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Pitted and Fluted Rocks in the Western Desert of Egypt: Viking Comparisons

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The Western Desert of Egypt is one of the most arid regions on Earth and is probably our closest terrestrial analog to the surface of Mars. An expedition to the area in 1978 revealed an abundance of quartzite and basalt rocks that have been pitted and fluted by wind erosion and deflation of the desert surface. These pitted rocks are internally homogeneous, show no internal holes or vesicles, and are considered an important but neglected type of ventifact. They bear a striking resemblance to the pitted and fluted rocks seen by the Viking Landers, rocks that have generally been interpreted as vesicular basalts only slightly modified by wind erosion. Wind tunnel studies of the air flow over and around nonstreamlined hand specimens from the Western Desert show that windward abrasion coupled with negative flow, secondary flow, and vorticity in a unidirectional wind can explain the complex arrays of pits and flutes. These field and laboratory observations suggest that the pitted rocks at the Viking Lander sites are also ventifacts, and thus the Martian surface may be far more wind eroded than previously thought.

INTRODUCTION

The region between the Kharga Oasis and the Gilf Kebir Plateau in southwestern Egypt (Figure 1) is devoid of any integrated drainage and is considered to be an eolian peneplain [*Said,* 1962]. The net trend of the water table has been downward in this region since at least Plio-Pleistocene time. At least four pluvial periods separated by periods of extreme aridity and intense eolian activity are recognized in the Late Quaternary [*Haynes,* 1978]. Similar climate fluctuations can be extrapolated back through Mousterian and even Acheulean time (more than 200 thousand years ago). The pluvial periods in southwestern Egypt produced conditions of semiaridity that coincided with episodes of occupation by early man. Ancient human occupation sites are mostly limited to the edges of wind-eroded playa deposits. The Western Desert was essentially abandoned by man about 6000 years ago, when extreme dryness set in again, and the region has been almost untouched since.

According to the Aridity Index Map of *Henning and Flohn* [1977], the Western Desert of Egypt, centered approximately around the junction of Egypt, Libya, and Sudan, is the largest expanse of hyperarid terrain on Earth. Only the very much smaller Atacama and Peruvian Deserts of South America have a comparable aridity index. The Budyko ratio that is the basis for this map has been called the 'radiational index of dryness;' it expresses the relationship between net radiation and precipitation at the surface. Both quantities are taken in energy units and applied to long-term yearly mean values. This ratio thus expresses the number of times the annual net radiation could evaporate the precipitation at a given place. The Budyko ratio is 200 for southwestern Egypt, whereas it is only 7 for the most arid parts of the southwestern United States and 50 or less for most of the Sahara in the western parts of North Africa.

In modern times only a few scientific expeditions have penetrated the Western Desert, including that of *Bagnold* [1939]. The preliminary results of our October 1978 expedition from Kharga to Uweinat are given in *El-Baz et al.* [1979]. A companion paper by El-Baz et al. describing Mars applications of large-scale eolian features in the Western Desert appears in this volume.

Many of the erosional windforms in the Western Desert are foreign to geologists who are more familiar with the less arid regions of the world. Large windforms include meter- to kilometer-sized yardangs (streamlined hills) cut into rocks ranging in type from weak lacustrine sediments to crystalline limestone and well-indurated sandstones [*El-Baz et al.,* this issue]. Small windforms of special relevance to interpretations of the Viking Lander pictures are the pitted and fluted rocks that are abundant on the desert floor. Most of these wind-carved rocks are derived from resistant, silicified layers of orthoquartzite in the sequence of rocks generally referred to as the Nubian sandstone. We think that most of these resistant rocks have been let down onto the present erosion surface by deflation. Resistant layers in the Nubian sometimes carry a trace of calcium carbonate cement, but most contain none. These orthoquartzites are internally homogeneous, break conchoidally across quartz grains, and ring when struck with a hammer. Pitting and fluting also occur in the talus from massive basalt plugs that were intruded into the Nubian. The top of the Gilf Kebir Plateau and the northeast side of Uweinat Mountain at the Libyan-Sudanese frontier also show remarkable arrays of similar small wind erosion forms.

Mutch [1978], in a summary of the Viking Lander Imaging Team analyses of the landscapes seen by Viking Lander 1 and 2, emphasized the diversity of opinions presented on the pits and flutes observed in the rocks on the Martian surface. Mutch pointed out that although these interpretations are based on analogy with Earth, they are constrained by our experience and are a function of our limited knowledge of terrestrial landforms. The observations presented here on the pitted and fluted rocks from one of the most arid regions on Earth should help to increase knowledge of erosional windforms and to aid in interpretation of Viking Lander pictures.

THE PITTED AND FLUTED ROCKS OF THE WESTERN DESERT OF EGYPT

The effective or sand carrying winds from Kharga to the southwestern corner of Egypt are northerly except where diverted by local topography in the Gilf Kebir and at Uweinat Mountain [*Wolfe and El-Baz,* 1979]. All of the pitted and fluted rocks described here are preferentially eroded from the north. Several undisturbed rings of hearth stones of probable Upper Paleolithic age (200,000 years) were encountered dur-

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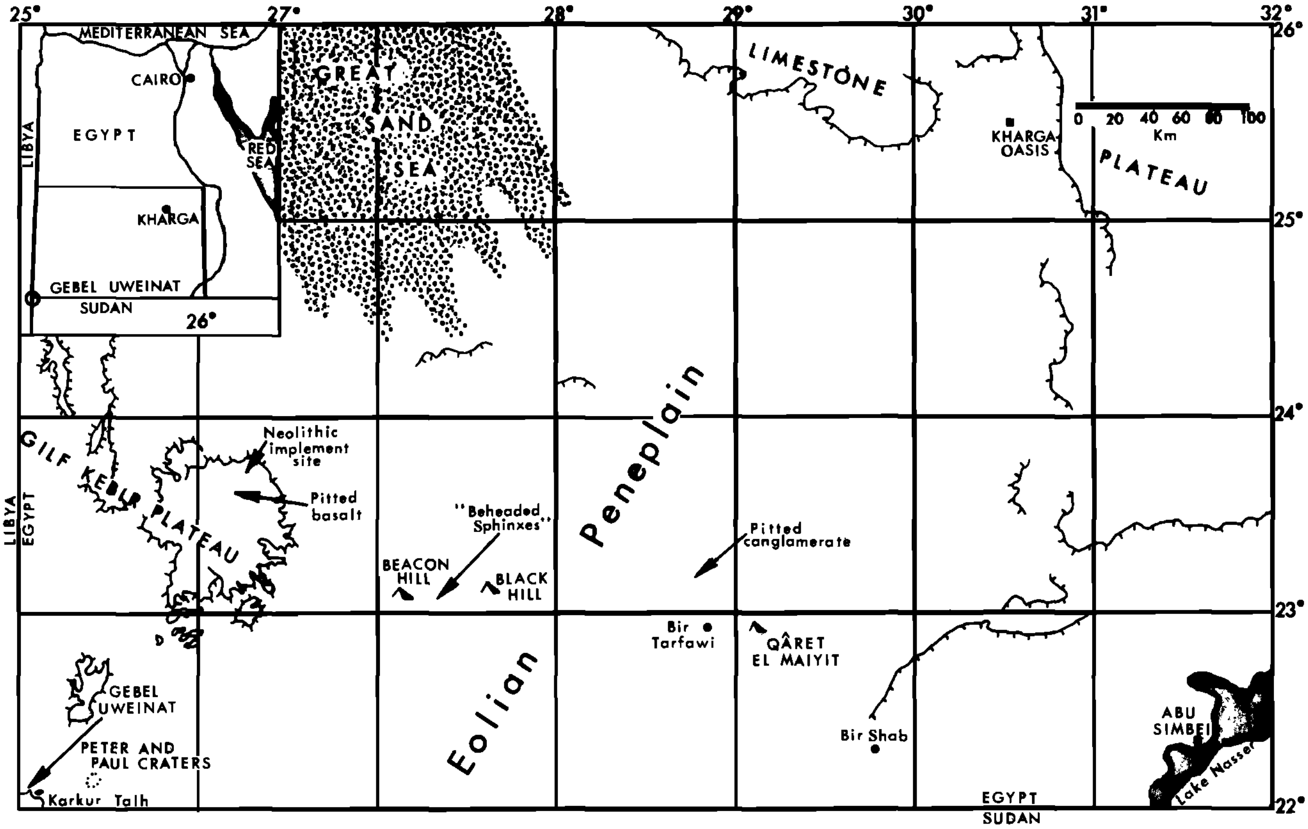

Fig. 1. Index map to localities in the Western Desert of Egypt.

ing our traverses. These were eroded to a depth of 2–4 cm on their north sides showing that the general direction of the effective winds in this part of Egypt has not changed appreciably since the time of early man. Hand-held anemometer readings taken at opportune moments during the day between September 26 and October 6 indicated peak northerly gusts of about 30 km/hr separated by 20- to 30-s lulls. Little or no sand or granule motion was observed even during the peak gusts. The intensity of the wind in October, however, is less than at other times of year. February is probably the windiest month in southwestern Egypt, based on extrapolation of data from the Bahariya Oasis weather station about 130 km northwest of Kharga Oasis.

An excellent example of deflation was noted near Beacon Hill (Figure 1), where scattered erosional remnants of gray quartzite lie on top of a softer, reddish unit in the Nubian sandstone. Behind many of the quartzite blocks are well-streamlined, small bedrock yardangs as much as a meter long (Figure 2). We gave these forms the name 'beheaded sphinxes' because of the manner in which the capping quartzite blocks are toppled forward by undercutting at their windward ends. The north sides and the tops of these rocks show more intense wind scour patterns then the other sides. The sand-poor, lag granule plain around the beheaded sphinxes is sparsely littered with intricately abraded quartzite fragments 10–40 cm long. These, as well as the heads of sphinxes, are erosional remnants derived from a massive quartzite layer, about 20–30 cm thick, that crops out on a nearby hill at a level about 6 m higher than the present plain. The remnant blocks have been let down from this layer onto the present erosional surface, not by random tumbling but by forward and backward rocking motions. They appear, however, to have maintained their general longitudinal orientation into the prevailing northerly wind as the softer bedrock beneath was deflated.

Extensive fields of wind-eroded rocks occur on the top of the 300-m-high Gilf Kebir Plateau, a region only discovered by the modern world in the 1920's. This plateau is a 12,000-km^2 erosional remnant of the upper parts of the Nubian strata that formerly covered much of the Western Desert. The top of the plateau is now littered with pitted and fluted and complexly scoured quartzite fragments. Some of these appear to be let down from an older caprock surface but most are remnants of the present caprock. These quartzite layers are so hard that they were used by Neolithic man to make blades, scrapers, and other stone implements. The implement making site discovered by William McHugh during our expedition [*El-Baz et al.,* 1979] and tentatively dated by McHugh as about 6,000 years old, showed evidence of wind erosion and pit formation on surfaces that had been slabbed for tool making. The undisturbed parts of the quartzite blocks at this site show even more extensive erosional pitting than the slabbed surfaces (Figure 3). The pits on the slabbed surfaces thus provide a measure of the small amount of erosion that has occurred on these very tough rocks in the last 6,000 years.

An array typical of the wind-eroded quartzite fragments at the top of the Gilf Kebir is seen in Figure 4. Many of these rocks are highly irregular and have either a cavernous or spongy morphology. Locally the textures observed are so complicated that they almost defy description. Most of the windward erosional projections break easily when touched and are too delicate to have undergone any fluvial activity. Overhanging windward projections several centimeters long, anchored by resistant spots in the rock or by individual quartz granules, are common (Figure 5). Other wind-eroded rocks in

Fig. 2. 'Beheaded sphinxes' near Beacon Hills (Figure 1). Pitted, relatively resistant quartzite boulders have been toppled forward into the north wind by undercutting. Meter-long bedrock yardangs cut in softer sandstone extend to leeward of the boulders.

Fig. 3. Pitted quartzite boulders at the top of the Gilf Kebir Plateau near Wadi Mashi. A major Neolithic implement shop was discovered here. The pre-Neolithic surfaces are extensively pitted (arrow). The surfaces that have been slabbed off to provide 'corestones' for implement flaking show renewed but very much less dense pit populations (near hand in middle ground of picture). This site is estimated to be about 6,000 years old.

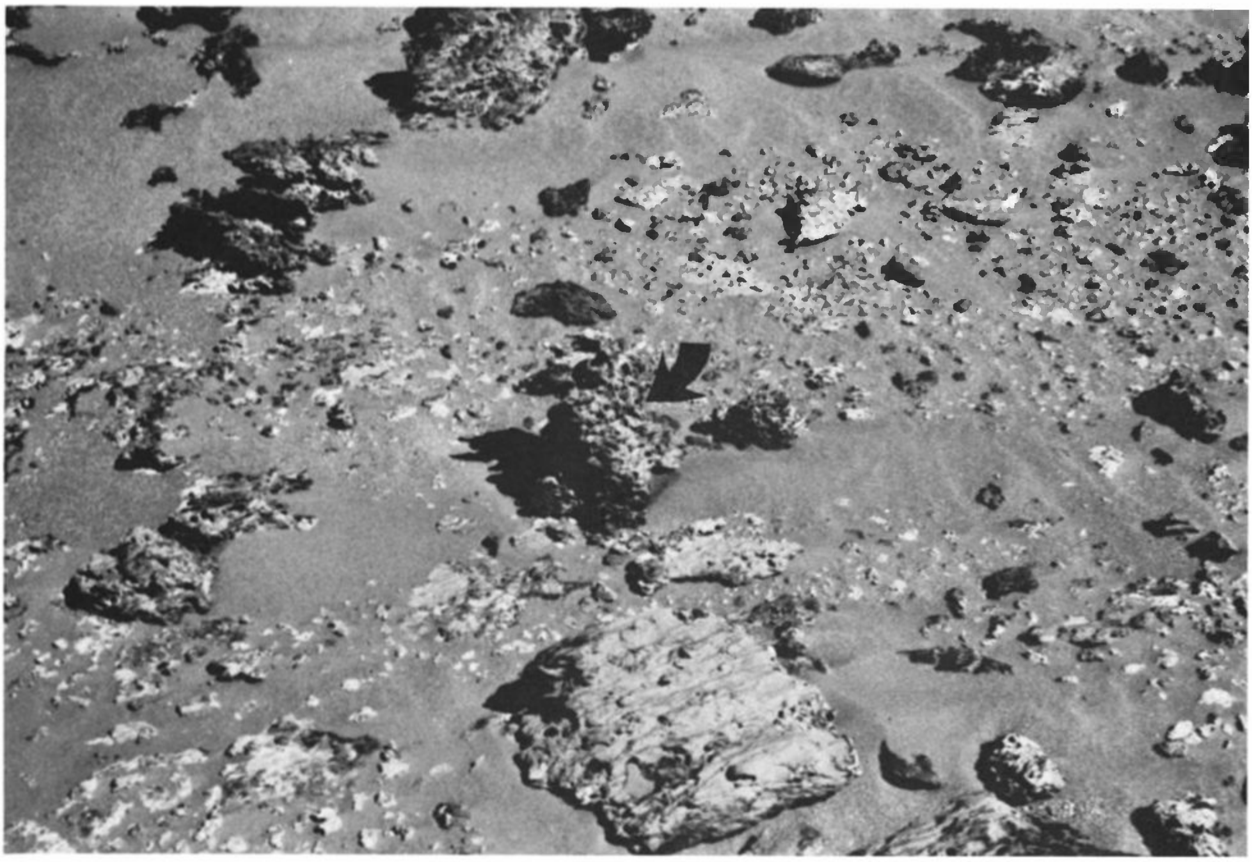

Fig. 4. Pitted and fluted quartzite fragments from a spur near the top of the eastern side of the Gilf Kebir Plateau. The spongelike rock in the center of the picture (arrow) is about 25 cm high. Effective wind is from lower left of picture. The rocks that form this incomplete lag surface have a highly eroded appearance but are internally massive.

Fig. 5. Wind-eroded quartzite from the same general location as Figure 3. Wind is from the lower left. The positive windward projections (arrow) are several centimeters long; they are anchored by hard spots or quartz grains in the quartzite. Rocks that are more homogeneous or that contain scattered soft spots tend to develop pits rather than projections.

the Gilf Kebir are characterized on all sides by irregular, elliptical and roughly circular pits. Individual pits frequently coalesce to form chains that are alined with shallow U-shaped troughs or flutes. Troughs are depressions open at both ends, flutes are outward flaring depressions that open to windward. Figure 6 is a close-up view of a quartzite rock with pits that tend to be aligned and elongated into the prevailing wind. Some pits are intricately interconnecting, others are overlapping. The insides of the pits are frequently quite smooth, some are partly filled with sand or coarser granules and in miniature resemble the well-known bedrock potholes found in stream channels. Many of the pits are bowl-shaped, while a few have upward flaring walls or 'trumpet' shapes.

Pitted textures also occur on many of the conical hills or inselbergs present in the Western Desert. One locality where we had time to examine pits and parallel flutes is about 25 km north of Bir Tarfawi (Figure 1) on a small inselberg of conglomeratic sandstone. A dark gray patina of desert varnish coats both the pits and flutes on this inselberg (Figure 7). The patina suggests that the rocks at this locality are not presently undergoing wind erosion. The pits and flutes observed probably formed during a prior period of more intense eolian activity.

Another type of pitted rock locality occurs along the north side of Wadi Mashi in the eastern part of the Gilf Kebir. Here the remnants of a basaltic plug intruded into Nubian rocks form a smooth rounded hill about 0.5 km in diameter. The talus fragments at the base of this hill, including some that are the result of columnar jointing, are extensively pitted on their tops and sides (Figure 8). Most of the pits on the tops of these fragments tend to be shallow scalloplike features with their long axes aligned parallel to the wind. The surface of many individual rocks is saturated with 0.5- to 1-cm pits; a few much larger, and proportionately deeper, bowl-shaped pits in the 1- to 2-cm range are present (Figure 9). Many of the pits are filled with fine sand. At first glance these pits appeared to be vesicles simply enlarged and slightly modified by wind action. Unlike vesicles, which generally are not mutually crosscutting, the larger pits on the surface of these basalts appear to have grown at the expense of the smaller ones. These rocks are almost homogeneous inside, only scattered 10-mm olivine grains mar their aphanitic texture, no vesicles could be found in the many rocks that were broken open.

Outcrops of finely pitted amphibolite and coarsely pitted granitic rocks of the Precambrian basement beneath the Nubian were observed a few kilometers north of Peter and Paul, two landmark volcanic edifices along the route between the Gilf Kebir and Uweinat. Pitted rocks also abound at the northeast side of the base of Uweinat Mountain just at the border intersection of Egypt, Libya, and Sudan. Because of its higher elevation, the Uweinat area has a somewhat less arid climate than other parts of the Western Desert. On the Egyptian side of Uweinat mountain, granitic rocks and gneisses are overlain by layers of sandstone, quartzite, and rhyolite of lower Paleozoic age. At the base of the cliffs in the Karkur Talh area, holes as much as 30 cm wide were observed in the sandstone. Similar but smaller holes were found on nearly vertical exposures near the tops of cliffs; some of these are ar-

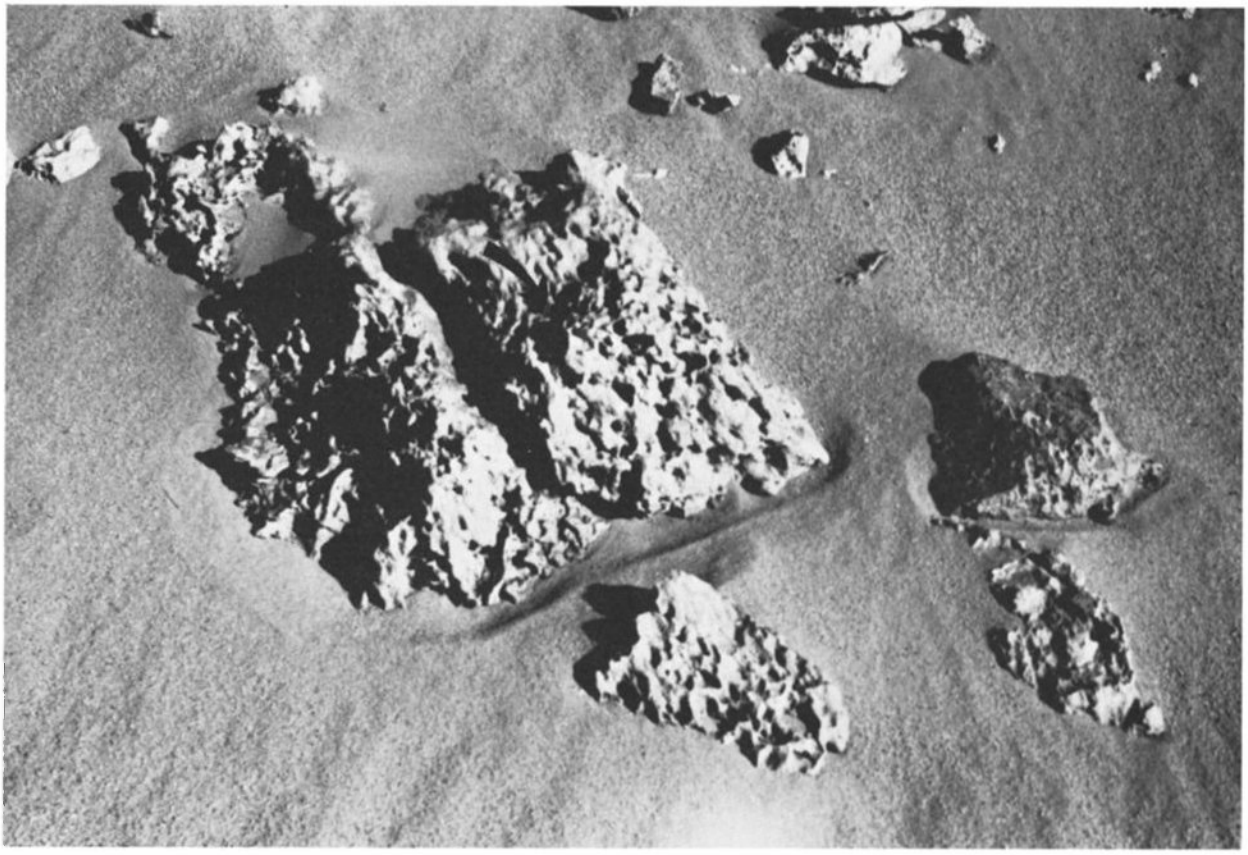

Fig. 6. Close-up of pitted and fluted quartzite fragments from same areas as Figures 3 and 4. Wind is from lower right. Note tendency of some pits to be slightly elongated parallel to the wind. Large pits about 2 cm in diameter (arrow) tend to form at the expence of smaller ones.

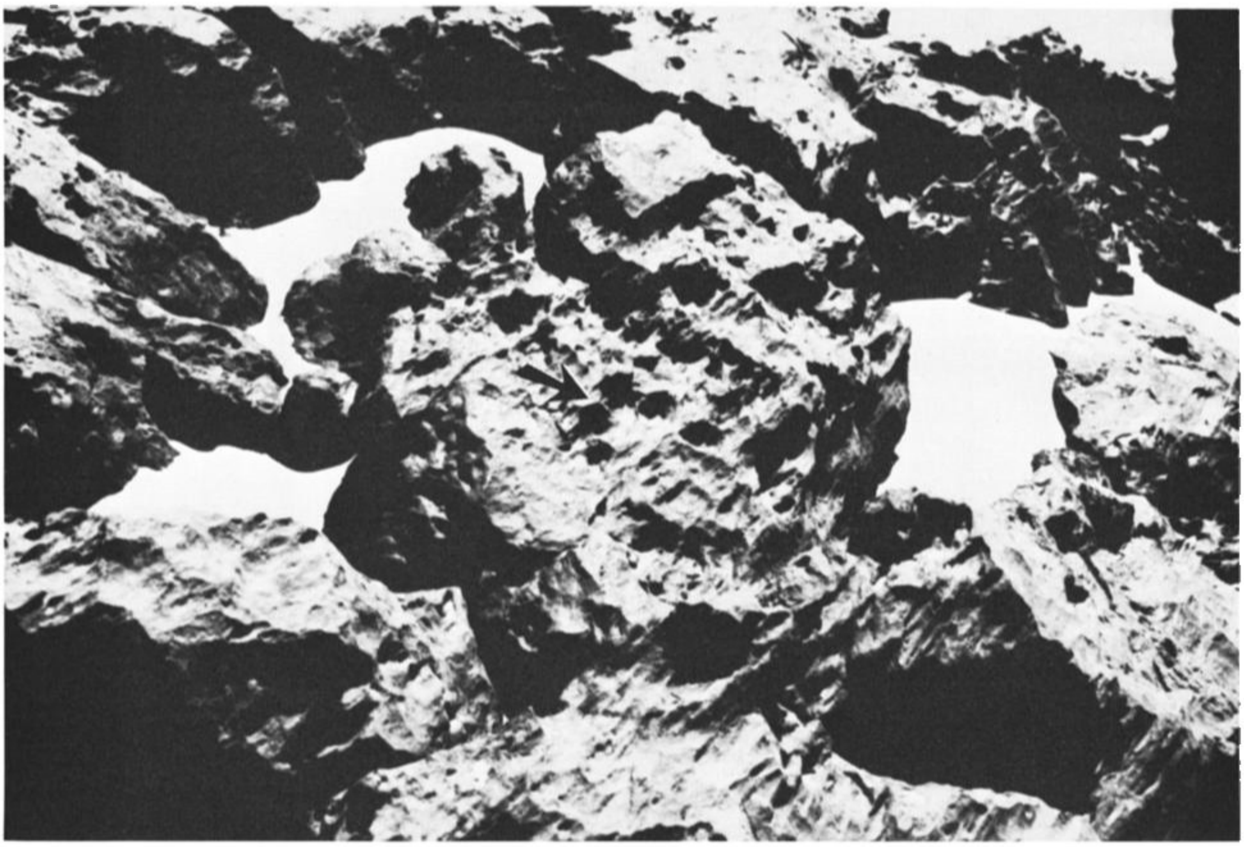

Fig. 7. Pitted and fluted boulders from a small inselberg of conglomerate sandstone about 25 km north of Bir Sahara. The large pits (arrow) are about 2–3 cm in diameter. The smoother surfaces of these rocks have a dark-gray patina of desert varnish. Many of the pits and flutes are also coated with varnish; others are partly filled with fine sand. This outcrop may not be undergoing active wind erosion as are the previously described localities about 300 km farther to the southwest.

Fig. 8. Pitted basalt talus fragments from the flanks of a massive and deeply eroded intrusive into the Nubian sandstone in Wadi Mashi. Some pits are irregular; some are arranged in rows or chains. Isolated larger pits 1.5–2 cm in diameter (arrows) tend to be symmetrical and bowl shaped.

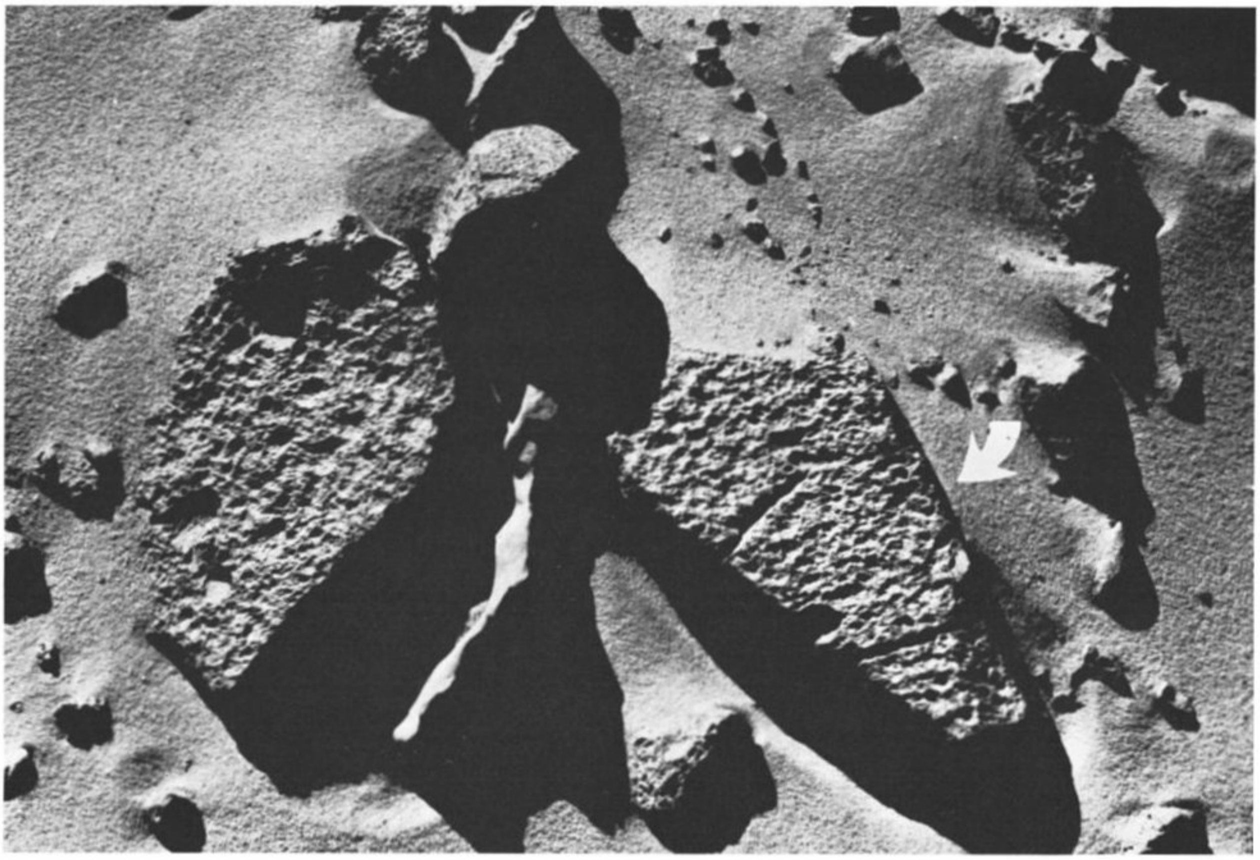

Fig. 9. Close-up of the surface of some of the Wadi Mashi basalt fragments. The rock on the right (arrow) is about 20 cm long. Scattered olivine crystals are present in these rocks, but no vesicles could be found. Some 'limonite' stain is present along fissures and on the undersides of fragments. Although the Western Desert is almost rainless, evening dews are known to occur. These are probably sufficient to promote chemical weathering of the olivine and to start formation of pits that are later enlarged by wind action.

ranged in rows (Figure 10*a*). On relatively flat surfaces the pits in the Uweinat area were partly filled with sand. As the wind gusted, the grains moved around inside indicating that these pits are presently being modified by abrasion (Figure 10*b*). At the very highest levels of the sandstone cliffs, the pits form lines or chains and join ends to form shallow furrows or flutes. Many of the smaller pits are ellipsoidal or spherical and are enlarged inward into the rock with thin canopylike overhangs outside. These pits tend to share common walls and to exhibit crude honeycomb patterns. Thus they are far closer to tafoni in their general characteristics [*Jennings,* 1968] than the pits previously described from the lower and dryer desert to the east.

Tafoni have a tendency to form in moist places on exposed rock surfaces such as along bedding planes and fissures. They are thought to be produced primarily by chemical weathering. A current model suggests that in arid and semiarid regions, solutions are brought to the surfaces of the rocks by capillary action and that SiO_2, Fe, and Mg are precipitated to form a hard rind. In the most moist places, no rinds form, and the weathered interior of the rocks are then excavated by either running water or the wind or both. It is often difficult to distinguish, even in the field, between vesicles, tafoni, and erosional vortex pits on individual specimens. In general it can be said that vesicles, except where deformed, tend to be spherical and to be separated from one another by walls. They can, however, occur as interconnected, closely packed arrays of bubbles of different sizes in frothy lavas. Tafoni, on the other hand, typically occur in honeycomb or boxwork patterns and tend to be localized in rows of walled pits along fissures or bedding planes.

DISCUSSION

Although much has been written on wind-faceted stones such as dreikanter and the like, descriptions of pitted and fluted rocks in desert regions are scarce. *Sharp* [1949] provides one of the most complete accounts of wind-produced pitting, fluting, and grooving on Pleistocene ventifacts east of the Big Horn Mountains, Wyoming. These ventifacts are lithologically diverse and are composed of chert, quartz, quartzite, quartzitic sandstone, gneiss, hornfels, pegmatite, diabase, and many varieties of granite. They were cut by northwesterly winds similar in direction to present day winds in the area. The erosion observed was ascribed to sand blasting, but the possibility that finer material caught in vortices might aid in the wind cutting process was considered. The multiple faces on ventifacts were explained by shifting of the stones with time, because the evidence is strong that the wind has blown consistently from one direction in this area since wind erosion began.

Higgins [1956], in a description of small, faceted Late Pleistocene ventifacts from Ocean Cove, California, recognized that fine abrasive material in suspension is probably important in the wind erosion process. He also addressed the

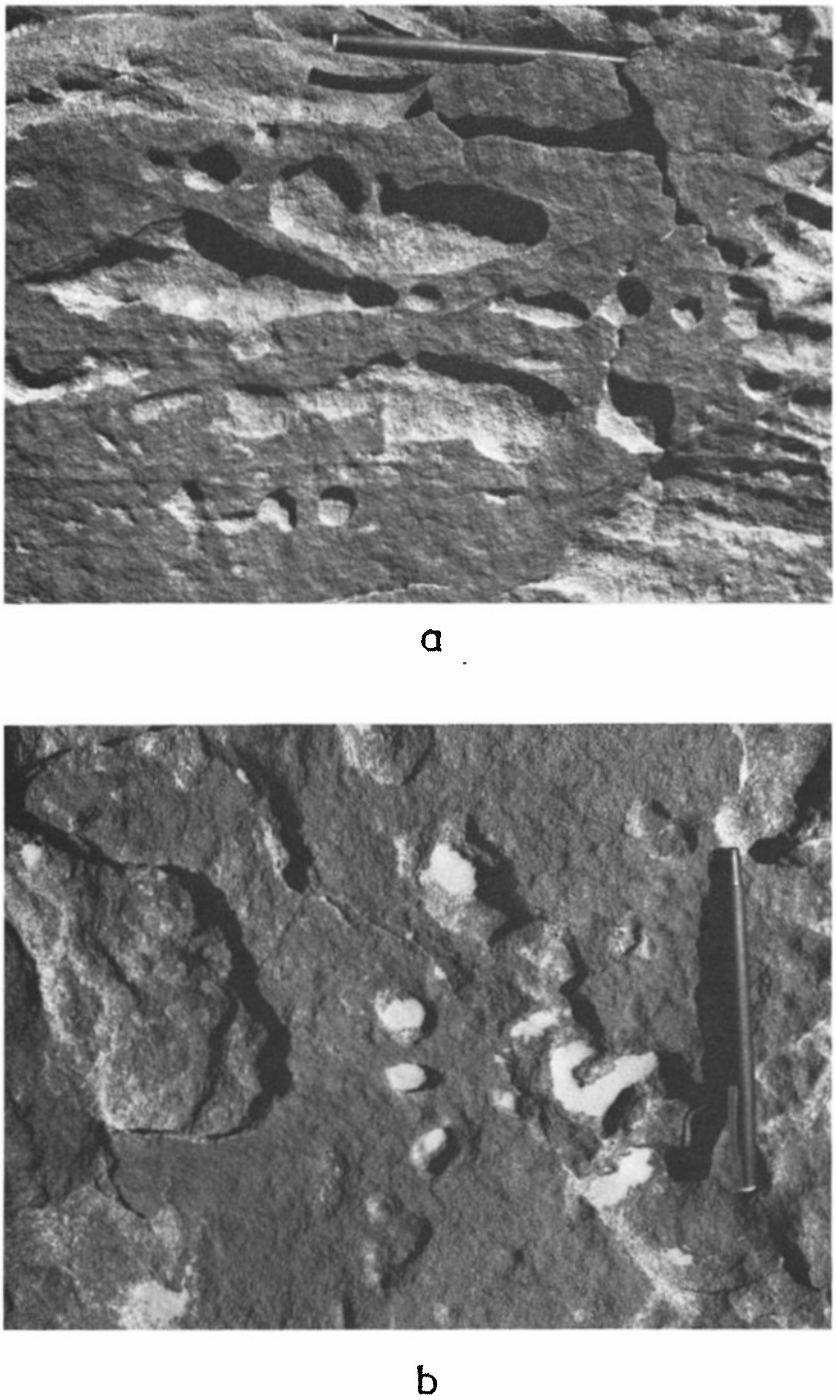

Fig. 10. Pitted rocks of probable hybrid origin (partly due to solution, but modified by wind) in the Uweinat area. (*a*) Close-up of sandstone cliff with tafoni-like pits. (*b*) Sand-filled pits on horizontal sandstone surface.

long standing leeward abrasion problem from the standpoint of architectural wind flow experiments on models of buildings of various shapes. His conclusion was that with gusty winds, scour by suspended material will be almost as effective on the leeward side as the windward side of a ventifact.

Whitney and Dietrich [1973] have shown from field and experimental studies that suspended dust is an important factor in ventifact sculpture. As a consequence of their work, they expanded the definition of a ventifact from a stone or pebble that has been faceted, cut, shaped, or worn by sand blast action to include 'any rock or mineral fragment which has been shaped, worn, or polished by wind-promoted activities.' They also point out that many of the fine erosional structures seen on ventifacts are too small or too fragile to have been produced by sand blast action. In addition, *Whitney and Dietrich* [1973] have shown experimentally that all surfaces of rocks can be eroded simultaneously, but at different rates, when subjected to prolonged impingement by directed airstreams. These observations eliminate much of the necessity for shifts in position of ventifacts with time in strongly directional wind regimes, as postulated by *Sharp* [1949] and many others. Another suggestion by Whitney and Dietrich which may have application to the pitted and fluted rocks from the Western Desert of Egypt is that slower winds carrying only dust particles may account for more wind erosion overall than the less frequent winds of sand-moving strength. In a later paper, *Whitney* [1978] emphasized the importance of vorticity and the role of positive, negative, and secondary flow in the production of small wind erosion features such as pits, flutes, and grooves. Negative and secondary flow in the lee of the upwind face on a ventifact results in erosion by dust-laden air in close contact with the rock surface. Negative and secondary flow also controls the distribution of small vortices that form normal to the surface and produce circular erosion pits. In general, the more irregular the shape of the rock the more the negative and secondary flow and the greater the degree of erosion.

We think the highly irregular, pitted, and fluted rocks described from Egypt with the exception of the tafoni of hybrid origin in the Uweinat area represent an important but neglected type of ventifact. Some solution has probably occurred on these ventifacts, primarily during the many periods of semiaridity that punctuate the history of the region. Solution phenomena have been noted at the microscopic scale on sand grains that we collected in the Western Desert (D. Krinsley, personal communication, 1979). These miniscule solution effects, however, cannot explain the millimeter to 10-cm scale, north-south trending erosion features seen on the quartzitic rocks described. The pitted and fluted igneous boulders from Wadi Mashi may be somewhat more modified by solution. Scattered olivine crystals in these rocks are limonite stained, indicative of chemical weathering. Some of the pits on the surfaces of the boulders may have begun by weathering out of the olivine, but the present scalloped textures appear to be almost entirely erosional.

To test the hypothesis that the pitted and fluted rocks of the Western Desert are ventifacts formed by northerly winds and that sand blasting is not necessarily the process by which they formed, we conducted a series of wind tunnel simulation studies on oriented specimens [*McCauley et al.*, 1979]. Visualization of low-speed air flow was provided by a bubble generating device produced by Sage Action Inc., Ithaca, New York. At tunnel velocities of about 1–2 m per second, the 2- to 3-mm bubbles produced simulate, in a general way, the behavior of atmospheric dust as it moves over and around a ventifact. The flow pattern around a typical pitted and fluted quartzite ventifact is shown in Figure 11.

Air flow separation and negative flow (reverse flow in the upwind direction) was observed behind rock faces inclined from 35° to 50° to windward. Secondary flow (transverse to the tunnel flow) was also observed. Vorticity normal to specimen faces occurred in the lees and on the sides of most of the irregular and apparently nonstreamlined rocks. Bubbles impacted on the windward faces or were pulled from the separated air flow and then moved in a reverse direction. Some of these bubbles moving in the reverse direction hovered behind or spiralled into pits, flutes, and irregular erosional concavities on the lee surfaces of the specimens. When the sample was oriented so that the flow direction in the tunnel matched the dominant wind in the field, bubble motions can be related to the erosional pattern on the rock.

When our northwardly eroded specimens were turned at angles of 45°, 90°, 135°, and 180° to the flow direction, the bubble pattern became disorganized, lost contact with the specimen, and had no relation to the surface morphology. From these experiments we conclude that the pits and flutes on all sides of these rocks can be explained by northerly winds and that abrasion by dust and silt, carried by everyday winds at velocities less than the threshold for sand, is probably responsible for most of the erosional patterns observed. Undoubtedly, sand blasting plays an episodic role in the development of these ventifacts, particularly during the windy winter months, but sand blasting cannot account for the small, fragile, and complicated features observed.

VIKING COMPARISONS

The views of the martian surface obtained by the Viking Landers show a variety of pitted and fluted rocks, strikingly like those from the Western Desert of Egypt. The surface features on these rocks have been generally interpreted as volcanic vesicles only slightly modified by wind action [*Binder et al.*, 1977; *Mutch et al.*, 1977]. Some of the rocks do appear to contain irregularly shaped but closely spaced pits with overhanging external canopies. These resemble tafoni and could be the products of chemical weathering and subsequent wind action. The presence of a duricrust or hardpan in the shallow subsurface at both Viking sites certainly raises the possibility of chemical weathering on Mars, but this problem is beyond our competence and the scope of this effort.

Viking investigators have commented that the pits in the martian rocks are larger and more widespread than those from any known terrestrial localities and that some of the rocks appear to be perched on pedestals, suggesting that some deflation has occurred. We think that the Egyptian data, the prior work of Whitney, and our wind tunnel experiments indicate that most of the rocks and boulders at both landing

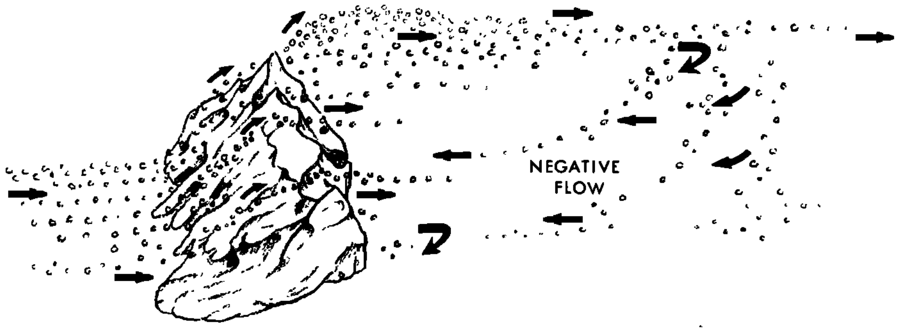

Fig. 11. Sketch by the authors of the bubble flow pattern observed over and around a pitted quartzite ventifact 10 cm wide and 7 cm high. The orientation of the specimen in the bubble train is the same as its orientation into the prevailing north wind of Egypt. Many bubbles went over the top, moved about one specimen length down tunnel, and returned to strike the rock surface or spiral in a clockwise direction in the lee. This figure illustrates the complexity of small-scale flow fields around nonstreamlined rocks even in unidirectional winds.

Fig. 12. 'Sponge' rock from Viking Lander 1 at center of picture. The drift pattern of most of the fine particulates indicates that the effective wind is from the left. Almost all of these rocks are pitted. Sponge rock shows alignement of small pits into chains, highly irregular pits, and a few larger round ones like the pitted rocks of the Western Desert (camera event label 11B144/059).

sites are ventifacts and that the overall degree of wind erosion on the surface of Mars has not been fully appreciated.

Figure 12 is a closeup view of 'sponge rock' at the Viking 1 site. The similarity to the ventifacts we have already described is obvious, even to the presence of a deflational moat in the loose sediments on the upwind side (see Figure 6 for comparison). At the Viking 2 site there is even more evidence of pit and flute formation by wind action. Some rocks resemble the classic 'dreikanter' and appear to be faceted, but most show the ubiquitous pitting characteristic of the boulder lags of the Western Desert (Figure 13). In Figure 14 we have our most convincing evidence that most of the Viking rocks are ventifacts. These boulders lie above a shallow duricrust layer and show no resemblance to vesicular basalts; erosional fluting parallel to the dominant wind is also evident. Implicit in the conclusion that the Viking rocks are mostly ventifacts is that they have been let down onto the present surface and that unidirectional winds may have been sufficient to account for all of the pitting and fluting seen. Recognition of the Viking rocks as ventifacts cut by wind blown dust alleviates many of the problems raised by the fact that Martian saltation velocity was never achieved during the lifetime of the Viking Landers, in our interpretation, saltation is not necessary for wind erosion to occur. Low wind velocities and the dust entrained in the Martian atmosphere are sufficient to account for all of the erosion features seen.

Fig. 13. General view of the near field from Viking Lander 2 showing the striking morphologic similarities between the martian rocks and the massive, pitted quartzites and basalts of the Western Desert. Note the large pit (curved arrow) that has apparently grown at the expense of smaller surrounding pits, indicating that it is a secondary feature. More massive, less pitted rocks and highly angular rocks are also seen (straight arrows). Part of camera event label 21B054.

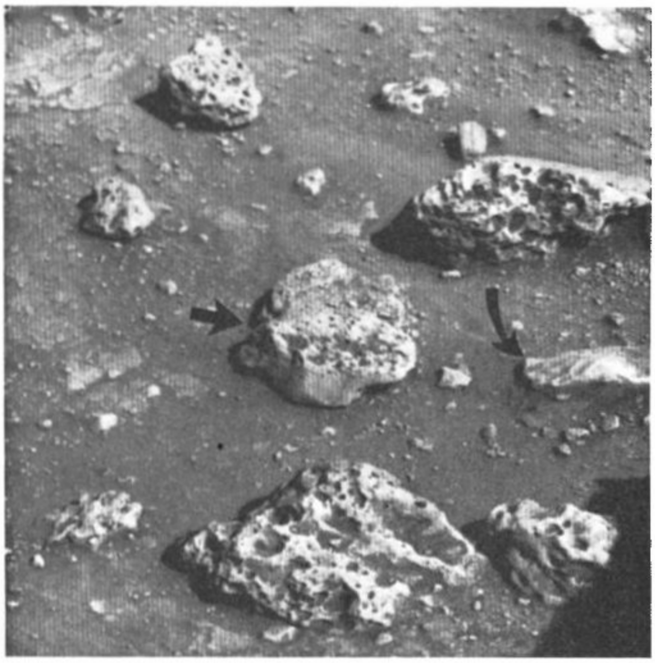

Fig. 14. Close-up of some of the more dramatically wind-sculptured rocks seen by Viking 2. Large sediment-filled pits with a tendency for alignement are present. Shallow flutes occur on the less pitted rock at right (curved arrow). An abrupt change from a dense array of small pits to a few scattered pits occurs on the rock in the center (straight arrow). The orientation of the boundary of this change suggests partial burial and later exhumation of the base of the rock (camera event label 21B021/033).

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