Looking down to the floor of Meteor Crater, Arizona—a depression 3,168 feet in diameter and 500-600 feet deep, formed by the impact of an iron meteorite perhaps not much more than 100 feet in diameter. Blocks in foreground are rock fragments thrown out of the crater to form a low detrital rim-ridge. Most craters on Mars and Moon are thought to be of similar origin.

Geomorphology In The Space Age

by Robert P. Sharp

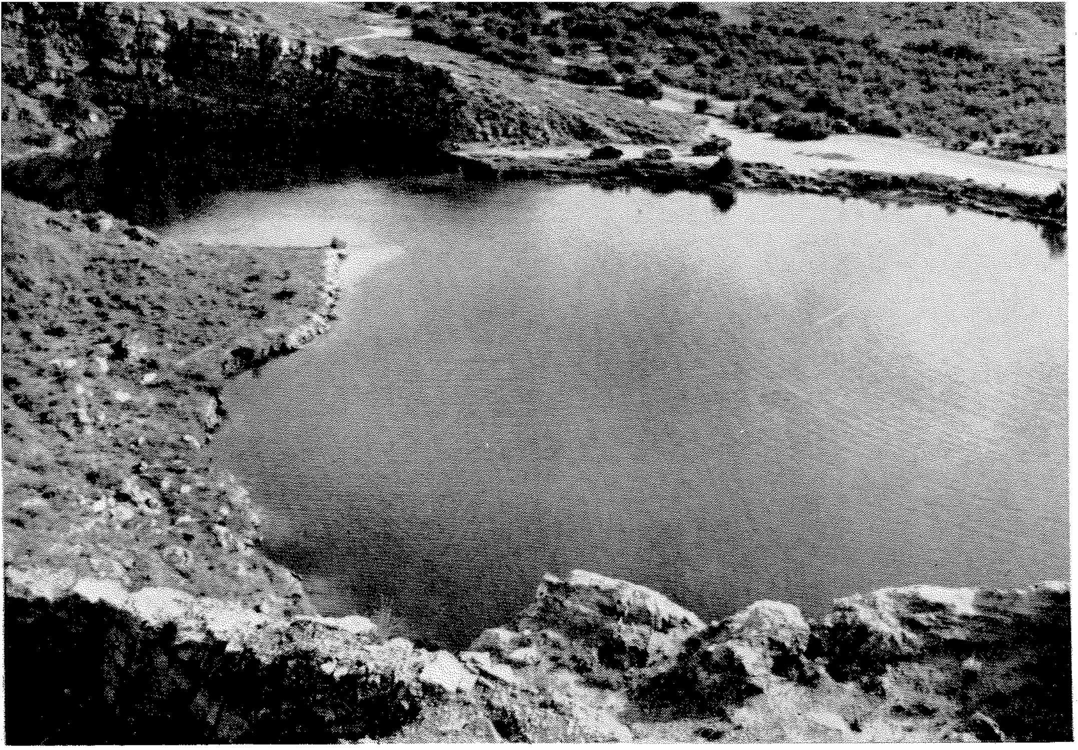
Geomorphology, the science of land forms, is one of the older classical subdisciplines of the earth sciences. Nonetheless, it maintains an encouraging viability within the framework of modern scientific endeavors. It was no accident that some of the major geological explorers of the Far West—Powell, Dutton, Russell, and Gilbert, to name a few—were accomplished geomorphologists. Geomorphology involves techniques which an experienced observer can apply to an unknown terrain with minimal equipment and maximum product. Observations of surface forms and features during their wilderness travels enabled these men to draw meaningful conclusions concerning the geological makeup and evolution of the regions traversed.

One of the great delights of science is the continual development of new fields to conquer. Currently, the geomorphologist has two enticing *terra incognita* to consider: the floor of the ocean and the surfaces of the moon and other planets. Both are well worth attention, but currently at Caltech our efforts focus more on the moon and planets.

For good reason, the early space probes launched toward Moon and Mars had as a principal mission the photographing of the surfaces of those bodies. Photographs provide the greatest amount of information, at the lowest cost, about lunar and planetary surface conditions. The interpretation of such photographs is largely, but not exclusively, a geomorphological procedure. The best analog from which to work is the earth, which geomorphologists know well.

Even the earliest telescopic observations of Moon showed its surface to be pocked with craters. What makes natural craters on Earth? Meteorite impacts, volcanic explosions, and subsurface collapses of a variety of origins are common causes. Painstaking study of earthly craters has led most investigators to conclude that lunar craters are largely the product of meteoroidal impact. Still there are those who stoutly support a volcanic explosive origin for some, if not a majority, of the lunar craters; and most serious students of the moon are far from ready to assert that there are no volcanic features such as craters, cones, lava domes, lava flows, and sheets of volcanic cinder and ash on its surface.

Furthermore, Ranger and Orbiter photos reveal small craters and linear features on the lunar surface not unlike forms created on Earth by collapse into subsurface openings. These features have caused some observers to speculate on the possible existence of an ice layer beneath the lunar surface that locally melts or evaporates, leading to the for-



So-called Bottomless Lake, New Mexico, affords a good example of a crater-like feature formed by collapse owing—in this instance—to removal of underlying limestone beds by ground-water solution. Many of the smaller craters on the moon look like collapse features, but the possible causes of lunar collapse remain a subject of speculation.

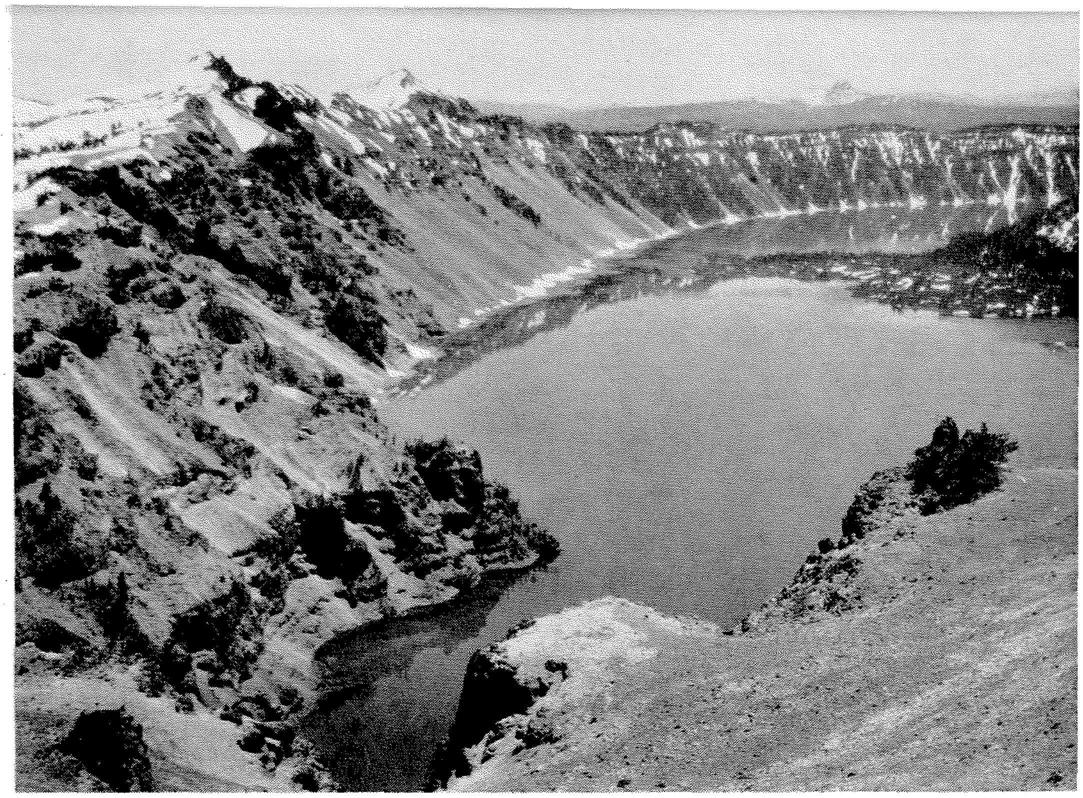
mation of collapse features on the surface. Whatever their cause, collapse features do seem to exist on the moon's surface.

One thing made clear by Ranger and Orbiter photos is the considerable modification undergone by many lunar craters. Great slump blocks are seen on the inner walls of large craters, and loose rubble has clearly flowed, crept, or slid down the crater walls. These sorts of transport are old friends to the geomorphologist, and he quickly appreciates their role in altering craters and other topographic forms. However, the principal process modifying lunar landscapes is something he is less familiar with in terms of earthly analogs.

Each time a new crater is formed on the moon, whether by meteorite impact or volcanic explosion, a curtain of ejected material is sprayed at high velocity and for great distance over the surrounding terrain. These flying fragments, unimpeded by any atmospheric envelope, impact and abrade everything in their path. As they hit the surface, a whole spectrum of secondary fragments can be launched which do likewise. Not only does the ejected material erode, but it blankets the terrain where it comes to rest. This combination of transport, erosion, and blanketing has been endlessly repeated through long eons of time and has greatly modified topographic features on the lunar surface.

Man has been excited by the surface appearance of Mars ever since he trained his first primitive telescope on the red planet. The dark areas (called *maria*), the light areas (called deserts), dark streaks (canals), polar caps, clouds, and the red color have intrigued him and have provided a fertile basis for much debate and speculation. The exciting thought that Mars, possessing an atmosphere, might provide an environment favorable to highly developed forms of life has slowly been dispelled by spectroscopic, polarimetric, infrared, and other indirect observations. Present-day information suggests that the martian environment could at best probably support only the simplest forms of life, perhaps unlike anything found on Earth. Mars is very dry—so dry that liquid water may never exist on its surface. And it is cold—the mean temperature for the whole planet probably being between -80° and -90°C (-112° to -130°F). Its atmosphere is very thin (0.5 to 1.0 percent of that of Earth) and composed predominantly of CO_2. The martian surface is also subject to a high flux of ultraviolet radiation.

Man's first close look at the martian surface provided by the spectacular Mariner IV photos brought the planet for the first time within the grasp of geomorphologists. Mars has craters—lots of them, of all sizes, characteristics, and degrees of preservation. Like lunar craters, they are probably of impact origin, but there is as yet no absolute proof of this. Martian craters, however, are less numerous than lunar craters, generally shallower, and with gentler slopes. Clearly they have been modified and even destroyed to a greater extent than lunar craters by some processes of erosion or deposition more effective on Mars than any combination of processes active on the moon. Even a greater facility for isostatic (plastic) readjustment in the martian crust than in the lunar crust would not compromise these



Crater Lake, Oregon, is a splendid example of a caldera —of which there are a number on the earth's surface. These huge craters, miles in diameter and thousands of feet deep, are formed by collapse following volcanic eruptions. If volcanism occurs on Mars or Moon, some of the lunar or martian craters could be calderas.

conclusions about such processes.

On Earth, liquid water is an essential element in chemical weathering, in the breakup and transport of rock debris by freeze and thaw, and in other processes producing and transporting rock detritus on slopes. Without liquid water, processes that might modify topographic forms on the martian surface are not easily deduced. Consideration of all possibilities, particularly in comparison with the moon, leads to the conclusion that wind and thermal creep are particularly worthy of consideration.

Wind has long been favored as an agent of transport, erosion, and deposition on Mars because the great yellow clouds episodically obscuring parts of its face are thought to be dust. This is a reasonable hypothesis, but there are some problems. Wind does not pick up fine dust easily, and the wind velocities required for effective eolian activity on Mars are impressively large, possibly in the neighborhood of 100-200 miles per hour. This is well in excess of the observed velocity of cloud movements across the face or along the limb of Mars. Still, the rigorous thermal regime of that planet gives some theoretical basis for postulating high wind velocities, so the possibility of effective eolian action on Mars must not be too greatly discounted. However, if wind is an effective agent on Mars, it probably modifies landscape features more by burying them with wind-blown sand and dust than by erosion.

Since the surface of Mars is heavily scarred by craters, it is a reasonable inference that its surface is mantled by a relatively fine rubble not unlike that revealed on the moon by Surveyor photos and experiments. If this be so, then another process of crater modification merits attention, namely thermal creep. The temperature regime of Mars is harsh, and daily extremes range over a span as great as 132°C (238°F), far surpassing anything known on Earth. Loose rocky debris creeps slowly downslope under repeated expansion and contraction caused by temperature changes. This could be an extremely important process on Mars, and much more effective there than on the moon because of the greater frequency (daily compared to monthly) of temperature change.

The rubble mantling slopes on both Moon and Mars will also creep downslope because of vibrations set up by meteoroidal impacts or seismic events. Vibrations of both origins may be more abundant on Mars than on Moon, and this could be a third but possibly less important influence contributing to the greater relative deterioration of martian topographic forms.

Time will tell how near to the fact are these speculations about geomorphological processes on Mars. However, this now becomes an exciting game because we are going to get more and more facts with which to test these speculations.

Some observers of the scene have suggested that, ideally, the first man to land on the moon should be a geologist. Some of us would go so far to say he should not only be of the genus *Geologist* but of the species *geomorphologist*—one who understands the meaning of topographic forms—because that is certainly what he is going to see the most of during the first short visit.