Submarine Geology by Diving Saucer

Bottom currents and precipitous submarine canyon walls continue to a depth of at least 300 meters.

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Exploration by submarine of narrow precipitous-walled canyons at depths of as much as 300 meters would have sounded like a Jules Verne story a few years ago. The bathyscaphe has been carrying men to great depths since 1953, but no one in his right mind would have dared to take this large unwieldy vessel into a narrow gorge. Jacques-Yves Cousteau, with his usual energy and initiative, developed a two-man diving saucer (Fig. 1), a much smaller craft, that has made it possible for scientists to view some of these previously inaccessible underwater features. Although the saucer has made many dives in the Mediterranean and Red Sea, including some into sediment-mantled canyons, it was not until February 1964 that it was taken into a narrow rocky submarine canyon. Through special arrangements made between Westinghouse Corporation and the Marine Physical Laboratory at Scripps Institution of Oceanography, we were able to lease the saucer for 2 weeks, together with its expert crew of French technicians and the tending ship *Surf Tide*. During this period, geologists made eight dives into Scripps and La Jolla submarine canyons (Fig. 2) and one dive to the shelf and upper slope nearby (Fig. 3). On each dive the saucer carried a French pilot and a scientist from the Scripps Institution.

Canyons

The dives permitted us to see the shelf and canyon for almost a mile seaward of regions explored by scuba diving, in areas inaccessible to a bathyscaphe. In all dives the position of the saucer was determined with a 37-kilocycle directional "pinger" on the saucer and a directional receiver in a skiff. Location of the skiff was determined by horizontal sextant angles between points on shore.

The precipitous and even overhanging walls, known already in the head of Scripps Canyon (*1*), continue seaward for the entire length (Fig. 4) of the canyon to where it joins La Jolla Canyon 2 kilometers from the coast. In places the walls are so close together that it was impossible to get the saucer (3 meters across) through to the bottom. The walls of La Jolla Canyon are mainly less precipitous but include vertical and overhanging sections with intervening talus sloping at about 30 degrees. Since there are many overhanging walls, it is clear that even the detailed soundings made previously by echo- and wire-sounding techniques were misleading for some places.

The description of Scripps Canyon may be simplified by considering the following three zones separately: (i) the shallow sandy bowls from near sea level to a depth of about 20 to 40 meters; (ii) an intermediate steep, rocky gorge extending to a depth of about 100 meters; and (iii) a deeper rocky gorge with lower average gradient including nearly horizontal platforms separated by rock steps. This portion extends to the junction of Scripps and La Jolla canyons at a depth of 300 meters.

The branches at the head of the canyon have been explored by scuba divers. The branches consist of wide dish-like depressions near the surf zone, narrowing abruptly at depths from about 20 to 40 meters into rocky channels with nearly vertical walls (*2*). The depressions are usually filled with sand and plant detritus sloping gently toward the channel. In the rocky channels, such as South Branch, and in the smaller tributaries at the head of Sumner Branch (Fig. 2), this detritus commonly lies near the angle of repose (25 to 30 degrees).

The steep intermediate zone includes the junctions of all the main tributaries. The mouth of South Branch, which joins Sumner Branch, forms a

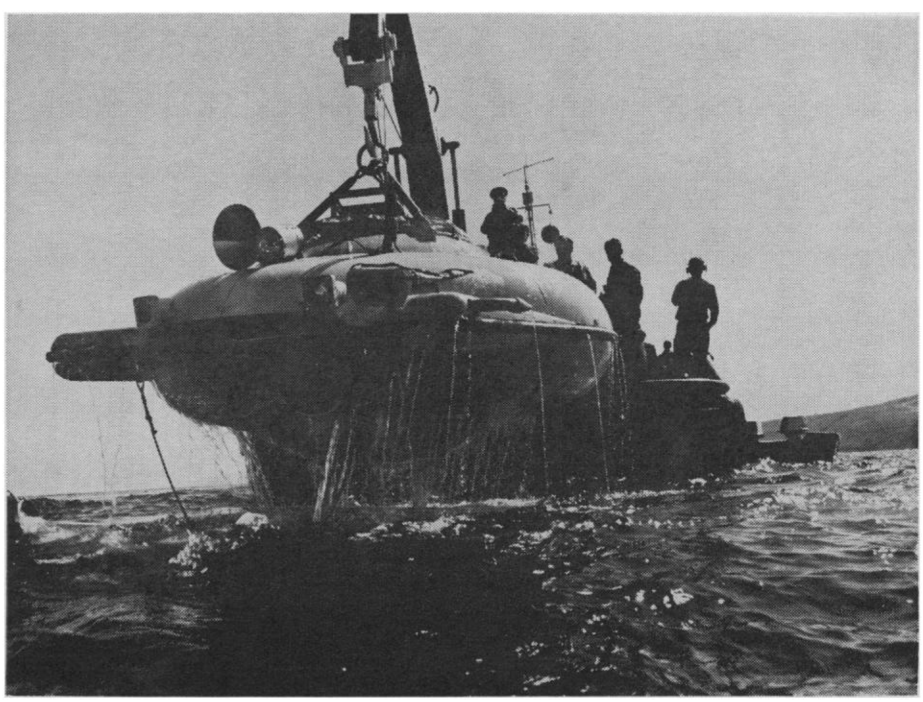

Fig. 1. The diving saucer coming up after a dive in the submarine canyon off La Jolla. [Ron Church]

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hanging valley at a depth of about 50 meters. At this point, Sumner Branch has a depth of about 65 meters. The longitudinal profile, as typified by Sumner Branch, consists of a series of closely spaced rock steps, perhaps controlled by the outcrops of resistant rock layers. Sand near the angle of repose covers the platform, and clean rock crops out along the lip of each step. The rock steps are not well developed and at times extend across the entire floor of the canyon, which is about 10 meters wide. The overall slope of the canyon axis is about 15 degrees. The rock steps are numerous, and the vertical drop on the down-canyon side generally does not exceed 1 meter, though some steps are as high as 4 meters. The canyon walls are vertical but in some areas are cut back as much as 1 meter, up to a height of 2 to 4 meters above the floor. The undercut portion of the wall and the rock outcrops in the floor are smooth and show little evidence of organic growth, and, where shale beds are undercut, there are truncated pholad holes and horizontal flutings. The walls above about 3 meters are liberally covered with organic growth: hyroids, chytopterous worms, ring corals, gorgonians, and boring clams.

The deep portion of the canyon, starting at the junction of North Branch and Sumner Branch (Fig. 2), extends seaward approximately 2 kilometers to the junction with La Jolla Canyon; the depth changes from about 100 to 300 meters, and the overall slope is about 5 degrees. This section, especially in the upper part, consists of a series of nearly horizontal platforms covered by sand and plant detritus and terminated by rock steps. Most steps extend completely across the canyon floor and have vertical drops of 2 to 8 meters on the down-canyon side. Elsewhere, except for the rock steps, the floor varies from nearly flat to hummocky and consists of sand that in places contacts both walls at right angles and at other places contacts the walls in a smooth curve. In two places, longitudinal depressions as much as half a meter in the sand floor were observed next to the rock walls. The walls are commonly undercut and smooth, without organic growth, to a height of 2 to 3 meters (Fig. 5). Above this height, as in the steep intermediate zone, the walls are covered with organic growth. The canyon floor generally varies in width from about 3 to 18 meters, but in a few places below depths of 170 meters the distance between the overhanging walls narrows to less than 3 meters.

There is an 8-meter rock step where Sumner and North Branches join to form Scripps Canyon. North Branch has many of the characteristics of Sumner Branch. However, it lies seaward, has fewer tributaries, and is wider. The lower portions of the axis are less steep and are covered with large blocks that have fallen from the steep west wall. The organic growth on the walls extends nearly to the floor.

Down-canyon currents of as much

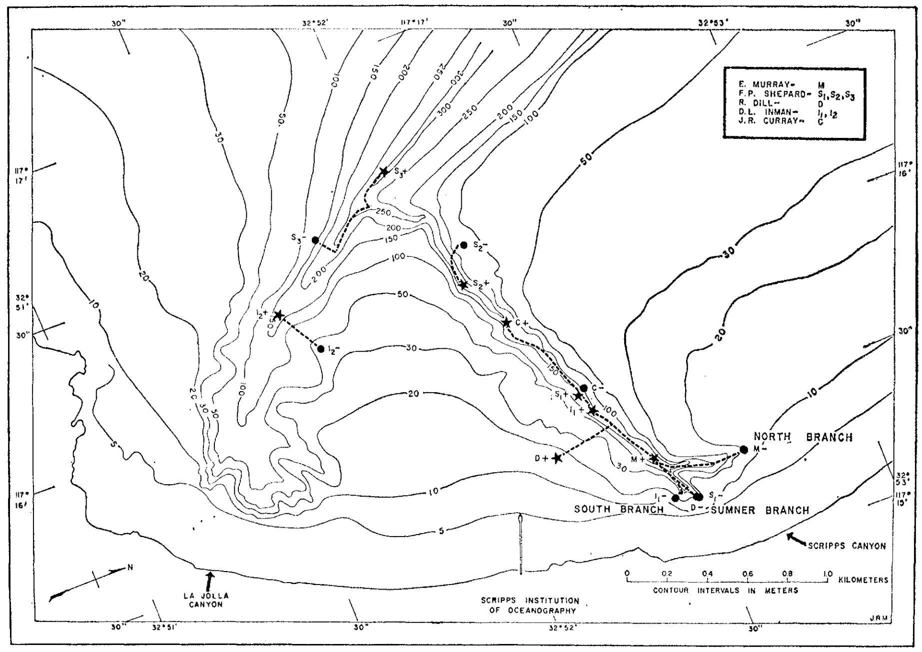

Fig. 2. Scripps and La Jolla submarine canyons, showing the routes for each dive (—, point of submergence of diving saucer; +, point of emergence).

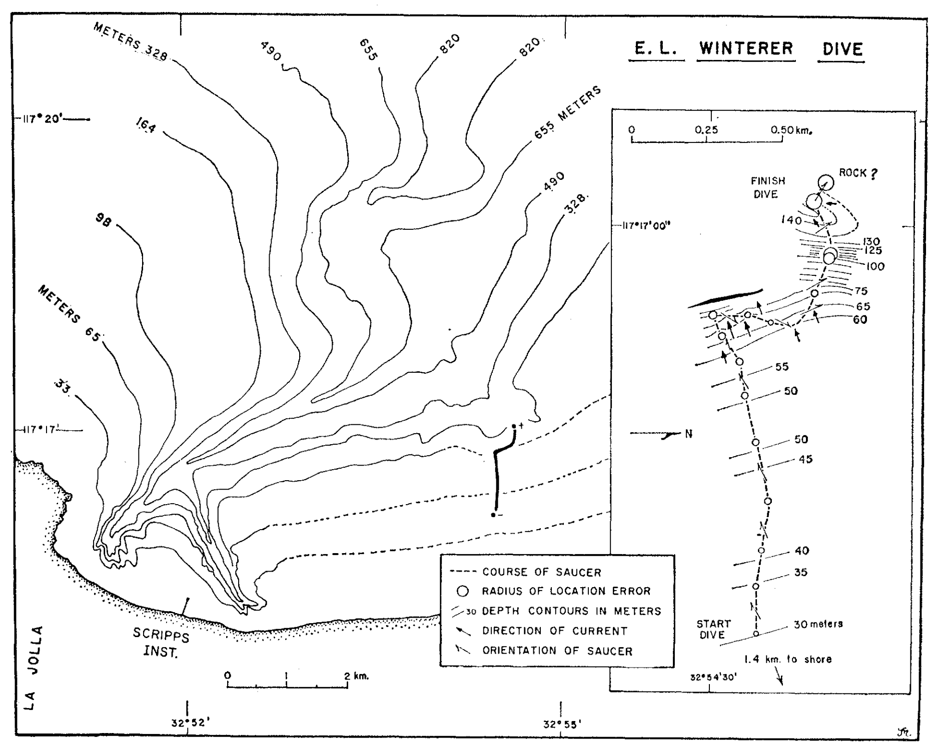

Fig. 3. Bathymetry in the vicinity of the dive on the outer shelf and upper slope. The inset shows the details of the bathymetry and the direction of currents observed along the routes of the saucer. For the circles indicating errors of location, a directional error of ±10 degrees is assumed for the pinger system and a ±5-meter error from sextant reading and plotting.

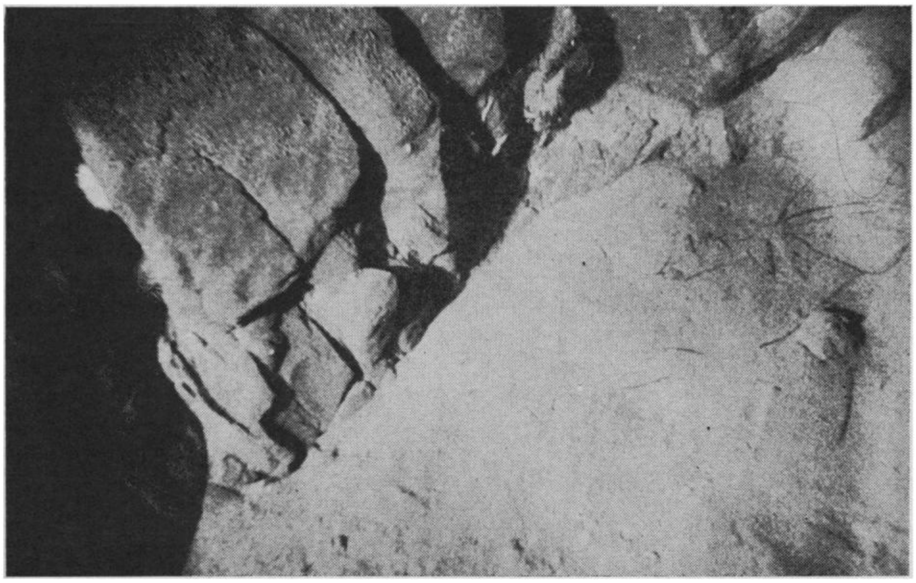

Fig. 4. Shepard, dive 3, depth 290 meters. Vertical and partly overhanging rock wall and sediment contact in lower part of Scripps Canyon. The lower part of the rock wall is virtually free of organisms, indicating recent erosion.

as 10 centimeters per second were observed at many places in the canyon, but especially at depths greater than about 100 meters. Weak up-canyon currents were observed on three occasions at depths between 140 and 170 meters. Wave surge was observed only in shallow water (less than 50 meters deep). Suspended matter was observed in the water column and on the walls and bottom, probably consisting of both fine sediment and organic matter. This suspended matter and the common occurrence of sand and mud talus slopes against the walls in the deeper portions of the canyon suggest that a considerable amount of sediment comes laterally into the canyon from the adjacent shelf, although the bulk of the sand is transported from the canyon heads.

The floor of La Jolla Canyon is generally wider than that of Scripps Canyon, about 10 to 30 meters across, and is covered with sand or muddy sand. At most places the walls of the outer portions of La Jolla Canyon have accumulations of talus at their junctions with the canyon floor. The walls are mostly sandstone and shale, though conglomerate was seen just beyond the junction with Scripps Canyon. The rocks in Scripps Canyon are nearly flat-lying beds of conglomerate, with lesser amounts of sandstone and shale, probably of Eocene age. The junction of Scripps and La Jolla canyons appears to be at grade, with the axes of both canyons converging at about the same degree of inclination.

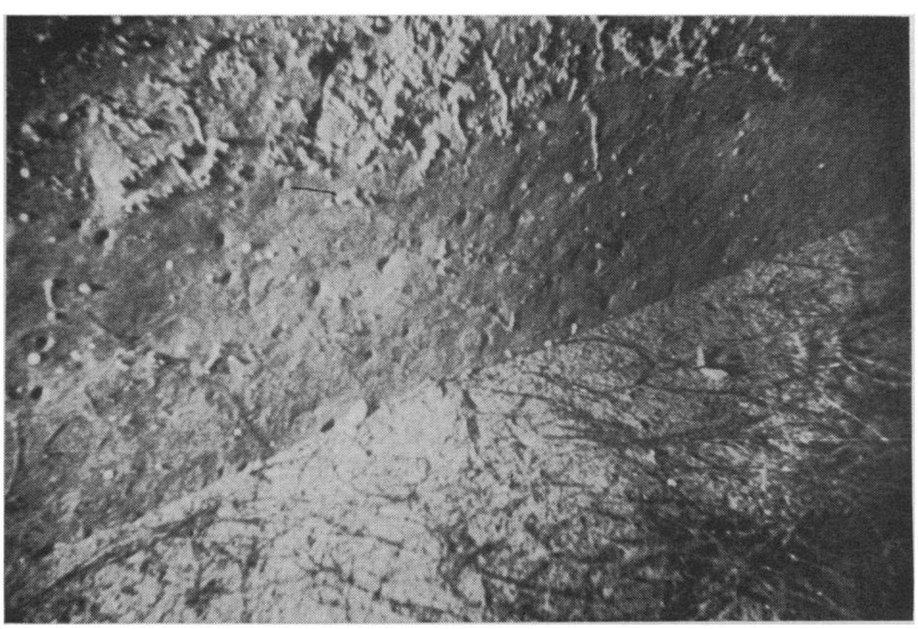

Fig. 5. Inman, dive 1, depth 140 meters. Scripps Canyon, showing contact of smooth rock wall with nearly horizontal sand floor (apparent slope due to perspective). Truncated pholad borings appear to be present in the vertical wall, and surfgrass is scattered over the floor.

The Open Shelf

The dive near the edge of the narrow shelf a few miles north of Scripps Submarine Canyon (Fig. 3) enabled us (i) to observe an area of modern sediment supply where sands close to the shore, already studied in nearby areas by scuba divers (*3*), might grade seaward into muddier sediments; (ii) to observe sediments and sedimentary processes near the outermost edge of the shelf and along the upper parts of the adjacent slope; (iii) to explore what appears on available charts to be a small submarine canyon heading at the shelf edge in some 75 meters of water; and (iv) to examine outcrops of bedrock on the slope and in the canyon.

On the day of the dive (4 February 1964), the range of the tides was only about 1 meter. A swell with a 12-second period from the WNW with waves about 1 meter high was augmented during the course of the 4-hour dive by local sea waves of short period, which made the sea choppy, and thus it was difficult to hold the tracking skiff on the surface exactly over the saucer.

The properties of the sediments on the shelf change very gradually from where the dive began at about 30 meters depth, seaward to the first important change in slope at about 60 meters. At 30 meters, the bottom consisted of fine micaceous sand formed into long-crested ripples about 2 cm high and 12 cm wave length. The ripples trended very nearly parallel to the bottom contours in this area, branching and joining at intervals of 1 or 2 meters. Very fine dark-colored organic material and mica flakes were concentrated along the ripple crests, moving to and fro with the 12-second rhythm of the swell, but the sand itself did not appear to be in motion. Pieces of kelp and surfgrass lay scattered here and there on the sand, moving back and forth at the orbital velocity of the waves. Seaward, the grain size decreased and the mica content increased while the height and wave length of the ripples decreased. Animal burrows, trails, and hollows became more frequent and tended to obscure the ripples; nonetheless, ripples persisted to a depth of 60 meters, and the rhythmic motion of the swell continued to move stray bits of vegetation and to sway the sea pens and partly buried strands of surfgrass.

At a depth of about 60 meters, the seaward slope of the bottom increases gradually to an angle of about 10 degrees and, although the back-and-forth motion of sea pens continued with the same regular period, a new and additional current was evident: whenever sediment was placed in suspension by a fish stirring the bottom or by a piece of anchored surfgrass swaying over the mud, for example, then the sediment was carried westward, down the gentle slope. The slope, which continues to a depth of 75 meters at about the same inclination, was crossed in three places during a period of 1 hour, and the same kind of current was noted everywhere: westward-flowing, downslope, superimposed on an east-west to-and-fro motion, and moving at least 10 cm per second. At one point, a large clump of kelp about 20 cm in diameter was seen rolling down the slope at a speed of about 30 cm/sec. On the lower part of this long slope, sets of nearly parallel grooves a few millimeters deep scribed the burrowed mud, marking out, most probably, the passage of other objects moving down the slope.

At a depth of about 75 meters, the gentle slope gives way abruptly to a series of rocky ledges and cliffs. The visibility, which was only a few meters on the shelf and gentle slope, increased dramatically to more than 10 meters. Sandstone and conglomerate, in general heavily encrusted with organisms, crop out on the cliffs; siltstone, covered with a thin mantle of mud, crops out on the more gently sloping ledges. To measure the strike of the beds, horizontal ledges were traced while the direction of the submarine was noted on the gyro compass, a hand-held inclinometer being used to measure the dip. By ascending the cliffs slowly and noting the changes in depth on the depth gauge or on the surface-directed echo sounder, the stratigraphic section can be described in the conventional manner. Attached to the saucer is a movable arm and claw used for taking samples which are stored in a basket mounted outside the saucer.

During the maneuvers along the cliffs, especially near the shelf break, such strong surges of current were pushing the submarine that the pilot could not hold its position or orientation.

Below a depth of 125 meters, the outcrops end and the bottom consists of a westward-sloping surface of burrowed micaceous mud, like that on the gentle slopes above. The slope continues to a depth of 145 meters, flattening gradually from about 15 degrees at the edge of the outcrops to the bottom of a smooth trough whose axis appeared to slope southwest. No coarse sediment was seen in the trough, nor was there any sign of mass movement of the muds; on the contrary, the impression was that we were in an inactive valley. Yet even here a current was flowing southwestward, down the valley, at about 10 cm/sec, carrying with it mud stirred into suspension by fish on the bottom.

Conclusions

The longitudinal profile of Scripps Canyon shows marked changes in average gradient at about 20 to 40 meters and at about 100 meters. These changes in gradient may be due to (i) differential erosion and influence of bedrock, (ii) the influence of changes in the Quaternary sea level, or (iii) differences in mode or rate of transportation of sediment down the canyon. Tentative results from these dives support both (i) and (ii) as principal factors in causing the changes in gradient. Erosion by down-canyon sediment transport is now modifying the upper portion of the canyon, but is not responsible for the changes in gradient. Hypothesis (ii), that fluctuations in sea level may be the dominant factor, is preferred for the deeper change in gradient because of the similarity of the 100-meter depths to the depth at which a change of gradient occurs on open shelves. The average depth at the edge of the continental shelf off La Jolla is about 100 meters; the worldwide average is about 130 meters. Many shelves around the world also show an increase in gradient at about 60 meters, as reported for our dive to the open shelf.

Most of the currents measured during these dives on the floor of Scripps Canyon flowed in a down-canyon direction with estimated velocities as high as 10 cm/sec; observations of the open shelf and slope indicate similar down-slope velocities. The origin of these currents is unknown and their significance cannot be evaluated without further systematic observation. Internal waves, surf beat, or seaward return flow of water carried inshore by surface swell are possible explanations. If these currents are persistent, they may be of significance in the transportation of sediment across the continental shelf, the prevention of deposition of fine sediment at the shelf break, and the entrapment in the canyon of sediment swept off the adjacent shelf. The sand load of the canyon must be derived primarily from the canyon head seaward of the surf zone, while the fine sediments known in the canyon floor and in the submarine fan at the mouth of the canyon must be at least in part derived laterally by this current drift from the adjacent shelf into the canyon.

Transportation of sediment must have occurred down Scripps Canyon in the past, and there is considerable evidence that such transport is occurring today. (i) Despite the known contributions of sediment, the canyon is not full. (ii) There is a lack of growth on the lower portions of the walls of the canyon compared with the higher portions; the lower portions are polished and smoothed and contain truncated pholad borings (*2*). (iii) The thickness of the sediment fill in the canyon heads changes frequently. (iv) At a place where the axis of the canyon is 190 meters deep, a heavy anchor chain is looped over a pinnacle on the wall of the canyon and is pulled taut in a down-canyon direction. (v) Man-made objects put in the canyon are displaced down-canyon.

The modes of transportation of sediment and hence the causes of erosion are not yet understood and are highly controversial. Several possibilities may be suggested: slow creep, sand flow, a series of progressive slumps and slides, rapid turbidity currents, or dilute bottom currents of the type observed during the dives. A whole spectrum of possibilities exists and further observations and measurements are needed to resolve the problem.

References and Notes

1. F. P. Shepard, *Bull. Geol. Soc. Am.* **60**, 1597 (1949).
2. T. K. Chamberlain, thesis, Univ. of Calif., Scripps Inst. Oceanog. (1960); R. F. Dill, thesis, Univ. of Calif., Scripps Inst. Oceanog. (1964).
3. D. L. Inman, *Beach Erosion Board Tech. Mem.* **100** (1957).

4. Support for this research came from the Office of Naval Research. Expert piloting by A. Falco and A. Laban contributed immeasurably to the success of the operations.

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Ranger Moon Pictures: Implications

Prior to the Ranger pictures the information about the small-scale structure of the lunar surface had been limited to that obtainable by telescope and radar observations. Earthbound telescope observations had given information down to a scale of about 1 km, and had clearly shown that craters existed in all stages of "freshness." Craters that would be judged old by the criterion of overlap by others, were generally seen to be smoother, less high for a given diameter, and often had a rather smooth interior. Young craters had apparently sharp rims and steep, rugged features. From the consistency of this effect it had been concluded that there was an active erosion process continuously degrading the features of the moon much as erosion alters the surface of the earth. This posed the question of a mechanism for transportation in the absence of agencies that erode on earth. The required rates are of course very low compared with terrestrial ones; removal of 1 micron per year from high ground and deposition on low would suffice to create the observed effects in all of geologic time. This could still lead to deposits 4 km deep. It is very difficult to judge such very slight processes in unusual conditions. However no processes could be envisioned that would transport large pieces of rock except the impact explosions. Those, however, convert much material into fine powder, and even with their action one could not contemplate a large fraction of the deposit on low ground being in any state other than dust. However the rates that could be ascribed to this process are too low in view of the number of small craters seen, and an additional process is required. Several processes can be suggested that may be effective in transporting material downhill, but only if it is in finely divided form. This was the origin of the suggestion that rock dust was the major constituent of the lunar surface, and that low regions had accumulations of it down to the depth of the original features, judged in some cases to be 2 or 3 km.

The fact that deposits of dust may be kilometers deep must not be taken to mean that the material maintains the consistency of a fine powder at great depths, no more than it does on the earth. Sediments originally made of fine particles may be in various stages of cementation. The agencies causing cementation of sediments on the earth are mostly different from those that could be active on the moon. There vacuum welding may be very important, especially for particles that are pressed together for such long periods of time that solid-state diffusion is a significant effect. Close to the surface, effects of sputtering and of evaporation and condensation can also assist in cementing grains together. The discussion of the mechanical properties of such sediments is clearly very important for future exploration of the moon, and measurements of these must receive a high priority in future missions to the moon. But it is important to keep separate the discussion of the origin of the material and its present mechanical properties—a point which has been confused in the literature and in popular writings where it has often been implied that if the low ground is filled with dust sediment then it will be loose and soft to some great depth. This is no more a direct implication there than it would be in the Mississippi basin. Nevertheless, such an origin raises the question of the bearing strength of the surface for exploration purposes, while an igneous origin would have implied almost inevitably an adequate strength.

Erosion and a sedimentary origin for the *mare* material was also implied by a different observation. Almost without exception craters that fell partly on highland and partly on *mare* ground had the *mare* portion much more heavily eroded, and often it had disappeared altogether. Thus *mare* material appeared generally more susceptible to erosion, and therefore, most likely, it was not as solid a material as much or all of the highlands. One is there concerned with thicknesses up to 3 km, and the argument is independent of thin layers that may influence the radio, thermal, or optical properties of the surface.

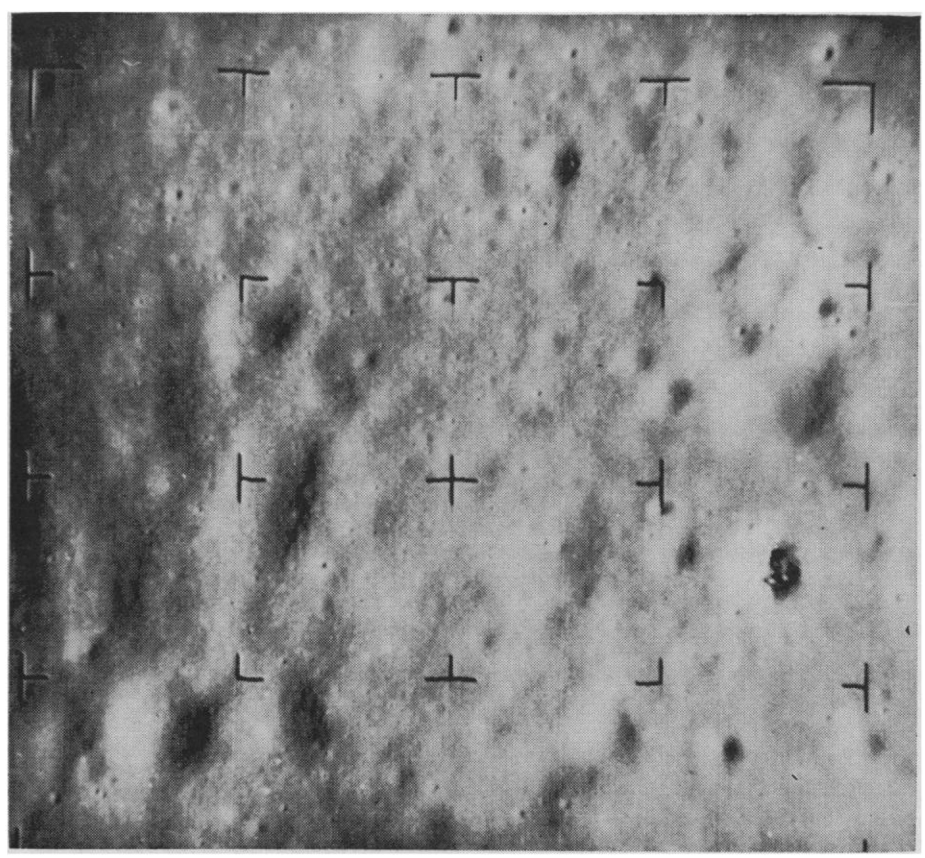

Fig. 1. High definition Ranger picture [scale, 1⅔ mile (2.6 km) on a side], showing many gently rounded craters in otherwise featureless terrain. Note the resolution of the photograph by means of the few small sharp-featured craters.