Proc. Lunar Planet. Sci. Conf. 11th (1980), p. 2437–2446.
Printed in the United States of America

The geology and morphology of Ina

P. L. Strain and F. El-Baz

Center for Earth and Planetary Studies, National Air and Space Museum, Washington, D.C. 20560

Abstract—Ina is a unique D-shaped depression located atop a 15-km diameter extrusive dome southeast of the Imbrium basin. It lies in a region that is dissected by lineations radial to both Imbrium and Serenitatis. The rim of Ina is characterized by discontinuous concentric fractures, flows, and a smooth raised border. The floor contains 4 separate units, including smooth, sparsely cratered protrusions or mounds ranging in height from 5 to 25 m. The mounds are compared to the terrestrial lava pillars called Dimmuborgir located in northern Iceland. These pillars are morphologically similar to the Ina mounds and may have formed by the collapse and subsidence of a partially solidified lava lake. However, the distribution of the mounds in Ina, the disparate heights of their summits, and the frequent presence of moats around their bases suggest that the mounds originated as discrete extrusive features.

The dome underlying Ina appears comparable to low terrestrial basaltic shields although it exhibits some morphological differences. The unusual morphology of the Ina structure may have been influenced by its location in a highly fractured region between two of the largest nearside impact basins, and by the composition of the magma.

INTRODUCTION

The lunar feature Ina, an unusual D-shaped depression, is located in Lacus Felicitatis north of Mare Vaporum (Fig. 1). Before being officially named by the International Astronomical Union, it was sometimes informally referred to as "D-Caldera" (El-Baz, 1973). Attention was drawn to the feature because of its strange "blistered" appearance. It was first noticed on Apollo 15 panoramic camera photographs by E. A. Whitaker (1972a) who pointed out its apparently unique character. El-Baz (1972; 1973) proposed that it was a collapse caldera displaying evidence of episodic volcanic activity. Using detailed topographic data available from the Lunar Topographic Orthophotomap (LTO) series, we can now depict the morphology and structure of Ina and the surrounding region more accurately than was previously possible. The maps used in this study are 41C3 and 41C4 at 1:250,000 scale, and 41C3S1 (Ina) at 1:10,000 scale. In addition, profile data were specially produced by the Defense Mapping Agency/Topographic Center.

REGIONAL SETTING

Ina lies in a region between the Apennine Mountains of the Imbrium basin and the Haemus Mountains of Serenitatis. The area is characterized by highland materials dominated by northwest-southeast trending lineations radial to Imbrium (El-Baz, 1973). A pattern radial to Serenitatis is also evident, although less pronounced. Irregular patches of maria (lacus) are present and are often bordered by scarps radial to the basins (Fig. 1). Ina is located atop a raised basalt plateau that bisects Lacus Felicitatis. The plateau is tilted towards the west. Its western scarp reaches heights of more than 200 m while the eastern scarp is about 600 m high. The scarps bordering the plateau have slopes of about 9°. The western scarp extends into the highlands to the south and appears to emerge as a mare ridge that crosses Mare Vaporum (see Fig. 30-11, El-Baz, 1973) and terminates northeast of Sinus Medii in a region marked by dark mantle material (Wilhelms and McCauley, 1971). In Mare Vaporum the ridge marks a change in elevation on the order of 100 m.

The surface of Lacus Odii, located northeast of Felicitatis, also slopes down to the west, exhibiting a drop in elevation of more than 400 m. A lobate flow front (Fig. 1) indicates that during a late episode of extrusion, lava in Odii flowed

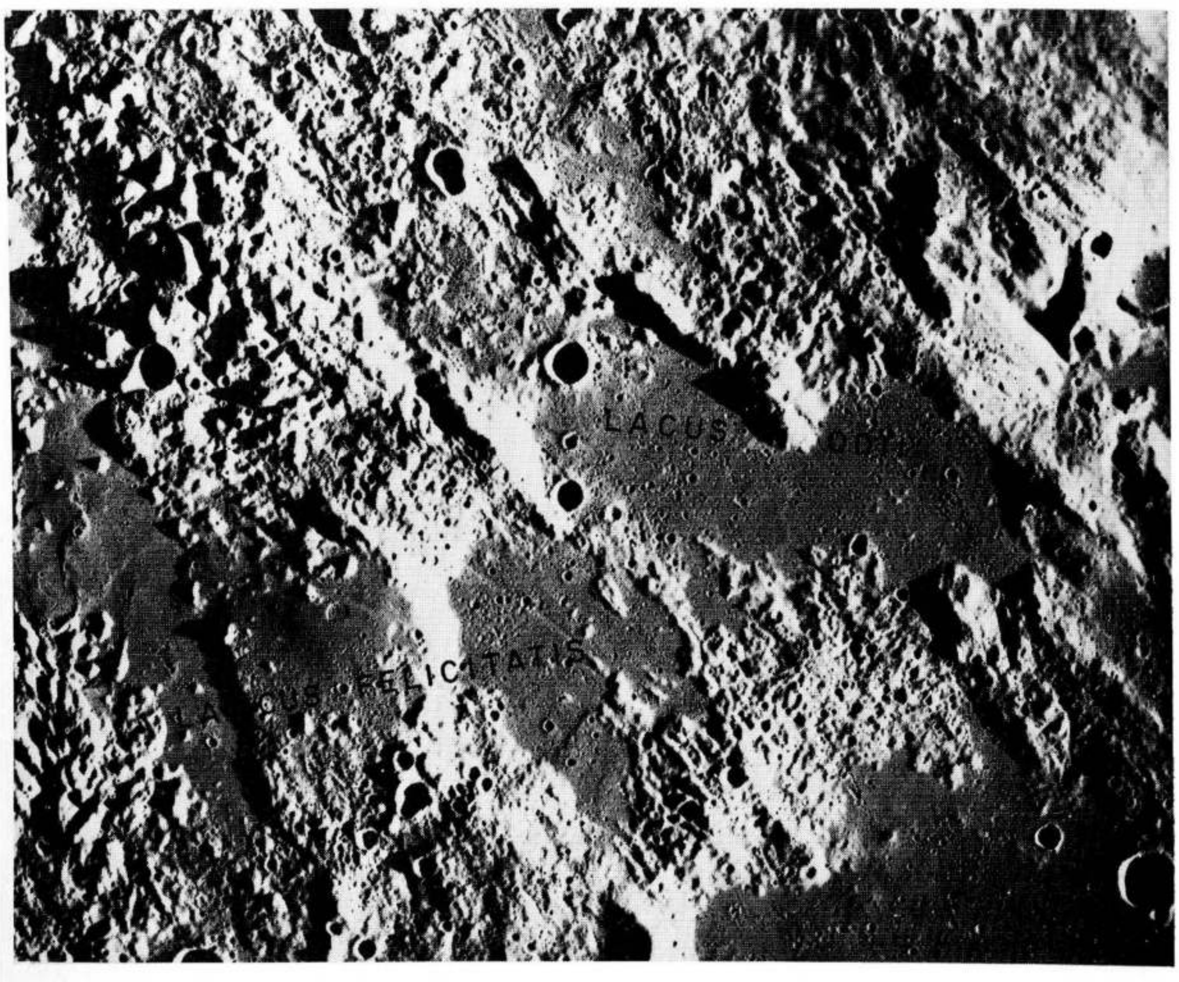

Fig. 1. Apollo 17 metric view of the Ina region. Ina, the D-shaped depression in Lacus Felicitatis, is about 2.7 km along its straight edge. Arrow designates lobate flow front discussed in text (AS17-M-1517).

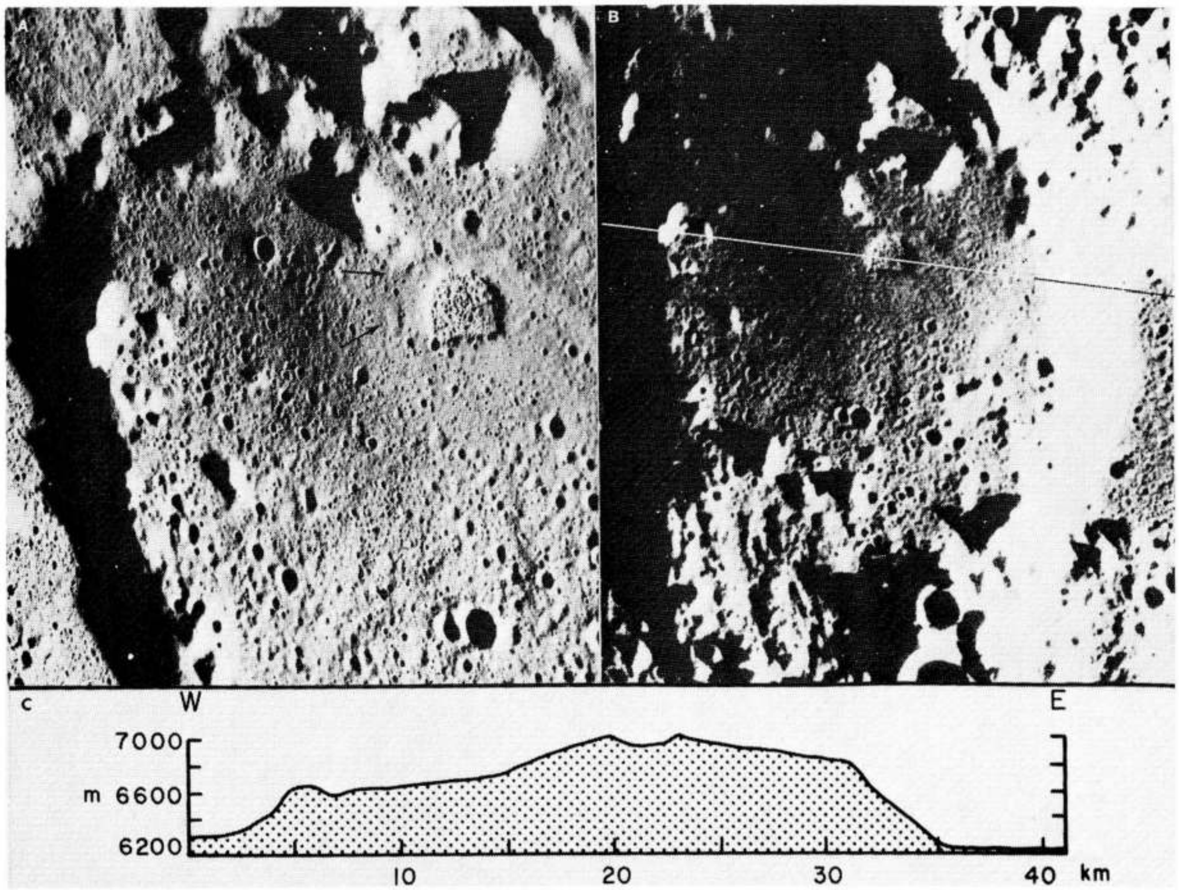

Fig. 2. (a, b) Low sun views of Ina dome (AS17-154-23672, AS17-159-23931). Arrows mark depressions along Ina's rim. (c) Profile across dome. Vertical exaggeration is about 6X. Trace marked in b.

from west to east. This suggests the original topographic slope was different from that of the present day. This evidence, coupled with the existence of the relatively raised Felicitatis plateau indicates a vertical displacement of several hundred meters for much of the maria in the region.

MORPHOLOGIC CHARACTERISTICS AND ORIGINS OF FEATURES

The dome. Topographic maps indicate that Ina is located on a dome which is about 15 km in diameter and which rises up to 300 m above the surrounding mare surface (Fig. 2). Its flanks slope at about 2–3°. Comparison with other analogous lunar domes, which range from 3–17 km in diameter (Head and Gifford, 1980), shows it to be among the largest on the moon. The dome's profile is somewhat asymmetric, perhaps the result of the tilting of the plateau. Atop the dome and along Ina's rim is a raised "collar". It is about 1.6 km wide and is bordered on the north and west by discontinuous graben-like depressions concentric to Ina (Fig. 2). Both on the collar and adjacent dome overlapping flow fronts indicate flow away from Ina.

Close examination of the dome reveals evidence for three lava surfaces of increasing age (i.e., increasing relative crater densities). The youngest is a very sparsely cratered unit found on the dome's summit. Another more densely cratered unit exists on the lower portions of the dome. A population of relatively large, flat-floored and apparently flooded craters suggests a third surface covered by thin younger flows. The dome as a whole exhibits a lower density of craters > 300 m than the surrounding mare units. Although the small areas involved and the flooded nature of many of the craters on the dome make age determinations by conventional crater counting methods unreliable and inconclusive, the relative crater densities indicate that the dome is younger than the mare material of the rest of the plateau, which has been mapped as Eratosthenian by Wilhelms and McCauley (1971).

The extrusive nature of the dome is supported both by its lower crater density and by its distinct color on the IR-UV photographs of Whitaker (1972b). These photographs are constructed by combining an IR positive and a UV negative. The process results in the enhancement of color differences. Color differences in the maria have been related to compositional variations (Whitaker, 1972b). On the IR-UV photos the dome correlates with a region that is bluer than the surrounding materials. This is in keeping with the observation made from orbit by the Apollo 17 astronauts that the Ina structure has a bluish tint (Evans and El-Baz, 1973).

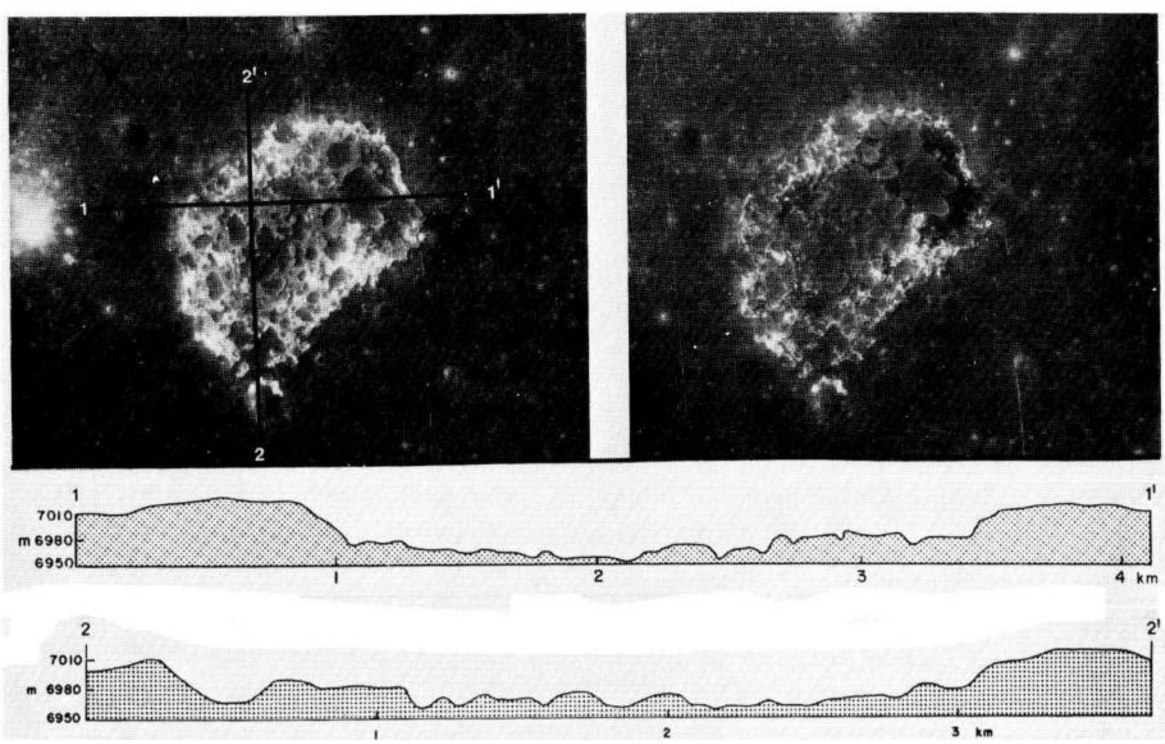

Fig. 3. Top. Stereo pair showing diverse units on floor of Ina (Apollo 15 pan 176, 181). Bottom. Profiles across Ina. Vertical exaggeration is about 3X. Data supplied by Defense Mapping Agency/Topographic Center.

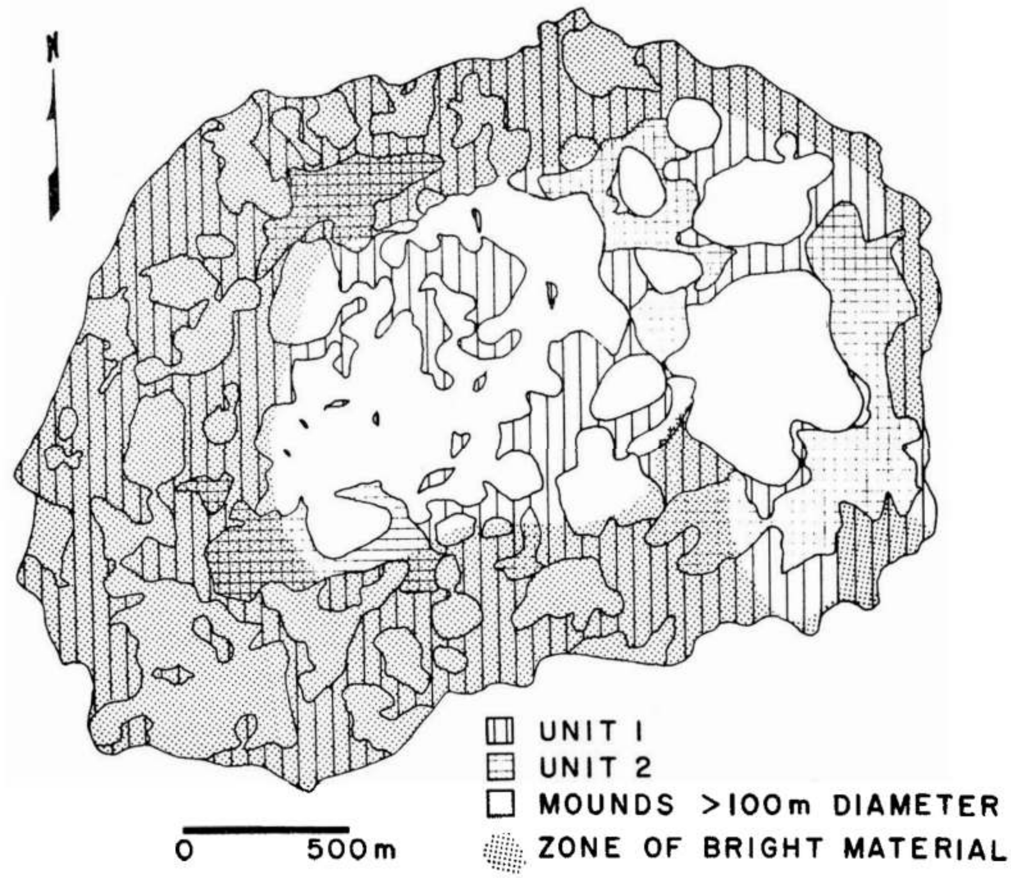

Fig. 4. Sketch map of units on floor of Ina. The stippled area marks the zone of the major occurrence of bright material.

Ina. Ina's diameter ranges from about 2.7 km along its straight edge to 2.9 km at its widest point. It is about 60 m deep. Its rim and walls are composed of mare basalts. Four units can be distinguished on the floor (Figs. 3 and 4): (1) A light-colored, low relief, roughly-textured unit covering much of the floor. This largely uncratered surface displays subdued interlocking polygonal hummocks and small sinuous scarps that may be flow features. (2) A dark-colored, hilly unit found predominantly along the eastern edge of the depression and in small patches on the floor. It is covered with rimless craters, often found at hill summits. (3) Smooth textured, extremely sparsely cratered protrusions, here referred to as mounds (Fig. 5). The mounds are often ringed by small depressions or "moats". (4) A unit found along most of the outer edge of the floor characterized by bright material around positive features and along the base of the wall. The zone in which the material occurs is bordered in places by patches of unit 2.

The morphologies of these units suggest that most or all are volcanic in origin. The possible flow fronts of unit 1 as well as its polygonal texture, which is reminiscent of the surfaces of terrestrial lava lakes dissected by cooling fractures, indicate an extrusive origin. The low albedo of unit 2 suggests a mantle of pyroclastic materials. The nature and origin of the mounds are discussed in detail below. The bright material of unit 4 is generally restricted to the outer edge of the depression. The variation between this outer portion of the floor and the central part may be compositional or physical. For example the bright material may mark a more highly fractured zone, which would be in keeping with its previous interpretation as sublimates deposited along cracks in the surface (Whitaker, 1972a). Alternatively, the bright unit may represent freshly exposed fine material eroded from high areas and collected in low-lying zones such as the moats around the mounds.

The Mounds. The material composing the mounds (unit 3) appears to be very similar to the mare basalts found on Ina's rim and walls. This similarity is substantiated by observations of the Apollo 17 astronauts that the mounds and the material surrounding Ina are the same color (Evans and El-Baz, 1973). Many of these structures are somewhat flat-topped while others are more rounded. The individual mounds have heights ranging from about 5 m to more than 25 m and areas from .003 km^2 to .26 km^2.

Some of the mounds appear to have summit craters (El-Baz, 1973). These craters resemble small vents as they are often roughly centrally located, rimless, and rayless. However, there is no consistent relation between summit crater diameter and mound diameter as has been noted by Head and Gifford (1980) for lunar mare domes in general. Some of the craters may, therefore, be fortuitous impacts. There is, however, a tendency for the craters to favor the tallest mounds. More than 80% of the mounds over 15 m high have the large summit craters, while less than 15% of those below 15 m do. This may result from the fact that craters on the smaller mounds may be too small to be resolved, or that they may be small enough to be easily filled.

Along the margins of Ina's floor the mounds are discrete, whereas in the center they coalesce to form one large complex exhibiting a concentric pattern (Fig. 5). It has been previously suggested by El-Baz (1973) that the mounds are extrusive features. Their preferential location in the lower central part of the depression and the concentric plan, which may reflect a fracture system, support this hypothesis.

Alternatively, however, the mounds may be analogous to the features called Dimmuborgir (Dark Castles) found near Mývatn, northern Iceland (Fig. 6), as was suggested by Wood *et al.* (1977). Although there are differences in morphology between the two sites (particularly, differences in scale and steepness of slopes), when photographs of similar resolution are compared, the features are quite similar in form. Despite the discrepancies, which might be explained by differences in the terrestrial and lunar environments, the Dark Castles are apparently the terrestrial features whose morphology most closely resembles that of the Ina mounds. As described by Barth (1950) the Dark Castles are "lava pillars" found in a circular depression at the center of a slightly raised area in a lava plain. The depression is about 15 m deep and the pillars are tall enough to reach the level of the surface surrounding the depression. Barth (1950) suggested the area was a lava lake that had drained leaving the pillars (areas that had already solidifed) standing. In support of this theory he cited vertical grooves similar to slickensides, and horizontal markings at different levels on the pillars as evidence

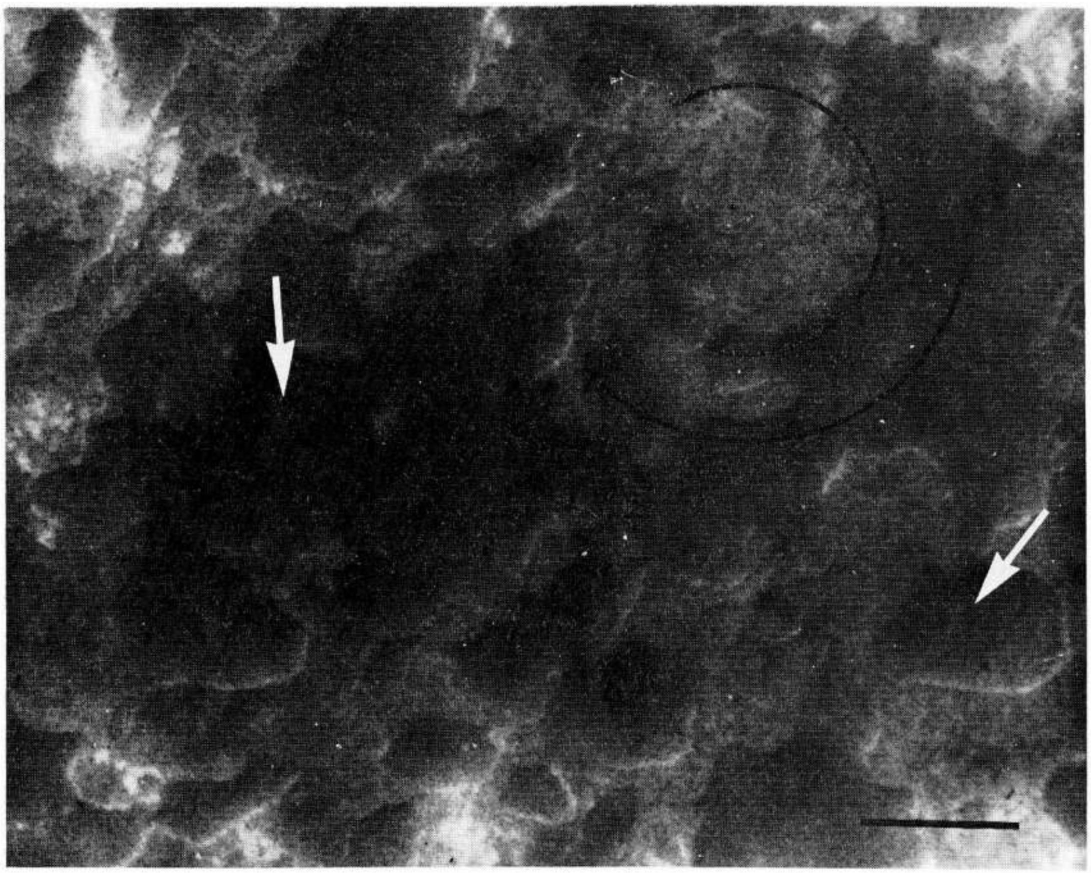

Fig. 5. Mounds on the floor of Ina. Note concentric pattern. Scale bar is about 200 m. Arrows indicate summit craters.

of the sinking of the lake's crust. Similarly, Wood (pers. comm.) suggests that the often flat tops and relatively steep slopes indicate that the Ina mounds may represent the remnants of a former surface which has partially collapsed. However, a difficulty exists in that the Ina mounds, unlike the Dark Castles, are not at similar levels. Topographic data indicate that their summits differ in elevation over a range of 25 m.

Another obstacle to this theory is the presence of moats around some of the mounds. Such features would not be expected in a simple collapse model. If the mounds were formed by extrusive flows, the loading of lava above and withdrawal below could cause the contemporaneous collapse of the surface and the formation of a depression in the vicinity of the mound. This is similar to a mechanism discussed by Schultz and Greeley (1976) for the formation of ring-moat structures on the lunar maria (see also McKee and Stradling, 1970, which describes the terrestrial analogue). We are not proposing that the Ina mounds are comparable to these ringed domes, nor that the mechanisms are identical. We merely suggest that there may be some similarities. The ring-moat structure theory involves the squeezing up of lava as a result of the sinking of the mare above. This process alone would not be sufficient to account for the considerable heights of the Ina mounds which might be better explained by continuous extrusions.

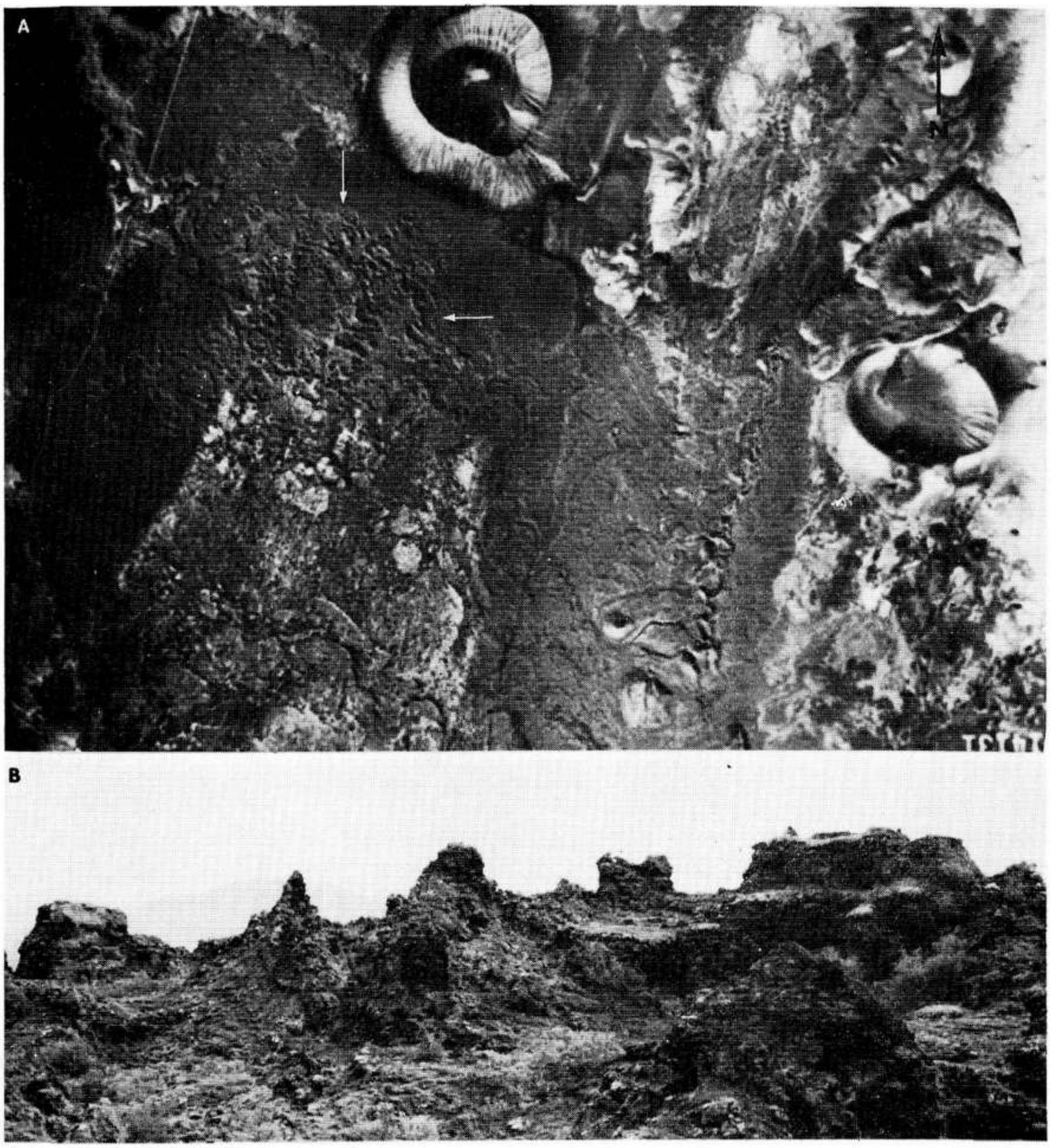

Fig. 6. (a) Arrows indicate location of Dimmuborgir on this aerial view. The large crater at the top of the photo is about 1 km in diameter. (Photo courtesy of C. A. Wood). (b) Lava pillars of Dimmuborgir (photo courtesy of C. A. Wood).

Although in some places the mounds appear connected to the mare unit on the wall and rim, they do not represent the same surface. The two units have different crater densities, the mounds appearing younger than the wall and rim material. There is no evidence, such as a high lava mark along the wall to indicate the former existence of a younger surface within the depression. Considering the distribution of the mounds, the heights of their summits, the presence of moats, the distribution of summit pits, and the lack of high lava marks, we favor the hypothesis that the mounds formed as discrete extrusive features.

CONCLUSION

Ina is an apparently unique volcanic feature. It rests on a dome displaying evidence of episodic extrusive activity. Its odd D-shape is probably related to a local fracture pattern, since the straight edge is aligned with other small lineaments in the area (El-Baz, 1973). Ina's floor exhibits several volcanic units including unusual mounds which we propose are small extrusive features. The exceedingly low crater density of the mounds (less even than that of the youngest unit on the dome) suggests that they may represent some of the youngest volcanism on the moon (El-Baz, 1972). Units on Ina's floor appear to be the culmination of a series of extrusive events spanning a considerable time period, as evidenced by the sequence of decreasing crater densities noted on the Ina structure and dome. The unusual morphology of the floor units may indicate changes in composition of the magma through this time span by differentiation in a localized magma source.

The extensive fracturing of the Ina region, caused by its proximity to two of the largest nearside impact basins, may have allowed abundant extrusion of lavas and the later collapse and subsidence of some mare units, as evidenced by their obvious vertical displacement. The unique morphology of Ina may have also been influenced by this structural setting, the numerous fractures perhaps serving as extrusive outlets. The diverse volcanic units on Ina's floor and the location of the depression on one of the largest lunar domes may reflect the ease with which the volcanic materials found their way to the surface. The correlation between dome formation and regions at the intersection of basins has been observed elsewhere on the moon. Head and Gifford (1980) noted that two of the three regions where lunar domes are found to be most highly concentrated (the areas around the craters Cauchy and Hortensius) lie near basin intersections. The combination of the possible existence of the differentiated magma source and the easy access of this magma to the surface may help to explain the unique nature of the Ina structure.

We believe the dome on which Ina rests is somewhat comparable to low terrestrial shields, the possibility of which was discussed by Pike (1978). Head and Gifford (1980) and Wood (1979) have proposed that lunar mare domes in general may be similar to these terrestrial structures. By comparing topographic dimensions, Pike (1979) showed that mare domes for which good Apollo topographic data exist do not closely resemble any terrestrial volcano class, but they have similarities to the low basaltic shields. Comparison with Pike's (1978) data shows that the Ina dome is morphologically similar to terrestrial shields. The diameter and height of the dome and the depth and depth/diameter ratio of the summit crater are all within the range of values measured for the terrestrial shields. Only the diameter of the summit crater exceeds the terrestrial range, although the diameter of the dome is also larger than most terrestrial examples. The ratio of summit crater diameter to dome diameter is higher than the average terrestrial case (Wood, 1979). However, Wood (1979) has suggested that differences between the diameters of such summit craters may be explained by the difference in gravitational acceleration for the earth and the moon, and consequently need not preclude similar origins for the features.

Ina's location at the summit of an extrusive dome, evidence of flows and fractures along the rim, and the morphology of the diverse floor units confirm its volcanic origin. It is questionable, however, if the term caldera, which has been previously proposed for the feature, is entirely appropriate. Since differences in the lunar and terrestrial environments may effect the morphologies of features formed by similar processes, it is not odd that it is difficult to place Ina strictly into any terrestrial classification scheme. However, it is a caldera in the sense that it is a volcanic crater larger than 1 mile in diameter, as defined by MacDonald (1972). As a shallow, single depression, however, it does not appear to have the scale or complexity often attributed to a true caldera.

Acknowledgments—The authors wish to thank C. A. Wood, T. A. Maxwell, J. Fink, J. L. Whitford-Stark, and P. Mouginis-Mark for their helpful comments. This work was performed under NASA Grant NSG-7188.

REFERENCES

Barth T. F. W. (1950) Volcanic geology, hot springs and geysers of Iceland. *Carnegie Inst. Wash., Publ. 587*. 174 pp.

El-Baz F. (1972) New geological findings in Apollo 15 photography. *Proc. Lunar Sci. Conf. 3rd*, p. 39–61.

El-Baz F. (1973) "D-Caldera": New photographs of a unique feature. *Apollo 17 Prelim. Sci. Rep.*, NASA SP-330, p. 30–13 to 30–16.

Evans R. E. and El-Baz F. (1973) Geological observations from lunar orbit. *Apollo 17 Prelim. Sci. Rep.*, NASA SP-330, p. 28–1 to 28–24.

Head J. W. and Gifford A. W. (1980) Lunar Mare Domes: Classification and modes of origin. *Moon and Planets* **22,** 235–258.

MacDonald G. A. (1972) *Volcanoes*. Prentice-Hall, N.J. 510 pp.

McKee B. and Stradling D. (1970) The sag flowout: A newly described volcanic structure. *Bull. Geol. Soc. Amer.* **81,** 2035–2043.

Pike R. J. (1978) Volcanoes on the inner planets: Some preliminary comparisons of gross topography. *Proc. Lunar Planet. Sci. Conf. 9th*, p. 3239–3273.

Schultz P. H. and Greeley R. (1976) Ring-moat structures: Preserved flow morphology on lunar maria (abstract). In *Lunar Science VII*, p. 788–790. The Lunar Science Institute, Houston.

Whitaker E. (1972a) An unusual mare feature. *Apollo 15 Prelim. Sci. Rep.*, NASA SP-289, p. 25–84 to 25–85.

Whitaker E. (1972b) Lunar color boundaries and their relationship to topographic features: A preliminary survey. *The Moon* **4,** 348–355.

Wilhelms D. E. and McCauley J. F. (1971) Geologic map of the near side of the moon. U.S. Geol. Survey, Misc. Geol. Inv. Map I-703.

Wood C. A. (1979) Monogenetic volcanoes of the terrestrial planets. *Proc. Lunar Planet. Sci. Conf. 10th*, p. 2815–2840.

Wood C. A., Whitford-Stark J. L., and Head J. W. (1977) Iceland Field Itinerary. Basaltic Volcanism Study Project, Contrib. no. 6. Brown University, Providence.