*Proc. Lunar Sci. Conf. 7th* (1976), p. 2903–2912.
Printed in the United States of America

# Photogeology of the multi-ringed crater Haldane in Mare Smythii

R. W. WOLFE and FAROUK EL-BAZ

National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560

**Abstract**—Haldane is a 40 km multi-ringed crater that occurs along with similar structures in a belt within the Smythii Basin. It is the best developed structurally of all craters in this belt and displays examples of all materials units of Mare Smythii. In addition to the outer rim, the crater displays a sharp-crested, nearly complete inner ring, and a complex central peak of round hills that are 300–600 m higher than the floor. There are two fracture systems associated with Haldane, one annular and the other radial. The annular fractures seem to control the deposition of mare basalts and dark mantle units in and around the crater. Topographic evidence and flow scarps indicate that the crater was the source of mare basalts and associated dark mantle, rather than its being flooded by such deposits. There are numerous indications that most of the features in and around Haldane are attributable to volcano-tectonic modifications of an original crater-form.

## INTRODUCTION

THE SMYTHII BASIN, located on the eastern limb of the moon, is one of the oldest circular mare basins (Stuart-Alexander and Howard, 1970). The rim is prominent on the western margin of the basin, but has been obliterated elsewhere by superposed craters. Only traces of outer rings are observable. Terra materials which have been interpreted as mostly Crisium Basin ejecta (Stewart *et al.*, 1975) occupy a major part of the basin (Fig. 1). Mare basalts continuously fill only the northeastern quadrant of the basin and, with other young, low-albedo materials, occupy low areas near the basin margins. Within the intrabasin terra unit, basalts occur only as isolated patches that are associated with several unusual multi-ringed craters. These craters occur in a belt around the southern and western margins of Mare Smythii.

The multi-ringed craters have been interpreted as volcanic collapse calderas (El-Baz, 1971) and as endogenically modified impact craters (Schultz, 1974; Brennan, 1975; Schultz, 1976). The morphologically most prominent of these craters, Haldane, is selected for detailed study because it is structurally the best developed and it alone contains examples of all materials units associated with the multi-ringed craters in Mare Smythii. Haldane was photogeologically studied at the scale of 1:250,000 using Apollo 15–17 metric and panoramic photographs, and a base of Lunar Topographic Orthophotomaps 81B1 and 81B2.

## MORPHOLOGY AND STRUCTURE

The 40-km diameter crater Haldane is notable for its sharp-crested, nearly complete inner ring (Fig. 2). In places the inner ring is higher than parts of the outer rim, and the inner ring and much of the outer rim are ridge-like with the

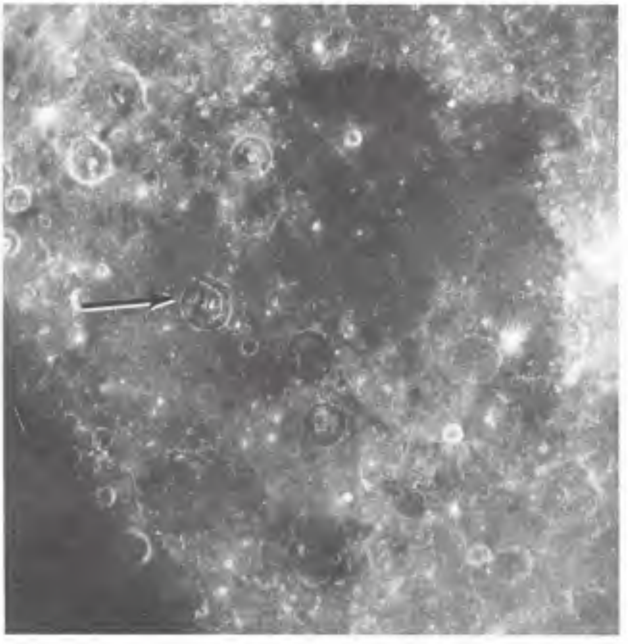

Fig. 1. Mare Smythii; Haldane is the prominent multi-ringed crater indicated by an arrow. (AS10-27-3918).

inward-facing slopes steeper than the outer slopes. There is no evidence of hummocky rim deposits, and in places the outer rim, though raised, grades imperceptibly into the surrounding terrain. The hilly mantled-looking terrain around Haldane appears to be a continuous unit that fills most of the southern half of the Smythii Basin.

Despite the old relative age of Haldane, the walls are free of slumps and the rims are virtually undisturbed by younger craters larger than a kilometer. The northwestern outer rim is breached where Haldane intersects a somewhat larger and older crater. On the western side, most of an older, 12-km crater is perched nearly a kilometer above the remainder of its deposits on the floor of Haldane.

Some of the area between the outer rim and inner ring is flooded by mare basalts that also fill an adjoining crater. The level of the basalt within Haldane, however, is about 200–400 m above that outside the crater. This elevation difference may be a result of uplift of the floor subsequent to mare flooding; however, a few rather indistinct flow scarps suggest that Haldane was the source of basalt rather than being flooded from without.

In addition to the regional pattern of north-south trending fractures in western Mare Smythii there are two systems of fractures associated with Haldane, one annular and the other radial. Fractures of the annular system lie near or on the rim-floor boundary and nearly encircle Haldane at a distance of 1.5 times the radius of the outer rim. The morphology of Haldane itself appears to be largely

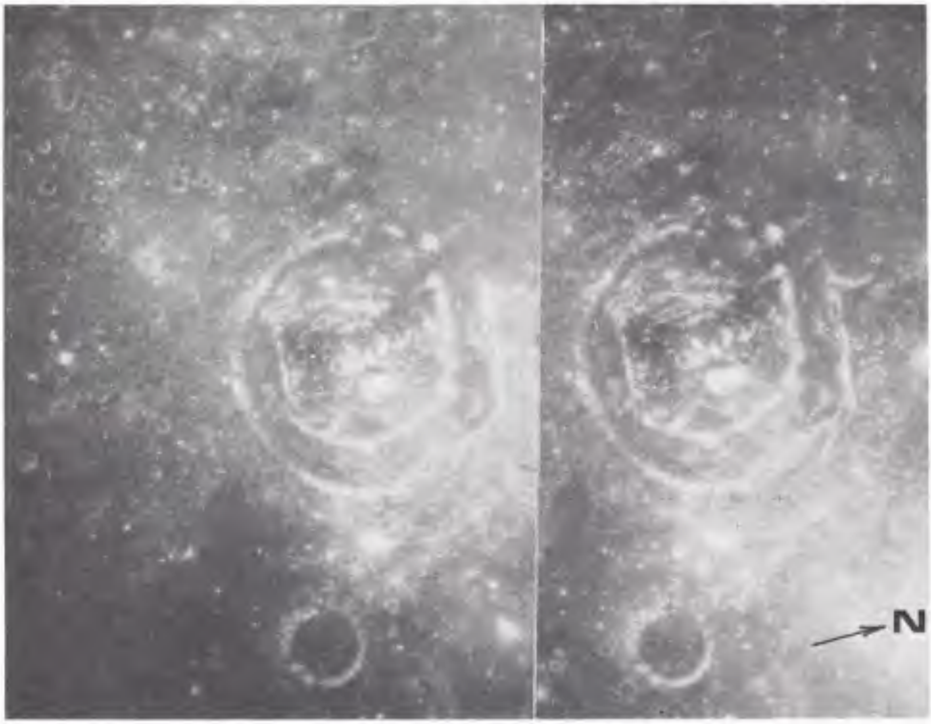


Fig. 2. Stereo pair of the multi-ringed crater Haldane. (AS15-M-0926 and 0927).

related to movement on this system of annual fractures (Fig. 3). Except where covered by basalt these faults are visible at the base of the walls of the outer rim and a partial third ring. The walls are therefore interpreted as fault scarps. Where fractures of the annular system are visible at the inner ring, they lie at the base of outward—not inward—facing slopes (Fig. 4a). The central peak complex, which is also bounded by annular faults, consists of a ring of rounded hills separated by a graben from a larger and higher massif. The central peaks range from 300 to 600 m higher than the terrain surrounding the crater and the larger massif exceeds the height of parts of Haldane's outer rim. Such relative elevations are common in floor-fractured craters (Schultz, 1976) and indicate, for Haldane, uplift of the crater floor by about 3 km compared to relatively fresh impact craters of the same diameter.

Radial fractures are not visible in the northwestern quadrant of the crater, but they may be present and covered by mare basalt. Elsewhere, these fractures occur in floor and rim materials alike and extend into the surrounding terrain. No clear cross-cutting relationships are seen between the annular and radial systems of fractures.

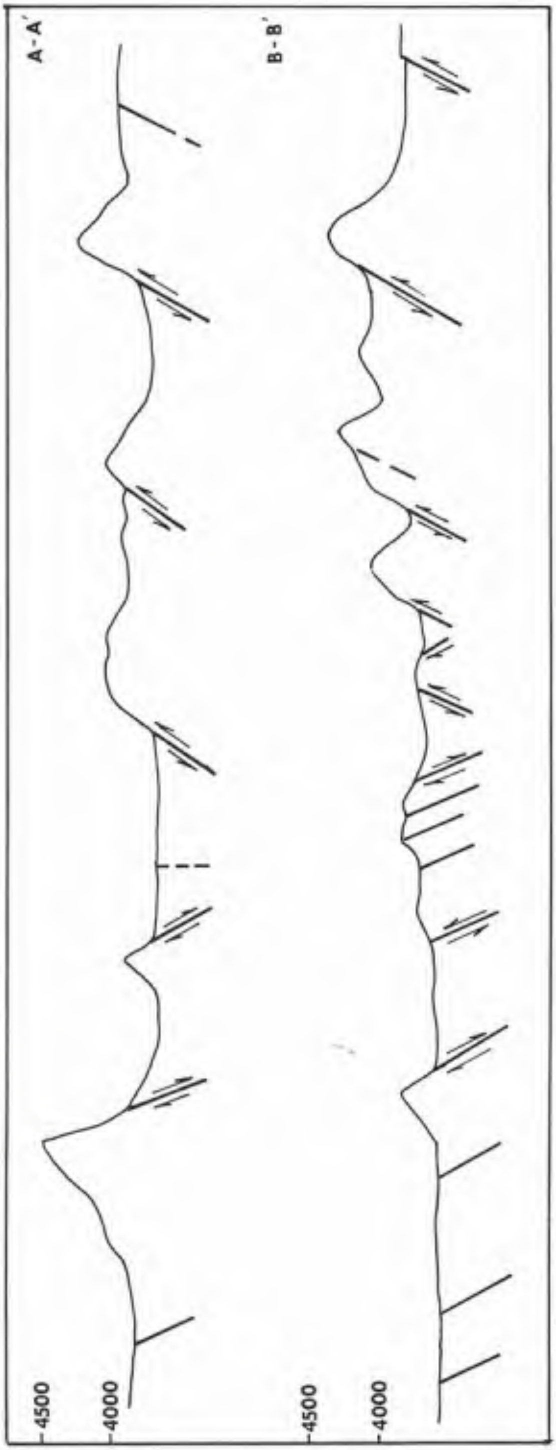


Fig. 3. Structural cross-sections of the crater Haldane. The points A, A′, B, and B′ are located on the geologic map (Fig. 4a). Vertical exaggeration is 12.5 times.

## Stratigraphy

The areal distribution of material units is shown in the geologic map (Fig. 4a) and the stratigraphic column in Fig. 4b. In addition to crater units of Imbrian through Copernican age the Haldane area contains, from oldest to youngest, the following material units.

### *Mantled terra*

The mantled terra surrounds most of Haldane, and is nearly as high in albedo as the highlands adjacent to the Smythii Basin. The unit is heavily cratered by small ($D < 5$ km) impacts and displays a smoothly rolling appearance on a fine scale. It covers a wide range of elevations, a fact attributed to the large (20–80 km) Nectarian and possibly pre-Nectarian craters over which this unit is draped. The Humboldt crater sculpture in the region is mantled, whereas rim deposits of other Imbrian age craters in the region are not or only slightly mantled. An Imbrian age is, therefore, assigned to the mantled terra unit, which agrees with the conclusion of El-Baz and Wilhelms (1975) and Wilhelms and El-Baz (1976).

### *Central massifs*

The central massifs material, characterized by its very high albedo, forms the cluster of steep-sided, rounded hills in the middle of the Haldane crater floor. This unit is interpreted as uplifted blocks of the crater floor. There is no evidence that the hills may be constructional volcanic landforms.

### *Mare basalts*

The mare units, mare basalt and dark mantle, are distinguished from other units by their smoothness and relatively lower albedo, and from each other by the very low albedo of the dark mantle material. As in the Taurus-Littrow region (Lucchitta, 1973), no clear stratigraphic relationship is discernable where these two units are in contact. The distribution of the dark mantle material is structurally controlled with nearly all of the mantle associated with the annular system of fractures. It is interesting to note that, within the crater and around it, the dark mantle materials are everywhere higher in elevation than the mare basalt.

## Evolution of the Structure

The multi-ringed structure of Haldane may be interpreted as developing by volcano-tectonic modification of an original crater-form (Fig. 5a). Modification has been so extensive that there is no clear-cut evidence to the origin of the initial depression. The most pronounced modification is the uplift of the floor which, were Haldane an impact crater, may have been as much as 3 km. Absence of a hummocky ejecta blanket and a perched crater on the rim, however, indicate that


Fig. 4. Photogeology of Haldane. (a) Geologic map showing areal distribution of major material units.

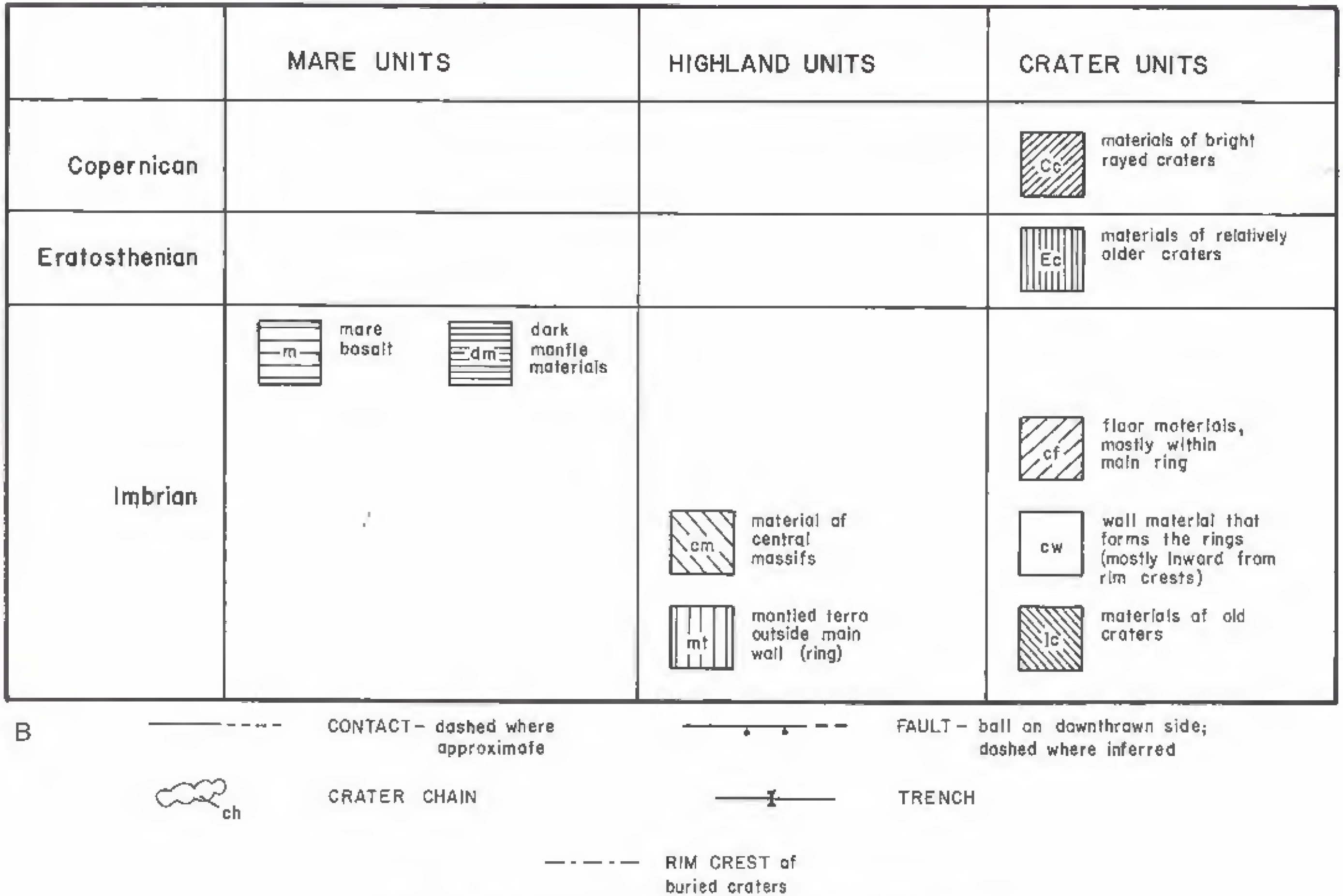


Fig. 4. (*Continued*). (b) Stratigraphic column and legend to the map.

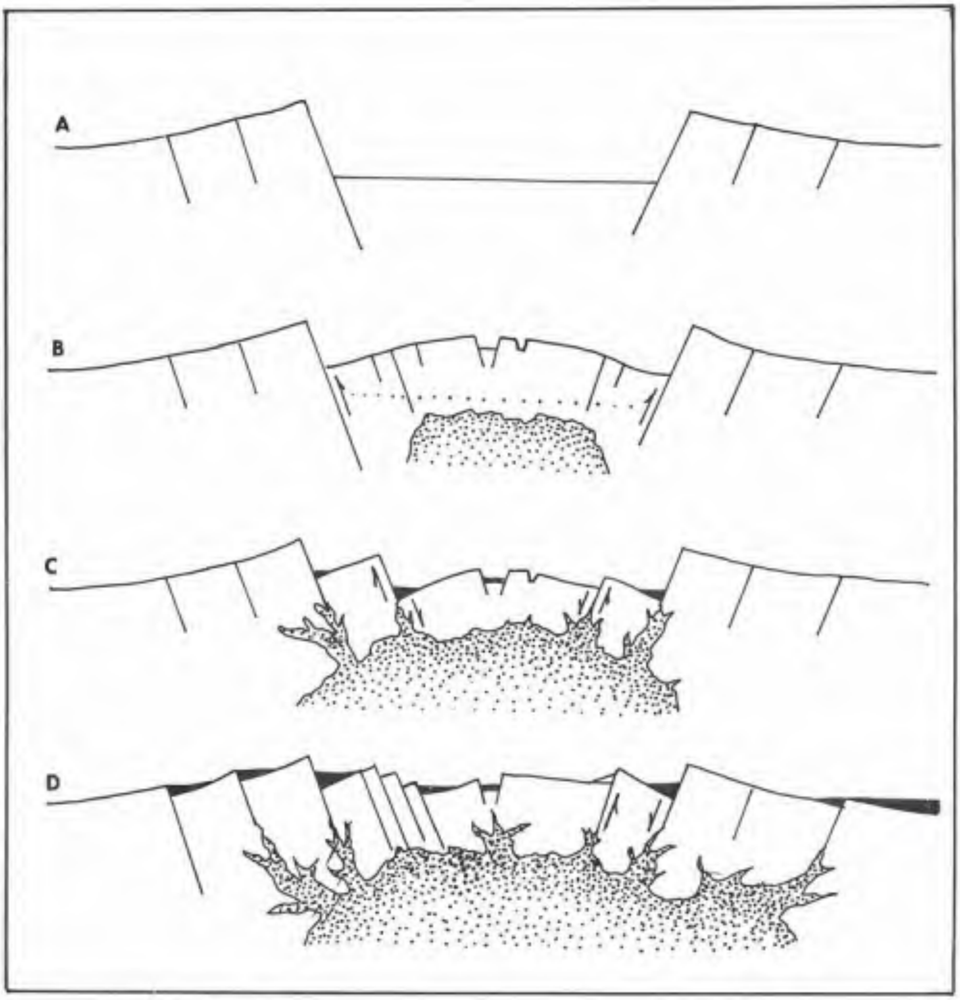


Fig. 5. Model stages for the development of Haldane. (a) Assumed initial crater-form structure. Outer ring fractures may not have been present at this stage but developed later. (b) Doming over a developing magma chamber with formation of ring fractures and apical graben. (c) Down-faulting of the central part of the floor accompanied by ring fracture volcanism. (d) Faulting and tilting of the inner ring of Haldane and major volcanism.

the original depression was relatively old and may have been highly degraded by mass wasting and isostatic adjustment of the floor.

Aforementioned evidence that Haldane appears to be a local source for mare volcanism suggests that a magma chamber may have been situated beneath the floor. If true, much of the modification of the crater may be attributed to the pressure of this magma. The structure of the central uplift within the inner ring of Haldane is strikingly similar to that of the resurgent domes in terrestrial calderas

(Smith and Bailey, 1968; Carr and Quinlivan, 1968) and to fractures developed above models of salt domes (Parker and MacDowell, 1955). An apical graben (which in Haldane separates the central peak ring from the larger central massif) and a system of radial faults (also present in Haldane) characterize structures that form by uplift and doming in the terrestrial cases.

In the interpretation presented here, emplacement of a small magma chamber caused the floor of Haldane to be uplifted (Fig. 5b). A system of concentric, inward-dipping fractures developed in response to initial tumescence and, as doming progressed with growth of the magma chamber, distensional fractures developed, namely, the radial system and the apical graben. With further expansion of the magma chamber (Fig. 5c), the central portion of the domed floor detached and dropped along the inward-dipping faults relative to the part adjacent to the crater wall. The faults, now covered, mark the boundary between the inner scarp of the inner ring and the central floor of Haldane. In this stage in the development of Haldane, ring fracture volcanism may have begun.

Increased build-up of magma pressure faulted or tilted parts of the inner ring and culminated in the major episode of mare volcanism in the Haldane region (Fig. 5d). Basaltic lavas flooded much of the floor and emanated from Haldane to fill the adjacent depression to the northwest (Fig. 4a). The contribution of volcanism through outer ring fractures to this filling cannot be assessed because the fractures are covered or possibly not present. Outside the crater to the southeast, however, mare basalt appears to have been erupted from fractures of the same system (Fig. 4a). Eruptions of low albedo, possibly pyroclastic, material from the annular fractures—both inside and outside the crater—were probably contemporaneous with eruptions of basaltic lava, although no clear stratigraphic relationships exist. The latest structural adjustment at Haldane, a small subsidence along part of the outer ring fracture to the east, was most likely in response to detumescence with depletion or withdrawal of magma.

## Discussion

The interpretation of the volcano-tectonic modifications of Haldane made here differs only little from that of class III floor-fractured craters by Schultz (1976) who noted that Haldane is more highly modified than other craters of the class. Whereas he interpreted much of the floor uplift to be block-like, we propose that it was accompanied by doming. In either case, terrestrial resurgent calderas may be useful as analogs to the modifications of class III floor-fractured craters and possibly other volcano-tectonically modified lunar craters.

Resurgence of terrestrial caldera floors is favored by silicic and presumably highly viscous magma, but other factors are also important (Smith and Bailey, 1968). These include the degree of deformation, relative size and thickness, and density of the uplifted floor block. Examination of these factors may prove instructive in understanding the distribution of lunar floor-fractured and other volcano-tectonically modified craters. It may also help answer questions of differences in degree and style of modification or why some craters are modified and others are not.

*Acknowledgments*—The authors wish to thank P. H. Schultz, R. J. Pike, and D. E. Wilhelms for their helpful comments. This work was supported in part by NASA grant 7188.

## References

Brennan W. J. (1975) Modification of pre-mare impact craters by volcanism and tectonism. *The Moon* **12**, 449–461.

Carr W. J. and Quinlivan W. D. (1968) Structure of the Timber Mountain resurgent dome, Nevada Test Site. In *Nevada Test Site* (E. B. Bickel, ed.), p. 99–108. Geol. Soc. Am. Memoir 110.

El-Baz F. (1971) Volcanic features in the far-side highlands. In *Apollo 14 Prelim. Sci. Rep.*, NASA publication SP-272, p. 267–274.

El-Baz F. and Wilhelms D. E. (1975) Photogeological, geophysical, and geochemical data on the East Side of the Moon. *Proc. Lunar Sci. Conf. 6th*, p. 2721–2738.

Lucchitta B. K. (1973) Photogeology of the dark mantle material in the Taurus-Littrow region of the Moon. *Proc. Lunar Sci. Conf. 4th*, p. 149–162.

Parker T. J. and McDowell A. N. (1955) Model studies of salt dome tectonics. *Bull. Am. Assoc. Petrol. Geol.* **39**, 2384–2470.

Schultz P. H. (1974) Floor-fractured lunar craters (abstract). In *Lunar Science V*, p. 651–683. The Lunar Science Institute, Houston.

Schultz P. H. (1976) Floor-fractured lunar craters. *The Moon.* In press.

Smith R. L. and Bailey R. A. (1968) Resurgent cauldrons. In *Studies in Volcanology* (R. R. Coats, R. L. Hay, and C. A. Anderson, eds.), p. 613–662. Geol. Soc. Am. Memoir 116.

Stewart H. E., Waskom J. D., and DeHon R. A. (1975) Photogeology and basin configuration of Mare Smythii. *Proc. Lunar Sci. Conf. 6th*, p. 2541–2551.

Stuart-Alexander D. E. and Howard K. A. (1970) Lunar maria and circular basins—A review. *Icarus* **12**, 440–456.

Wilhelms D. E. and El-Baz F. (1976) Geologic map of the east side of the moon. U.S. Geol. Surv. Inv. Map I-948.