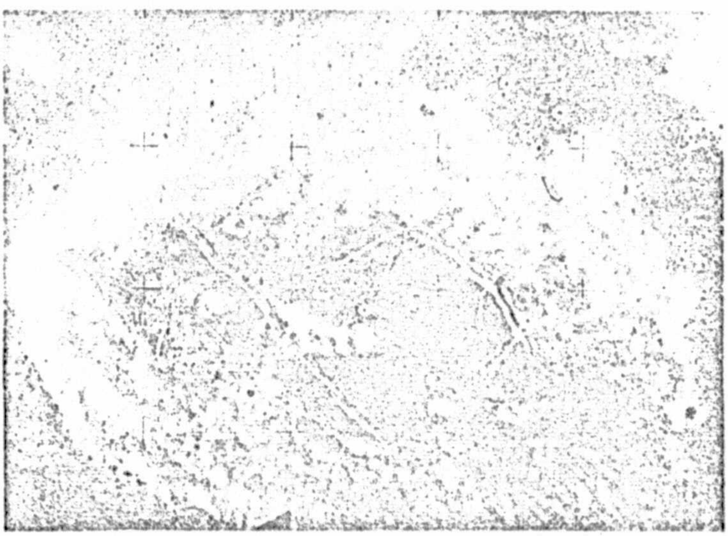

Fig. 4. Vertical view of Goclenius, showing pattern of rilles and albedo variations on crater floor. Metric photo AS16-0417.

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all strongly suggest an internal (presumably volcanic) origin for the crater. Murray and Guest (1970) concluded that impact craters tend to be distinctly circular, regardless of size, while volcanic calderas and ring structures become less circular as their size increases. However, it has also been shown that preexisting structural lineaments may influence the form of impact craters, giving them a polygonal rather than perfectly circular form (Guest, 1971). If Goclenius is an impact crater influenced by preexisting structures, it is surprising that craters Gutenberg and Gutenberg E are not shaped by the same rimae which apparently delineate Goclenius (Fig. 2). A possible explanation would be that the structural lineaments postdate Gutenberg but predate Goclenius. The somewhat fortuitous location of this impact event, centered near the intersection of Rima Gutenberg with Rima Goclenius II and its adjacent rimae, may have made Goclenius a more favorable site for post-impact volcanism and volcano–tectonic collapse. We suggest that these later events initially triggered by impact have enlarged and modified the original crater along the predominant existing fracture patterns in the adjacent lunar crust. If this interpretation is correct, an appreciable amount of rim material may have subsided into the crater toward the northeast and southwest extremities, thus accounting for the relative lack of rim deposits at those locations.

The overall dome-like morphology of the internal dark fill suggests that it may have been built up as a broad shield volcano within the floor. Rilles and lines of pits extend north, south and west from the central high point near the west end of the light-colored central hill (5F, Fig. 3). These may represent master feeder tubes which distributed lava over the floor. The pits at 8 and 13, Fig. 3, may be collapsed tumuli as described by Greeley and Hyde (1973). The dark halo craters at 1 and 2, Fig. 3, are suggestive of cinder cones associated with ash eruptions, and appear to be localized on the extension of Rima Gutenberg and by the small rille adjacent to Rima Goclenius II. Pits at 6, 7, 9, 10, and 12 also show indications of structural control. It seems unlikely that all of these craters would be so fortuitously located along rilles or at rille intersections if they are of impact origin.

The light cratered mound (11, Fig. 3, also Fig. 4) which overlaps the rille near the south side of the crater may be an ash cone built up over the rille. Possibly the central hill, which also appears to be the source of rilles near 13 in Fig. 3, has a similar origin, but there is no direct evidence for this. The dark floor has been differentially uplifted along the moat-like marginal rille at the base of the northeast wall. Schultz (1974) has noted that annular depressions associated with fractured crater floor are usually best developed on the side facing the adjacent mare basin. He attributes this fact to fracturing and uplift due to intrusion of mare magma beneath the crater floor, an explanation which appears to fit the relations in Goclenius.

The graben faulting associated with Rima Goclenius II crosscuts rim and floor material in Goclenius and thus must be one of the latest events in the evolution of the crater. Because the rimae appear to have controlled the shape of the crater during collapse of the walls and have also apparently localized some volcanic events within the crater, these grabens must have developed over preexisting deep-seated fracture trends in the crust. It seems unlikely that these fractures were produced by the impact that formed Goclenius, because they are not symmetrically disposed relative to the crater, and they extend some 250 km to the northwest of it. Instead, they appear to represent a set of the pervasive northwest-trending ancient fractures related to the lunar grid system. The northeast-trending fracture set has influenced the trend of the north wall of Goclenius, and may have controlled some of the cross trends in the fractured inner floor. We suggest that, with the filling of Mare Fecunditatis, isostatic down-warping of the mare produced tensional stress across the northwest-trending fracture set tangent to the margin of the basin, while the complimentary northeast-trending set was not affected by this stress. This implies also that the postulated volcanic activity in Goclenius was contemporary with the filling of Mare Fecunditatis. It is possible that the Goclenius impact even coincided with the beginning of the major volcanic episode which filled Mare Fecunditatis, and Goclenius therefore continued to participate in the volcanic and tectonic events associated with that filling.

Acknowledgments—This research was supported by NASA grant NAS9-12564. We thank C. O. Bowin and P. H. Schultz for valuable criticism of the manuscript.

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PART C

SOME VOLCANIC AND STRUCTURAL FEATURES OF MARE SERENITATIS

W. B. Bryan[a] *and Mary-Linda Adams*[a]

Relationships between volcanic and structural features along the southern edge of Mare Serenitatis can be examined in detail because of the favorable low-angle lighting in the Apollo 17 photography. Metric camera photographs enlarged 2X were observed at 1X or 6X magnification. Relief was estimated from parallax differences, assuming a nominal spacecraft elevation of 110 km and a mean photographic scale of 0.7 km/mm.

This section includes a summary of observations of (1) contact relations between the dark border material and the central mare fill, (2) a late-stage lava flow with associated cinder cones, and (3) certain structural features related to the development of the mare basin and its associated volcanic landforms. The section is concluded with a chronologic summary of volcanic and structural events that we believe are critical to understanding the development of Mare Serenitatis.

DARK MARGIN AND CENTRAL MARE FILL

In figure 30-9, the contact relation between the light central fill and the marginal dark border fill is clearly shown. In addition to the obvious albedo difference, a contrast in surface texture is evident. Impact cratering and ridges on the light central fill appear crisp, whereas many craters, ridges, and rilles in the dark border appear softer and more subdued. The boundary between the light and dark fill corresponds to a distinct break in slope and has the general character of a shoreline. The relatively flat, smooth surface of the light-colored material enters small embayments in the inclined, undulating surface of the dark border material. A crater, approximately 10 km in diameter (lower center, fig. 30-9), is partly inundated by the light central fill, which has left a "high lava mark" on the inner wall of the crater. No evidence of fracturing or buckling of mare material is apparent along the albedo boundary, as would be expected if it were a structurally produced hinge line.

The dark fill in and near the Apollo 17 landing site is topographically lower than the dark border fill on the southern side of Mare Serenitatis. We have been unable to identify faults of sufficient magnitude to account for this elevation difference. The dark mantle on highland material in this area is not as conspicuous in these low-Sun-angle photographs as it is in the

FIGURE 30-9.–Southern margin of central light fill in Mare Serenitatis. Note sharp to degraded tensional faults in dark border material, concentric and radial wrinkle ridges in light mare material, and subdued extension of radial wrinkle ridges into dark border material (Apollo 17 metric camera frame AS17-0451).

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Apollo 15 photographs, which were made at a higher Sun angle.

LAVA AND EXTRUSIVE VENTS EAST OF DAWES CENTER

On the southeastern side of Mare Serenitatis (fig. 30-10), graben fractures in the dark border are buried beneath lighter colored mare material, evidently a late-stage flow, which appears to have originated outside the mare and flowed down the sloping dark border surface, following a shallow depression in this surface. This flow appears on the lower left side of figure 30-10. Howard et al. (part A of sec. 29) have called it the Dawes basalt. Two rille-like features on its surface converge on a line of four vents 1 to 2 km in diameter.

Two of these vents (B in fig. 30-10) are cones distinct in their morphology from the many small impact craters of similar diameter adjacent to them on the Dawes basalt surface. The northern cone is breached on its downslope side, as would be expected of a cone serving as a vent for lava flow. A very faint, rille-like channel can be traced for approximately 10 km downslope from this cone. Both this cone and the larger southern cone are distinct, raised mounds with rounded rims and crater floors that are above the general surface of the surrounding basalt. Internal and external slopes are approximately equal. These features are typical of terrestrial volcanic cinder cones, in which the cone is a positive addition of material composed of ejected debris around a relatively small central vent. In contrast, the nearby small impact craters are steep-walled, conical pits with sharp rims and outer walls sloping much more gently than the inner walls; they are predominantly negative relief features representing excavation and dispersion of surface material. Applying these criteria, we feel confident that these two cones are extrusive volcanic features. The larger southern cone, approximately 1.5 km wide at its base and approximately 300 m high, is almost identical in size and shape to Sunset Crater in Arizona (ref. 30-6). The northern cone is slightly smaller, measuring approximately 1 km across its base and approximately 200 m high. A smaller cone approximately 5 km to the northwest may be a small satellite to this larger cone. Two irregular, pitted mounds between the northern and southern cinder cones may also be vents but do not show well-defined conical morphology.

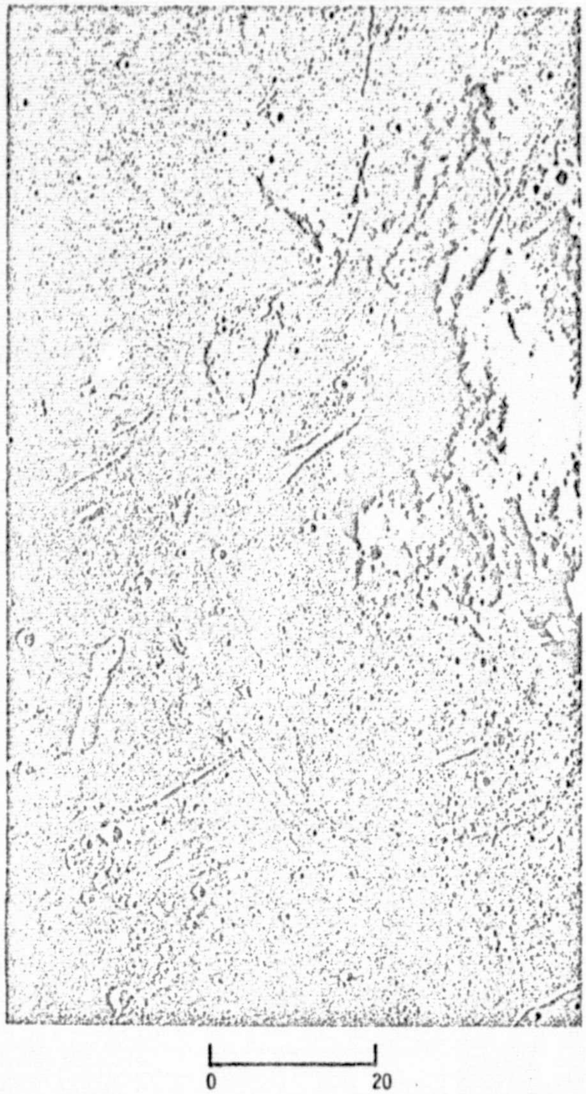

FIGURE 30-10.–Southeastern margin of Mare Serenitatis, showing margin of lava flow mantling dark borders (A), possible breached cinder cones (B), and collapsed and partly buried lava tube (C) (Apollo 17 metric camera frame AS17-0447).

The Dawes basalt can be distinguished from the adjacent dark mantle by its smoother surface, in which it resembles the central fill of Mare Serenitatis. The surface of the flow is slightly convex, with a subtle break in slope coinciding with the change from the smoother Dawes basalt surface to the more hummocky surface of the dark mantle. Albedo differences are slight, but the Dawes basalt appears to be slightly lighter in color. The boundaries of the Dawes basalt shown by Howard et al. (part A of sec.

29, fig. 29-5) are in reasonable agreement with the boundary indicated as "A" in figure 30-10. Dawes impact debris tends to obscure contact relations along the western side of the Dawes basalt, and contact relations between the Dawes and the light central Serenitatis fill are also extremely subtle.

The Dawes basalt is cut by several sharp rifts or lines of small pit craters that follow the general trend of the buried graben fractures. A larger, elongated pit on the left side of the lava flow is partly filled by ponded lava. It is alined with a small depression upslope and with irregular, rough features downslope that resemble partly collapsed domes or vent structures (C in fig. 30-10). These features may represent a large, partly collapsed lava tube that could be a source of some of the central mare fill.

STRUCTURAL FEATURES

Graben-like rilles are conspicuous in the dark border material (fig. 30-9). One of the sharpest and freshest of these grabens can be traced across the southern wall and floor of the large, partly drowned impact crater on the light-dark "shoreline," and thus is younger than the crater. In contrast, the blurred and degraded appearance of other grabens suggests that they are older features. These grabens crosscut highland material but are truncated or buried by the light central fill of Mare Serenitatis, as discussed in part A of section 29.

Wrinkle ridges are prominent in the light central fill of Mare Serenitatis (fig. 30-9). These have been discussed by Bryan (ref. 30-7) and by Howard and Muehlberger (part C of sec. 31), who attribute them to compressional deformation. There is a distinct change in the character of wrinkle ridge deformation between the light fill and dark border material where the radial ridges cross the light-dark boundary. Within the light fill, the ridges are broad, convex swells, commonly topped by intensely crumpled, sharp ridges. Some sharp ridges also appear to develop independently of preexisting swells. However, the sharp crumbling terminates abruptly at the albedo boundary, and the ridges continue into the dark border as low, undulating swells. Within the light central fill, many of the sharp ridges have a sawtoothed or zigzag pattern resulting from tilting and rotation of distinct blocky crustal units measuring 1 to 4 km on a side.

Laboratory experiments on fracturing of basalt (ref. 30-8) have shown that induced fractures tend to follow preexisting zones of weakness in the rock. This principle may explain both the large-scale and fine-scale patterns of fracturing, as well as the difference in response of the light and dark fill. Broad welts probably develop above preexisting zones of deformation in older buried mare fill, because less energy is expended in this way than in deforming previously undisturbed crust, especially if the same stress pattern continues to operate. For the same reason, the more intense crumpling produced by continued deformation is mainly localized along the crests of the broad welts. In detail, the intense crumpling developed by displacement around crustal blocks bounded by fractures or joints spaced at 1 to 4 km. The existence of these coherent blocks suggests that wrinkle ridge deformation took place before impact events had brecciated the surface and created a deep regolith. The absence of sharp, angular ridges in the dark border material may indicate that it consists of a relatively deep friable or highly brecciated regolith, which would tend to dissipate deforming stresses over many small-scale intergranular fractures.

VOLCANIC AND STRUCTURAL CHRONOLOGY

The sharp and relatively straight light-dark boundary relationship along the southern edge of Mare Serenitatis is difficult to explain if the dark material is assumed to be a younger deposit that covers the lighter fill. If the dark material consisted of young lava flows, these should produce a much more irregular, scalloped boundary, which is not observed. If the dark material were a young ash deposit, the boundary should be much less distinct. The shoreline relation, in which light material embays the dark material, indicates that it onlaps a preexisting sloping surface on the dark border material. The most reasonable interpretation is that the central, light-colored material is a younger mare fill that accumulated in a depression formed by isostatic subsidence of the older, dark fill. Although many workers have stated that the dark margin is relatively young, Howard et al. (part A of sec. 29) have reviewed the assumptions leading to this interpretation and also conclude that the dark margin represents the earliest filling of Mare Serenitatis. They note the similarity in color and albedo of the dark surfaces at the Apollo 11 and 17 landing sites and along the southern margin of Mare Serenitatis; this similarity in appearance also suggests similar composition and age of surface material at all of these locations.

The distinctly lower elevation of the dark border material at the Apollo 17 landing site compared to that of the southern side of Mare Serenitatis suggests that the dark material did not well up within the mare basin and overflow into adjacent valleys and into Mare Tranquillitatis. It seems more likely that the dark material originated in the highland valleys and flowed into the mare, much like the more recent Dawes basalt. These many independent flows would then have established their own local base levels where they are ponded or deflected by intervening highland barriers.

During and following this initial basin filling, collapse of the central part of the mare caused local marginal tension, producing a series of arcuate graben faults. Low swells and crenulations radial to the mare center may have also formed at this time. Impact events created a deep regolith on the dark border material. Filling of the mare basin continued, but the source and mechanism remain obscure. The Dawes basalt may represent a late-stage contribution to this fill. This light fill onlapped the sloping dark border, drowning preexisting grabens and impact craters. A "high lava mark" present locally suggests the occurrence of some drainback from the margins, implying vents within the mare, thermal shrinkage, or an early subsidence event shortly after ponding of the lava. Continued collapse of the central part of Mare Serenitatis caused compressional deformation of the crust, first forming low linear swells and welts, then more intense crumpling of the crust along crests of the welts. Some of this deformation extended into the dark margin, possibly localized by preexisting zones of weakness in the old fill. Differences in the response of the light and dark material to deformational stresses indicate that the dark margin is much more incoherent than the light fill, which tends to fracture around distinct blocky units. This difference suggests that the light fill was relatively fresh, brittle rock at the time of deformation, whereas the dark border may have been much more brecciated by impact events over an extended period.

Late-stage gas eruptions in the Taurus-Littrow area may have redistributed brecciated dark mantle as ash, as suggested by El-Baz (ref. 30-9). Some such mechanism seems necessary to explain the distribution of dark mantle over highland areas, but we have not identified cinder cones like those on the Dawes basalt. Possibly, much of this material was distributed by impact events. Although we do not exclude the possibility of volcanic activity associated with wrinkle ridges, the morphology of the ridges in the southern part of Mare Serenitatis is indicative of warped, crumpled, and broken surface crust rather than of freshly extruded volcanic material.

CONCLUSIONS

The Apollo 17 metric camera photographs provide definitive evidence for a sequence of volcanic and structural events associated with the development of Mare Serenitatis. These events are relevant to the interpretation of other orbital science experiments and to samples of dark border material collected at Apollo landing sites. Cinder cones associated with volcanic vents on the Dawes basalt are similar in size and shape to typical terrestrial cinder cones. Detailed morphology of deformational features produced by both tensional and compressional stresses suggests distinct differences in physical properties of the central light fill and dark border material.

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Apollo 17 Preliminary Science
Report NASA SP-330, 1973

PART C

VOLCANIC FEATURES OF FAR-SIDE CRATER AITKEN

W. B. Bryan[a] *and Mary-Linda Adams*[a]

The crater Aitken is on the lunar far side, centered at approximately latitude 17° S, longitude 173° E. Aitken Crater, which measures approximately 130 km from rim to rim, shows many of the features, usually attributed to impact, the most important being the terraced, hummocky inner crater walls and a raised central peak. In many respects, it resembles the well-known crater Tsiolkovsky, which is at the same latitude but approximately 40° to the west. However, the outer walls and surrounding slopes of Aitken Crater do not show the extensive ejecta blanket or the prominent landslide deposits so evident at Tsiolkovsky Crater.

Post-impact volcanism at Aitken Crater is suggested by several features (fig. 32-14), the most obvious being the mare-type filling that floors the crater and virtually makes an island of the central peak. Light-colored swirls on the surface of this filling resemble those in Mare Marginis: they do not appear to have any appreciable relief. The swirls may represent fumarolic alteration of the lava, or dust deposits from postfill landslides on the crater walls. The dark floor filling also shows several elongated pits and irregular rille-like features that also are characteristic of mare fill and that may represent vents or collapsed lava tubes.

Aitken Crater shows several unusual features that may represent volcanic events extending beyond the period of mare-type crater flooding. Among these are the circular, maar-like depressions that appear in the southern and northwestern parts of the crater. These might represent volcanic craters flooded by lava following a period of explosive eruptions; or, alternatively, they may be impact craters produced in thin crust of the ponded mare-type fill before this fill was completely crystallized. On the eastern side of the main crater floor, several more circular craters enclose peculiar clusters of dome-like features that might be extrusions of more viscous lava.

A small crater approximately 100 km west of Aitken Crater also shows what may be a filling of relatively viscous lava (fig. 32-15). It is difficult to interpret this crater filling as slump from walls of a crater produced by impact because the walls are only a little higher in elevation than the surface of the filling and because the central filling does not slope from the walls toward the center of the crater. Rather, the central filling has an almost horizontal (although rough) surface, and its contact with the crater walls closely follows a low, moat-like depression. The alinement of two large pits or craters ("B" in fig. 32-15) along the peripheral depression suggests that they originated internally; they may be explosion craters. The conspicuous fractures on the upper surface of the dome may have been produced by endogenous growth. By analogy with terrestrial volcanic domes, cooling might be expected to produce the hexagonal shrinkage cracks typical of columnar jointing. However, this fracturing probably would be much smaller in scale than that observed in this crater.

The volcanic fillings in Aitken Crater and in the smaller crater to the west are relatively youthful in appearance compared to the generally old highland-type topography surrounding them. Our initial impression, which should be checked by more detailed work, is that the volcanic activity is considerably younger than the impact events that produced the host craters and is probably contemporary with mare volcanism on the lunar near side.

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FIGURE 32-14.–The crater Aitken, showing elongated pits and rille-like features in mare-type filling (A), maar-like depressions (B), and depressions with clusters of possible lava domes (C) (Apollo 17 metric camera frame AS17-0481).

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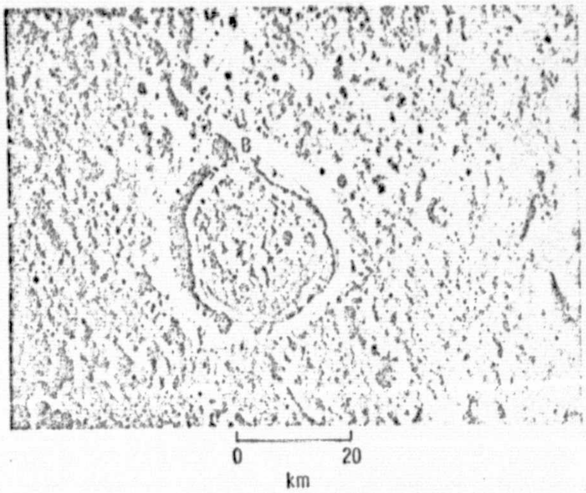

FIGURE 32-15.–Possible volcanic extrusion in small crater west of Aitken Crater. Note the irregular fractured surface; peripheral depression (A); and possible marginal explosion pits (B) (Apollo 17 metric camera frame AS17-0484).

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GEOMETRY AND PERSISTENCE OF THE LUNAR GRID: SOME IMPLICATIONS FOR TERRESTRIAL TECTONICS

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In our recent studies of volcanic and tectonic features on both the Earth and the Moon, we have been impressed by certain similarities between the apparent patterns and evolutionary history of linear features on both of these planetary bodies. Using the 1:2,750,000 scale lunar planning charts supplemented by Apollo orbital photos and 1/250,000 scale maps, we have compiled orientations for 982 major lunar lineaments between 40° N. and 40°S., on both the near and far sides. These fall into three groups with vector means and standard deviations as follows, in order of frequency:

324°, s.d. 14°; 037°, s.d. 14°; 002°, s.d. 5°.

As a further check on these orientations we have carried out more detailed studies using Apollo photography and 1/250,000 scale maps in and near mare Imbrium, mare Serenitatis, mare Procellarum, and at craters Goclenius and Tsiolkovsky. These studies confirm the presence of predominant trends which generally conform to the "lunar grid" as asserted by many other workers (1).

There are two especially intriguing features of the lunar grid. First, the grid directions persist through at least a billion years of lunar history, surviving a variety of impact and volcanic events. Ancient impact-degraded grabens follow grid directions in highland material adjacent to mare Imbrium and mare Serenitatis and are parallel to the polygonal margins of these impact-generated basins. These same orientations reappear in relatively young mare fill in a variety of forms. Wrinkle-ridges oblique to these trends nevertheless may show displaced rectangular blocks along their crests, with sides of the block parallel to the major northeast and northwest grid directions. Sinuous rilles may show sections which follow rectilinear zig-zag paths which parallel the major grid directions. Major graben-like rimae may crosscut mare fill and craters as at Goclenius (2), again running parallel to a major grid direction though obviously post-dating most impact and mare-fill events. Fault scarps and walls of moderate-size craters, as exemplified by Goclenius and Tsiolkovsky, tend to be aligned preferentially along grid directions. There is thus a strong tendency for the same patterns to be reimposed on younger materials, regardless of the mode of deformation. The second peculiarity of the grid is the persistence of the same orientations at least from 40° south to 40° north, extending completely around the Moon. The subordinate north-south trends can readily be visualized as segments of great circles passing through the north and south poles. However, the predominant northwest and northeast trends cannot be described as segments of great circles or small circles, as these must show constantly changing trends when traced obliquely across a sphere. This is demonstrated by the trace of spacecraft orbits projected on the lunar maps. These trends appear to be segments of lines of constant bearing; such lines describe a spiral path on a sphere and must pass through the poles. This geometry suggests a possible grid origin by torsional stresses about the spin axis of the Moon.

Although various respected authorities have postulated existence of a terrestrial tectonic grid (3), this is generally discounted on the assumption that continental drift and sea-floor spreading would destroy all or most of these structures. However, there is now great interest in "basement tectonics", in which it is recognized that old buried structural lineaments may be reimposed on younger overlying strata (4). Further, there is evidence that major sea-floor fracture zones may be the seaward continuation of older structural lines of weakness in the adjacent continental blocks (5). These fracture zones parallel the directions of spreading; hence the possible spreading directions of spreading; hence the possible spreading directions may be controlled by slip lines between major continental blocks, which are the traces of ancient segments of a terrestrial tectonic grid.

Existing data for fracture patterns within continental regions appears to be of such uneven quality as to preclude any conclusions about the geometry of the original terrestrial tectonic pattern. The small-circle geometry of sea-floor fracture zones is a necessary consequence of spreading geometry on a sphere and may represent a distortion of the continental pattern from which there were derived. It has been shown (6) that, when spreading has separated continental blocks so that they are no longer in contact along fracture zone offsets, a significant re-orientation of spreading may occur. This may represent a change from grid-related spreading geometry to the characteristic small-circle spreading geometry concentric about a pole of rotation. As an ocean basin grows, the structure of the sea-floor may begin to evolve independently of the adjacent continents. The Pacific Ocean is now almost completely surrounded by subduction zones which effectively de-couple it from the continents. This may be the reason that rather large changes in spreading direction have been possible in the Pacific (7).

We believe then, that great caution should be exercised in making any direct comparisons between sea-floor structural patterns and the lunar grid pattern. However, ancient grid patterns should survive within continental crustal plates and will be reimposed on new ocean basins at the initial stages of opening, controlling the trends of both tensional sutures along which opening occurs, and the orthogonal trends of fracture zones which determine the initial directions of spreading. Tectonic patterns in the centers of older ocean basins may develop trends unrelated to the ancient grid, but these will be erased as old sea floor is subducted beneath continents. Continental collisions may induce subtle adjustments along ancient basement lineaments which contributes to their extension upward into overlying strata, or laterally into newly accreted crystalline rock on continental margins. Thus, plate tectonics may provide the means of perpetuating and rejuvenating ancient tectonic patterns on the Earth.

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