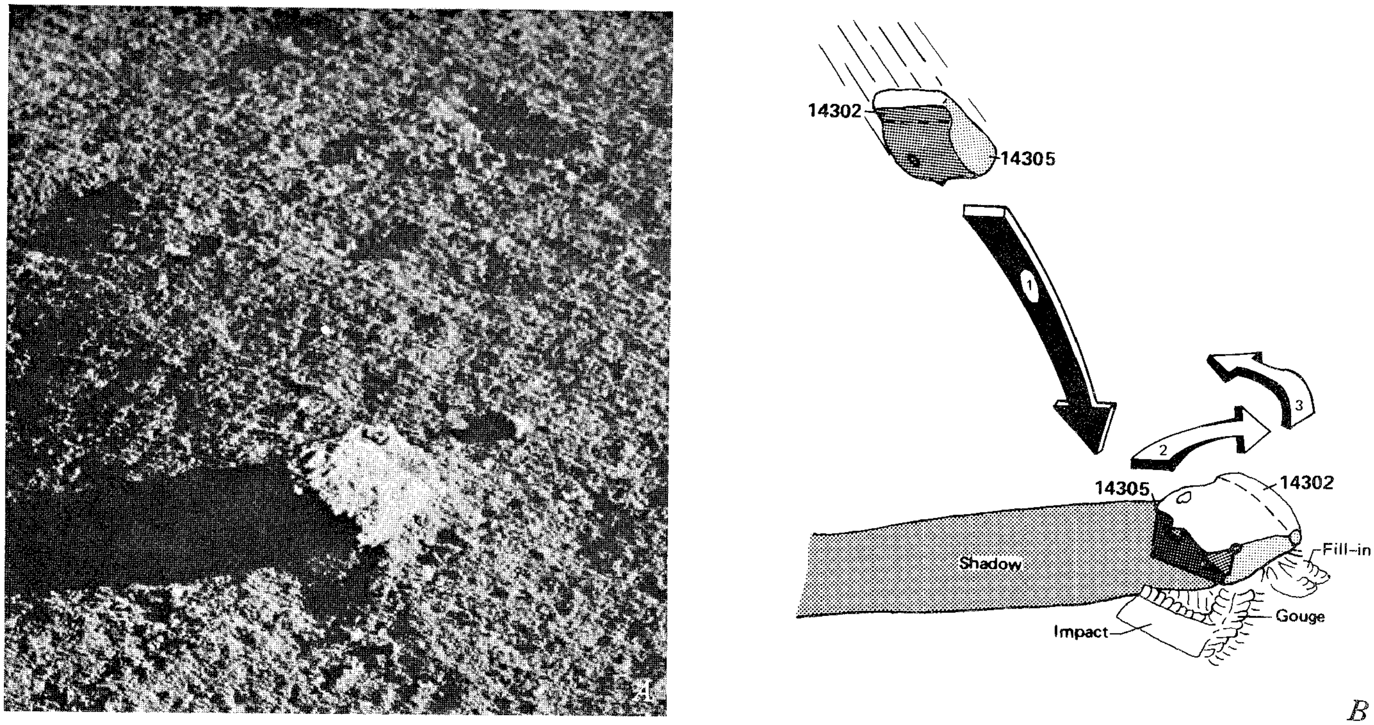


FIGURE 33.—Sample 14305. *A*, Shown before collection. Compare with figures 66 and 67. (Part of NASA photograph AS14–67–9393.) *B*, Diagram showing the possible route taken by the fragment to reach the position shown in *A* (Swann and others, 1971).

though the rock dug into the fine-grained surface material as it slid into the present position. The fillet partly fills the northwest side of two 3-cm raindrop depressions, which indicates that the fillet material moved away from the rock rather than toward it; such would be the case if the material were pushed out by impact of the rock rather than banked against the rock. The freshness of the crater formed by the rock and the angularity of the crater edges suggest that the rock has been in this position for a relatively short period of time. Features as small as the two raindrop depressions, which were formed before emplacement of 14305, should be destroyed in less than 10^6 yr (Shoemaker and others, 1970); yet they are still very sharp and fresh in appearance. Eldidge, O'Kelley, and Northcutt (1972) infer from exposure ages in the 10–20 m.y. range reported by Lunar Sample Preliminary Examination Team (1971) that the rock may have originated from Cone crater. If so, it probably has a complex history of transport and landed in its present position considerably more recently than the Cone crater event.

BOULDERS

Boulders at the Fra Mauro site provided the first opportunity to study the textures and fabrics of lunar bedrock. The fragmental nature of all of the boulders is evident in the photographs. Clasts from the limit of resolution (about 1 cm) up to 10 cm across are abundant, and the top of Layered rock near station C′ is interpreted to be a clast about 1.7 m across. Because the boulders are randomly oriented with respect to their original bedrock position, directional features mostly are referred to as left and right, top and bottom, with respect to the photograph; angles unless otherwise specified are with respect to the average ground surface.

In some of the boulders distinct lithologic layers are evident, whereas in others, evidence for lithologic differences between layers is subtle or absent. Parting planes that are interpreted as layers or bedding are referred to as S_a planes and are shown on the maps of the boulders as dashed lines. Some of the boulders have other moderately to well developed systematic sets of partings that are referred to as S_b, S_c, and S_d planes. No sequence of development is implied by the letter subscripts of the S-planes, except that S_a (bedding) is interpreted to be the oldest of the S-planes. A variety of less systematic, mostly curved fractures are also present in some of the boulders.

Most of the boulders are rounded and completely covered by zap pits as large as 1 cm across. Some of the boulders have knobby surfaces; others have subplanar surfaces. The relative size of boulders described below is shown in figure 34.

WEIRD ROCK

Weird rock (fig. 35), at station F, is about 2.5 m across at the base and protrudes about 1.5 m above the

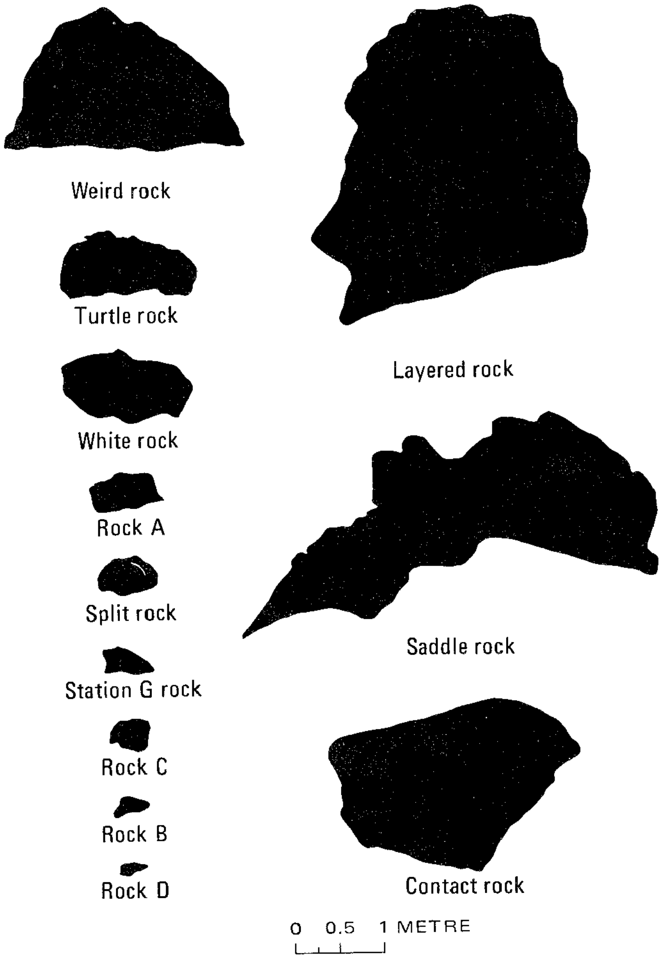


FIGURE 34.—Relative sizes of boulders.

ground surface. Its surface varies from subrounded to subangular and is hackly to knobby on a scale of about 10 cm.

The exposed lower 40 cm of the boulder has a pronounced set of approximately horizontal partings that is considered to be bedding (S_a). This set of partings is present, but weakly developed, in the upper part of the boulder. The lower part of the boulder, in the area of well-developed horizontal partings, contains two, and possibly three, relatively large clasts that are not crossed by the horizontal partings. A second set of partings (S_b) that dips to the right pervades the entire boulder, including the three clasts. A third set (S_c) that dips to the right is poorly developed in the upper part of the boulder.

The horizontal set is interpreted as partings along bedding planes developed in fine matrix material which was deposited simultaneously with the clasts in the lower part of the boulder. The matrix is not draped around the clasts, which indicates that differential compaction between the matrix and clasts has not taken place. Some of the clasts in the samples are crushed (Wilshire and Jackson, 1972), which suggests that the clasts in the boulder also may have been compacted along with the matrix material.

STATION H CLUSTER

A small blocky area photographed in the North Boulder Field contains four boulders with well-developed parting sets (fig. 36). Rocks A and B (figs. 37, 38) are subangular, with planar faces on their tops that appear to have been broken along the planes labeled S_a. Rocks C and D (figs. 39, 40) are subrounded and more knobby and irregular in shape. The differences in shape and rounding between A and B, and C and D, probably arise because the S_a planes are better developed in rocks A and B than in C and D. Three other parting sets are visible in rock A and are labeled S_b, S_c, and S_d in figure 37. Rock D has a second parting set labeled S_b in figure 40. Rocks B and C appear to have only one parting set; the other fractures appear to be randomly oriented (figs. 38, 39).

The S_a partings in rocks A and B are subhorizontal sets that are parallel to a well-developed alinement of light-colored tabular clasts (1–5 cm in long direction) (figs. 37 and 38). The tabular alinement of the clasts is interpreted as resulting from preferential orientation during deposition, and the partings therefore depict bedding planes. Rocks C and D have only a suggestion of tabular alinement of clasts. The alinement is parallel to fairly well-developed parting sets that also are interpreted as bedding planes.

The angle between the poles of the S_a and S_b planes of rocks A and D is approximately 60°. This suggests that the S_b planes of both rocks may have a common origin.

TURTLE ROCK

Turtle rock, approximately 1.5 m across (fig. 41), is the largest boulder in a field of rocks at station H. Two loose rocks (samples 14312 and 14319) were collected from the upper surface of Turtle rock and two chips (one identified as sample 14314) from the fillet adjacent to the boulder. The rock is subrounded, with a somewhat hackly surface. The discontinuous, subplanar surfaces on top of the rock are probably controlled by fractures.

Turtle rock contains abundant centimetre-size clasts; a few clasts are as large as 10 cm in an unresolvable matrix. The clasts are dark gray to white; most are approximately equant, but tabular, ellipsoidal, and contorted forms are common. Many of the white clasts are in depressions, which suggests that they may be softer and less resistant to erosion than the matrix. The surface of Turtle rock is covered with zap pits that generally range in diameter from a centimetre down to the limit of photographic resolution (about 2 mm). Several circular depressions as large as 4 cm in diameter may also be impact pits.

A moderately well developed but faint set of subparallel, discontinuous partings (S_a in fig. 41) are interpreted as bedding planes. Commonly they appear to abut against both sides of clasts along a line, but they do not cut across the clasts. There is some tendency toward convergence and divergence of the planes, and some planes are slightly curved, suggesting weakly developed crossbedding.

The other partings in the rock appear to be randomly oriented, and only one, a large fracture extending from the "turtle" to the ground, was mapped. Some of the fractures near the top of the rock appear to be spall fractures caused by micrometeorite bombardment, and their attitudes appear to be partly controlled by the bedding planes.

STATION G ROCK

An unnamed rock in the documentation photographs for sample 14306 (fig. 42) appears to be a medium-gray breccia with medium- to dark-gray clasts dominant and with sparse light clasts. The rock is subangular, with a knobby to hackly surface.

Two well-developed sets (S_a and S_b) and one poorly developed (S_c) set of partings are present (fig. 42). A planar face on the lower left part of the rock appears to be an S_a plane, and another, on the top left (not visible in the figure) appears to be an S_b plane. The S_a partings appear to be the most uniformly developed, and there is a faint suggestion of alinement of dark clasts parallel to these planes; it is upon these rather weak lines of evidence that this set is interpreted as bedding planes.

WHITE ROCKS

The White rocks at station C1 are the largest boulders examined by the astronaut crew. They exhibit a wide variety of structures and features. Four of the largest in the White rocks group were studied and named: White rock, Saddle rock, Layered rock, and Contact rock. Sample 14082 was chipped from White rock, the only rock in the group that was sampled. The rocks are categorized from photographs on the basis of light and dark rock types, as shown in figure 43.

Saddle rock is dominantly light with dark patches. Layered rock is the darkest of the group. Contact rock is approximately half light and half dark, and White rock (hidden in figure 43) is dominantly light. The major rock types within the light and dark groups are summarized in table 3.

The boulders contain a variety of planar surfaces including layering and closely spaced parting sets and large, well-defined fractures that appear to crosscut the layering. The general patterns of the traces of the partings on the rock surfaces are shown in figures 44 and 45.

White rock (figs. 45, 46) at the east side of White rocks boulder field, is about 1.25 m long in an east-west direction. It has a rather blocky shape and appears to be predominantly of one rock type, except for a prominent dark clast in its near end in figure 46. Two nearly orthogonal sets of widely spaced but well-developed planar surfaces are visible, but it is not apparent whether these surfaces represent layering or joints.

Saddle rock (figs. 44, 45), at the north end of the White rocks boulder field, is about 4.5 m long in its north-south direction. The rock has an irregular surface with dark hackly patches and resistant pinnacles. The crest line forms nearly a right angle toward the northwest, which may reflect internal structural control. Saddle rock shows evidence of at least three sets of planar surfaces. The most prominent surface, which is interpreted as layering, or S_a, is inclined to the right and is generally expressed as a series of parallel indentations and discontinuous ribs. The S_a-plane apparently controls the shape of the east face of the pinnacle that is immediately south of the saddle. The second most prominent set of S-planes, S_b, consists of subvertical fractures that are spaced a few centimetres apart with a north-northeast trend. These are expressed as closely spaced shadow lines inclined to the left crossing the short resistant ribs of the S_a planes. The S_c planes appear to be fine grooves that are traces of planes on the rock surfaces, the poles of which are oriented at about 70° to the poles of the S_b planes. Other fractures in Saddle rock appear to be curved and randomly oriented.

Layered rock (figs. 23, 44, 45), at the west end of White rocks boulder field, is approximately 3 m long and 2 m high. The upper three-fourths of the exposed part of the rock is composed of dark fragmental material, and the lower one-fourth is a layer of light material. The upper one-fourth of the rock has a knobby surface texture, and the lower three-fourths has an irregular, hackly surface texture. The light layer in the lower part appears similar in tone and texture to the light layer in White rock, and its composition may be represented by sample 14082 from White rock. The upper part of the rock is interpreted to be a clast about 1.7 m long, which in turn is dominated by clasts 30–40 cm long. Small light-colored spots are interpreted to be clasts within the 30–40 cm clasts. If this interpretation is correct, the 1.7-m clast is the largest recognized at the Fra Mauro site.

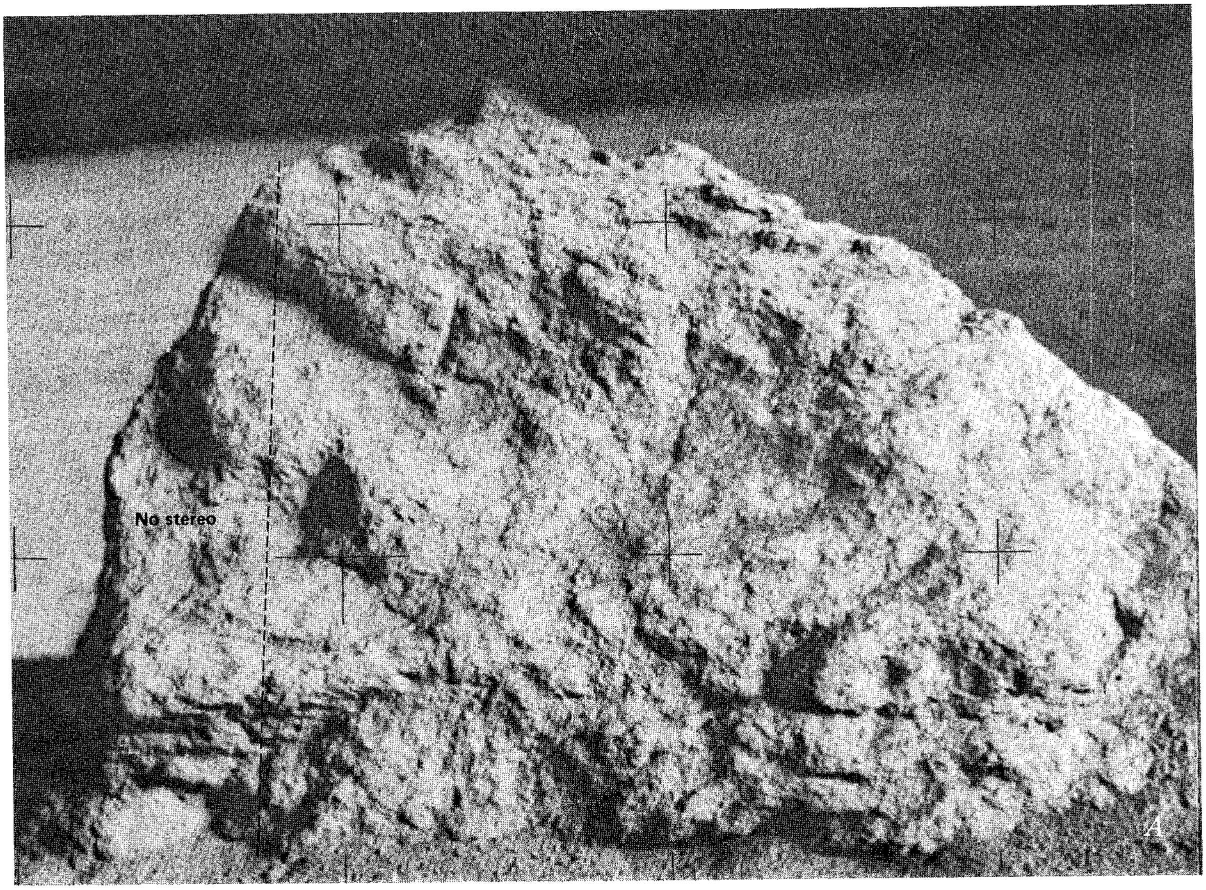


FIGURE 35.—Weird rock. *A*, View from the south. (NASA photograph AS14–64–9135.)

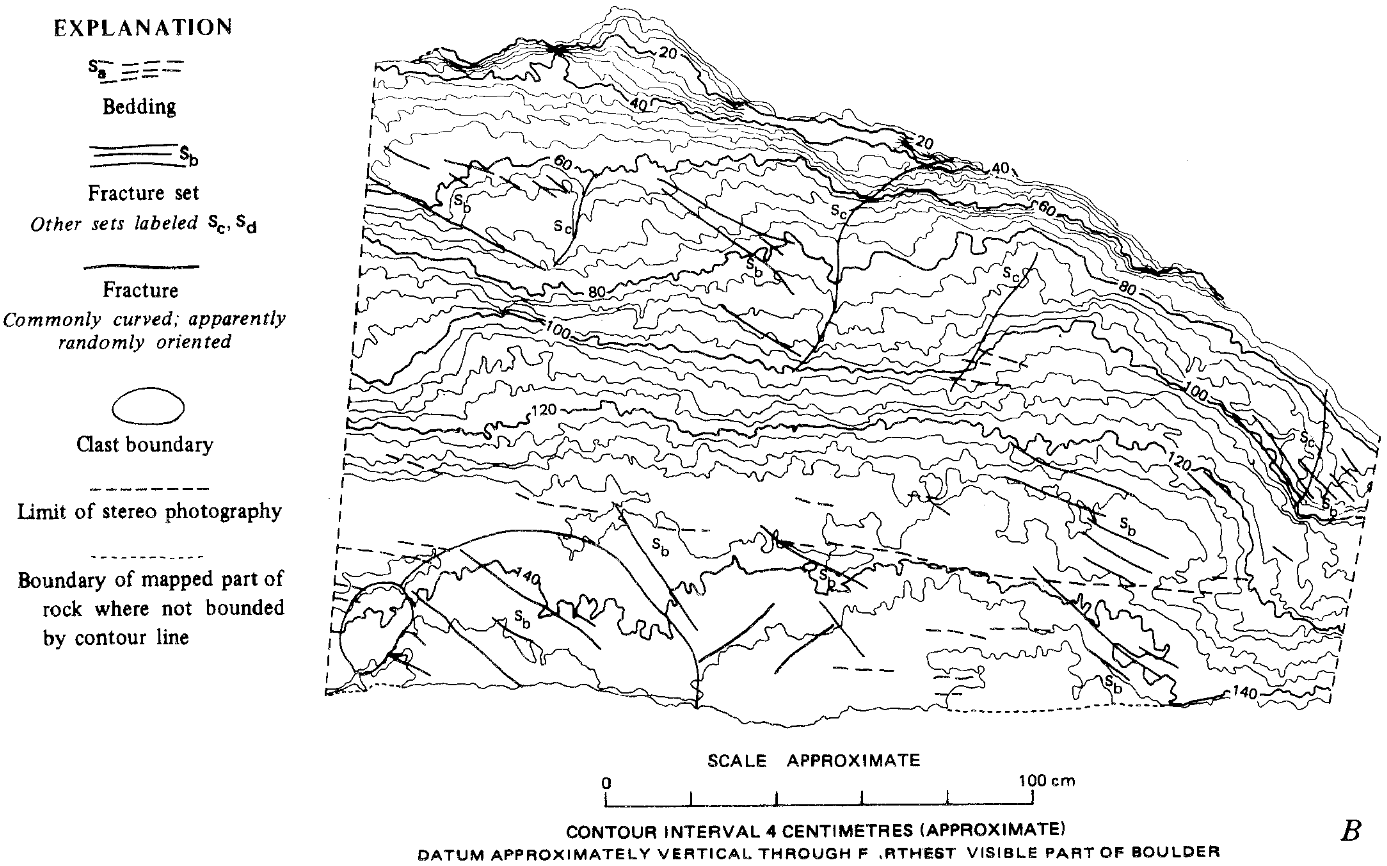
The rock may therefore represent three cycles of brecciation and deposition: (1) the formation and induration of fragmental debris that makes up the 20–30-cm clasts; (2) the formation and induration of fragmental debris that makes up the 1.7-m clast; and (3) the formation and induration of fragmental debris that makes up the entire rock and that gives it its layered appearance.

Contact rock at the south end of the field is approximately 3 m long in its north-south direction. The upper part of the rock is rounded and knobby, and the lower, lighter part is angular. The most striking feature is the irregular contact between the dark upper part and the lighter part below (figs. 19C, 44, 45). The light layer contains what appear to be fine fractures or possibly thin layers subparallel to the contact in the rock; these may represent parting planes along layering (S_a). Irregularities of the contact between the layers are similar in appearance and scale to layers within the ejecta blanket of Meteor Crater (fig. 47), as described by McCauley and Masursky (1969).

Contact rock is the only boulder of the four described that does not have a well-developed fillet. It rests in a depression with a slightly raised rim; the rim appears to have been made by impact of the rock with the surface. This suggests that the rock has not been in its present position for as long as the other boulders in the group, and that although the rock was originally ejected from Cone crater, it has been moved after the Cone crater event. The angularity of the lower part of the rock also suggests that this part of the rock has not been exposed to erosion for a long period of time. Contact rock is probably a large spall from a boulder that was struck by a meteorite and broken. It may have been broken from Layered or Saddle rock, and its original position may have been between Layered and Saddle rocks (figs. 44 and 45). The only other likely origin is that it was ejected from the 30-m crater at station C′. The rock is about two crater diameters away from this crater and appears rather large to have been ejected this far by such a small event.

SPLIT ROCK

At station C′, a boulder has broken into two large pieces (fig. 48). This well-rounded boulder, along with others in the strewn field, was probably ejected from Cone crater. The edges of the fracture that separates the boulder pieces are sharp. The rounding of the boul-



B, Topographic map showing fracture surfaces. Topography drawn by Raymond Jordan from NASA photographs AS14–64–9135, 9136.

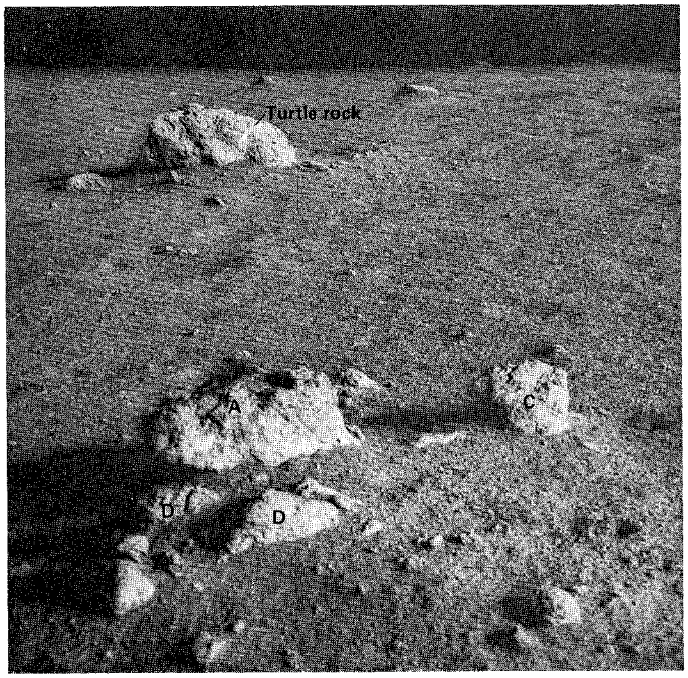


FIGURE 36.—North Boulder Field cluster (station H area). Letters refer to rocks in figures 37–40. (Part of NASA photograph AS14–68–9471.)

der is similar to that of most of the other boulders on the Cone crater ejecta blanket and probably occurred after the boulder was ejected from the crater. The sharpness of the fracture, however, suggests that the fracture is relatively recent and formed long after the boulder assumed its present rounded form. This type of fracture is probably caused by meteorite impact.

DISCUSSION

All the boulders whose surface textures and internal structures are visible in the photographs appear to be clastic rocks of impact origin. Layering, which is expressed as irregular compositional banding, alinement of tabular clasts, and regular fine-scale partings, is probably depositional layering and can be discerned on the photographs with varying degrees of certainty. Smaller scale layering in samples is reported by Wilshire and Jackson (1972) and is interpreted as primary layering from the Imbrium event. The layering therefore is the earliest structure recognizable in the boulders, and the other planar elements are interpreted as post-depositional fractures.

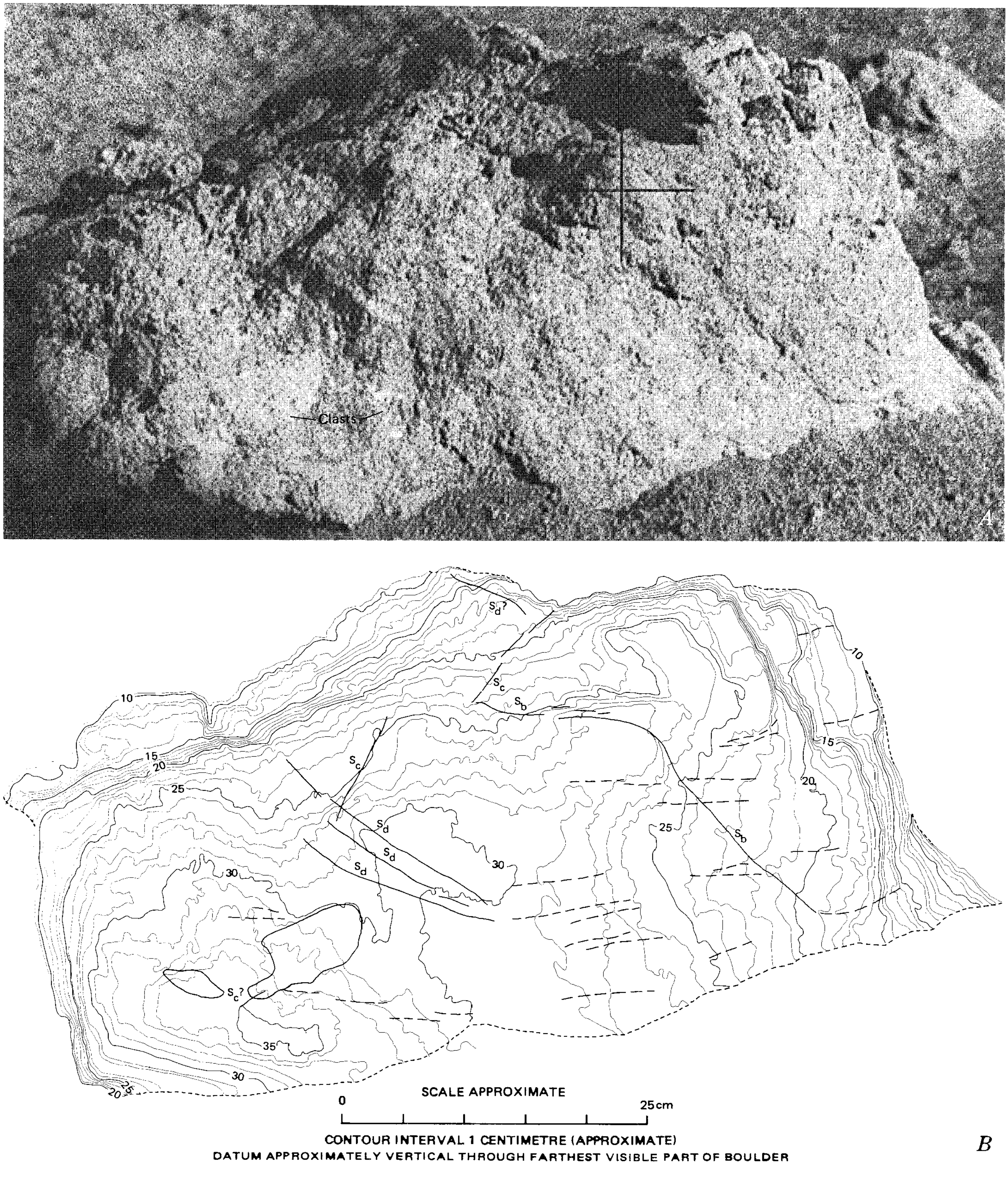


FIGURE 37.—Rock A in North Boulder Field cluster. *A*, View from south. Note alined light-colored tabular clasts. (Part of NASA photograph AS14–68–9468.) *B*, Topographic map showing relation of fractures and bedding. See figure 35 for explanation of symbols. Topography drawn by Raymond Jordan from NASA photographs AS14–68–9468, 9469.

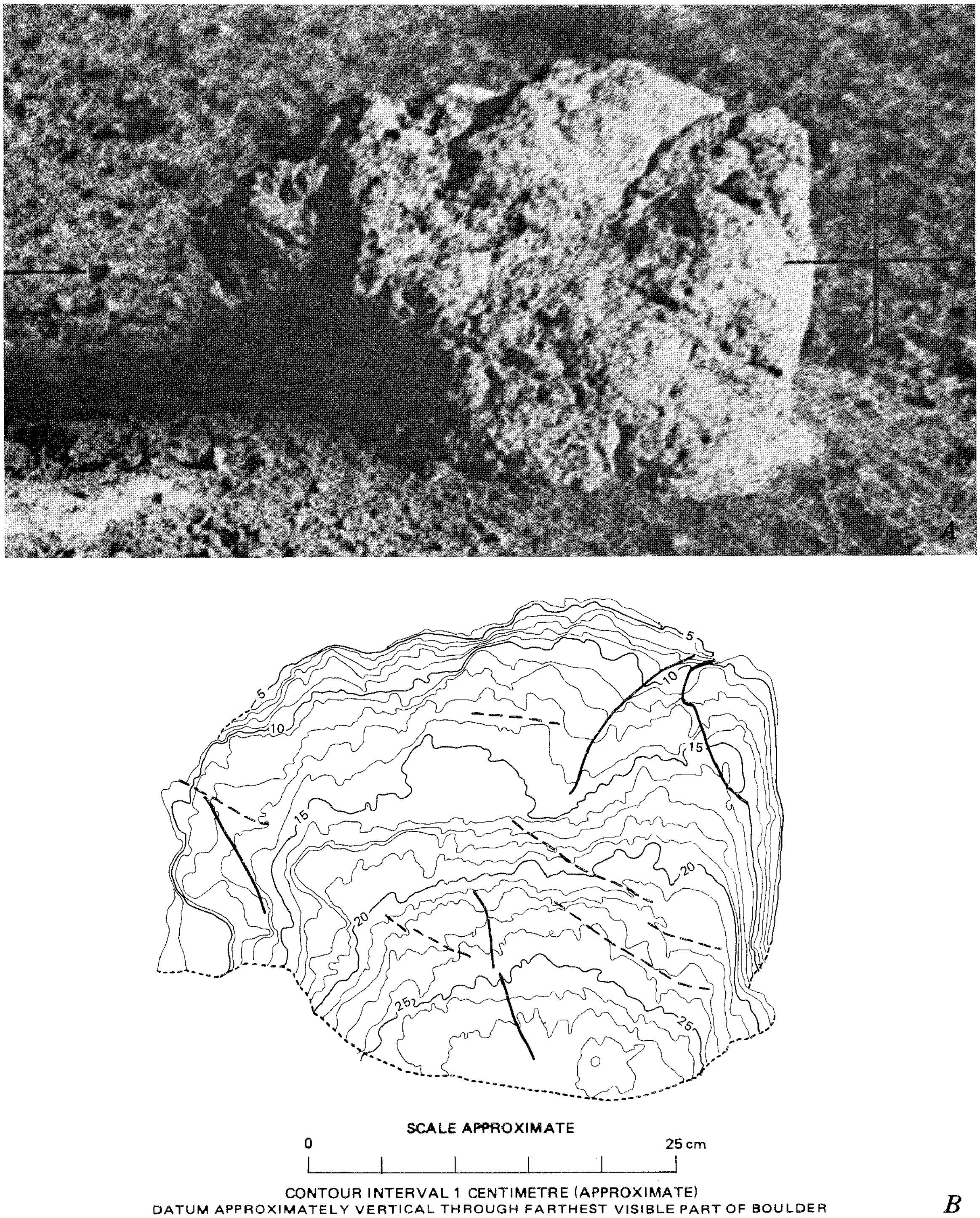


FIGURE 39.—Rock C in North Boulder Field cluster. *A*, View toward north. (Part of NASA photograph AS14–68–9468.) *B*, Topographic map showing fractures. See figure 35 for explanation of symbols. Topography drawn by Raymond Jordan from NASA photographs AS14–68–9468, 9469.

face. This is because large rocks are eroded by meteorite impact with a resulting increase in the number of smaller rocks. At about 6×10^5 to 1×10^6 fragments per 1000 m^2, a steady-state is reached at about a 1-cm fragment size, which indicates that fragments of this size are formed by shock-induration of fine regolith materials at about the same rate that the fragments are destroyed by meteorite impact.

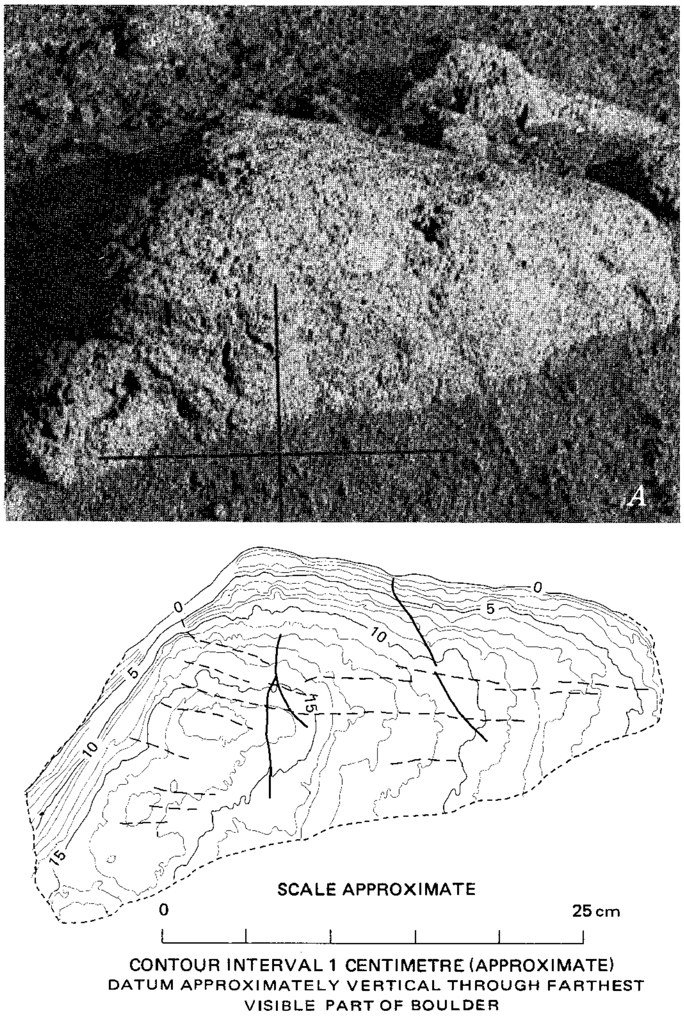


FIGURE 38.—Rock B in North Boulder Field cluster. *A*, View from south. Note alined light-colored tabular clasts. (Part of NASA photograph AS14–68–9468.) *B*, Topographic map showing relation of fractures. See figure 35 for explanation of symbols. Topography drawn by Raymond Jordan from NASA photographs AS14–68–9468, 9469.

These late fractures may be—

(1) Tensional joints formed by cooling after deposition of the ejecta from the Imbrium basin.

(2) Fractures that were formed in bedrock by Imbrian and Eratosthenian cratering events, especially from those Eratosthenian craters that occur near Cone crater (pl. 1).

(3) Fractures caused by the Cone crater event. It appears unlikely, however, that any one fracture or fracture set can be related with certainty to the Cone crater event from photographic evidence alone.

(4) The result of impacts that occurred after the rocks were brought to the surface by the Cone crater event. Several of the boulders such as Split rock, and possibly Layered and Contact rocks, appear to have been broken by meteorite impact long after being emplaced by the Cone crater event. Irregular fractures along the surfaces of rocks such as Turtle rock appear to be spall fractures caused by fatigue from repeated bombardment of micrometeorites, or possibly by diurnal thermal expansion and contraction. These spall fractures appear to be controlled to some extent by preexisting partings.

The fine matrix material of the boulders was probably produced by comminution caused by the Imbrium impact (Wilshire and Jackson, 1972). The largest probable clast is the 1.7-m one in the upper part of Layered rock. This indicates that the size of fragments that were ejected from the Imbrium basin at this distance from the impact ranged from below the limit of microscopic resolution to at least 1.7 m across.

SUMMARY OF CONCLUSIONS

At the Apollo 14 site, the Fra Mauro Formation consists of ejecta from the Imbrium basin. The upper 65 m is layered fragmental rock, some of which may have been derived from pre-Imbrian clastic rocks. Some of the pre-Imbrian cratering history therefore may be recorded in the multiple breccias of the Fra Mauro Formation. It also appears that some mare-type basalts existed in the area of the Imbrium basin before the basin formed.

The regolith in the Apollo 14 site is typically about 8.5 to 9.5 m thick, but on surfaces as old as that of the Fra Mauro Formation, areas with anomalously thick regolith are probably accumulations of fragmental debris that fill old craters. Comparison of regolith thicknesses at all Apollo landing sites shows that the rate of regolith formation fell off rapidly from about 3.7 to 3.4 b.y. ago. This agrees with other lines of evidence shown by other workers that the flux of meteorites decreased markedly during this time. After about 3.4 b.y. ago the growth rate of the Moon by accretion was probably insignificant.

The character of the regolith surface is an indicator of relative age, or maturity, of the surface. Young ejecta from craters tends to be ridgy, and as it matures it tends toward a morphology of coalescing closed depressions. Materials exposed at the lunar surface tend to darken with age, and variations in the albedos of surfaces of different ages are measureable at the Fra Mauro site. The albedos correlate with morphologic ages.

The slopes of cumulative size-frequency distribution curves for fragments increase with the age of the sur-

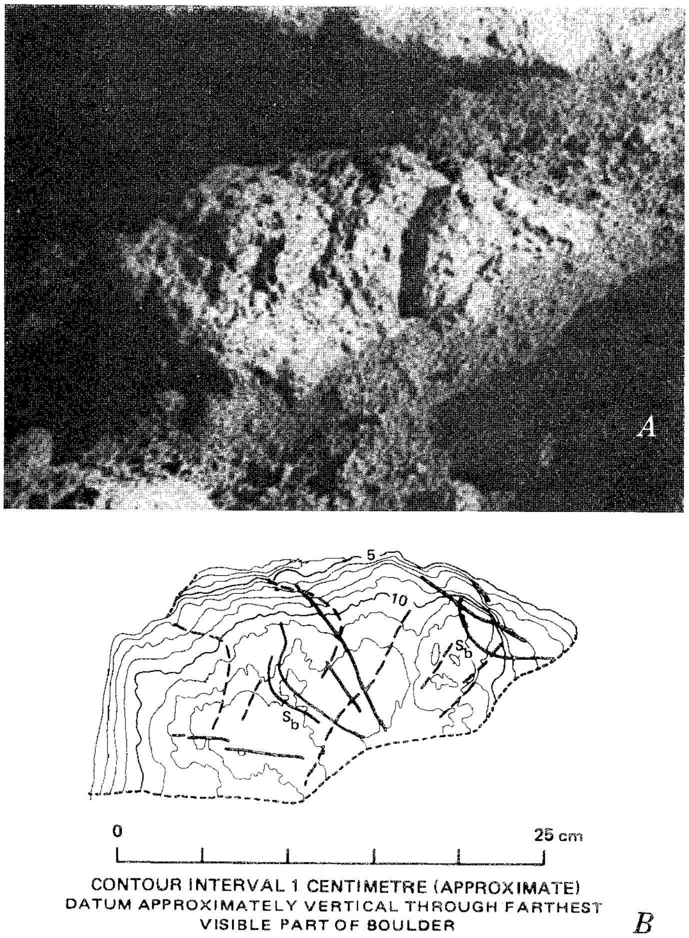


FIGURE 40.—Rock D in North Boulder Field cluster. *A*, View toward north. (Part of NASA photograph AS14–68–9468.) *B*, Topographic map showing fractures. See figure 35 for explanation of symbols. Topography drawn by Raymond Jordan from NASA photographs AS14–68–9468, 9469.

SAMPLE DOCUMENTATION AND ENVIRONMENTS

INTRODUCTION

Sample documentation includes all of the crew's observations and descriptions of samples and sample environments, as well as the lunar surface photographs that show the terrain of the landing site and which are used to determine sample distribution and lunar orientations. Documentation is required to help relate specific samples to the overall geology of the landing site.

This section is divided into two parts. The first includes illustrations of sample environments using selected lunar surface photographs. Samples are covered in sequence by ascending *Lunar Receiving Laboratory (LRL)* number. Where known, samples are identified, and insert photographs show the lunar orientation of certain rock samples as reconstructed by oblique lighting in the LRL. In several cases, model casts have been used instead of the actual samples. Orthogonal layouts show the lunar orientation and amount of burial of several samples, using selected photographs taken in the LRL. These photographs, commonly referred to as "mugshots," document the shapes of the samples from all sides.

The second part (tables 4, 5) summarizes all sample documentation, listing sample locations in sequence by traverse station, lunar surface documentary photographs, status of determining sample location and orientation, brief megascopic description of the samples, and comments by the astronaut crew at the time of sample collection (excerpted from the mission transcript). The sample descriptions are based on a very preliminary examination of the rock samples in the LRL, and should be considered analogous to a field description of the rocks that accompanies the crew's comments from the field.

We have tried to relate all the rock samples for which there are lunar surface documentary photographs to the specific and detailed geologic environments where those samples were collected (figs. 49 to 78). The purpose is to show the samples in their lunar settings—their orientations at the time of collection, their amount of burial, and their associations with other rock fragments in the immediate area, and the general charcter of the fine-grained regolith at the sample sites. All of these factors are important in reconstructing the history of any given sample on the lunar surface. It is clear, from samples returned by Apollo 14 and previous missions, that rocks are likely to be tumbled and broken from time to time during their exposure at the lunar surface. The rate of tumbling and regolith gardening may be further defined by studying samples.

Several terms are used in the sketches on the sample documentation photographs and in the tabulated data summarizing sample environments:

Area covered.—Perspective scales are included in most photographs to show distances and sizes of features. Most detail is, of course, seen within 3 m of the camera, and the environmental summaries are limited to the near field of view. The horizon on some photographs may be several kilometres away.

Rock burial and fillets.—Fillets are embankments of fine-grained material against rocks on the surface, and are discussed on pages 20–22 in this report. Burial refers to the amount of rock that is below the average ground surface, exclusive of the fillet.

Color.—Colors are interpreted from lunar surface photographs and from LRL sample photographs. They are subjective only and are mostly limited to relative

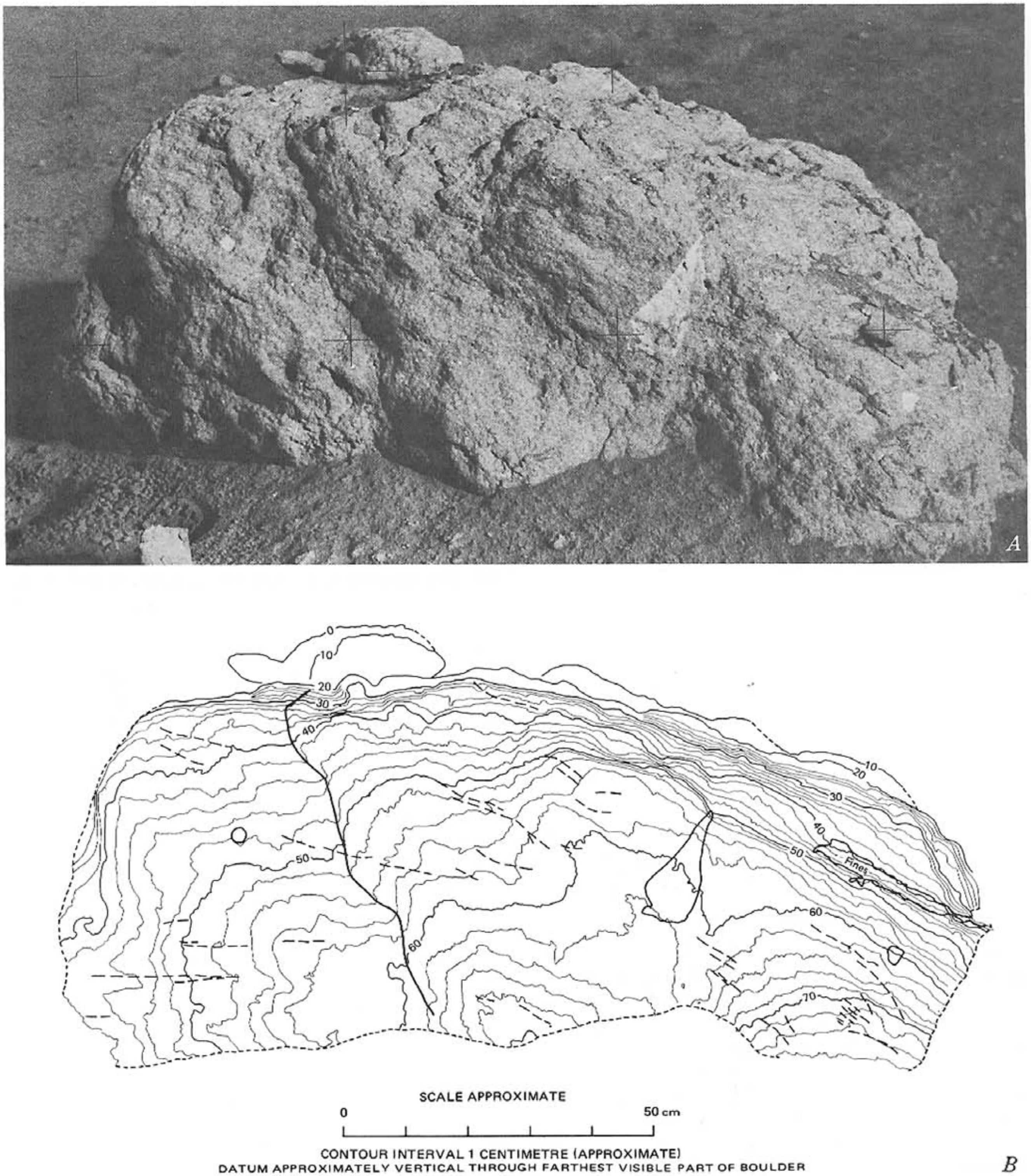


FIGURE 41.—Turtle rock. *A*, View toward north (note white clasts). (Part of NASA photograph AS14–68–9476.) *B*, Topographic map showing fractures and clasts. See figure 35 for explanation of symbols. Topography drawn by Raymond Jordan from NASA photographs AS14–68–9474, 9475.