Surface geology from Viking landers on Mars: A second look

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ABSTRACT

Aside from reddish dust, products of martian weathering are not abundantly obvious on Viking lander images. Surface stones appear sound, spalls and disintegration fragments are largely lacking, pitting of stones is probably not due to differential weathering, and reddish stone colors more likely result from adhered dust than from patination.

Judging from wind-scoured drifts, deflated ground, rippled bed forms, lee-side tails, basal scour, fretted rocks, and ubiquitous dust, wind is currently the most effective transportive and erosive agent. The dogma that martian eolian material is almost exclusively of 10–100 μ size is challenged by granule ripples and the possibility that wind-drifted deposits consist largely of sand-sized particles. Fretting is more common than faceting on martian ventifacts.

Crusts on martian surface fines are more akin to case-hardened rinds than to true duricrust. Crusting, a possibly continuing process, may be the product of atmospheric breathing of the regolith.

Pits on surfaces of many martian stones are probably vesicles modified by eolian erosion. Pits on nonvesicular rocks may be solely the product of wind blasting.

Vesicular lava, dense lava, and breccias are the most likely rocks among surface stones around the landers. The “bedrock” outcrops near VL-1 may be large boulders embedded in a breccia substrate. Pyroclastics seem a likely constituent of surface deposits.

INTRODUCTION

The focus here is principally upon what a pair of geologists might see and think while sitting in the Viking landers and peering out across the surrounding martian landscape. This is essentially the approach of the original Viking Lander Imaging Team, and we conduct our exercise with deepest respect and appreciation for their work performed under conditions of high pressure, short deadlines, and physical and emotional near-exhaustion. To sense these conditions, read the late Tim Mutch’s superbly crafted introductory section in The Martian Landscape (Mutch and Jones, 1978). Our aim is to inspect martian surface features with a different pair of glasses. In some instances, we see things the Viking teams may have overlooked; in other instances, our perceptions are different. Often, our observations are consistent, but the interpretations may differ. Interpretations of martian features inevitably involve much subjective speculation. This article is in part a review and a synthesis, but it also attempts to challenge some martian dogmas.

Spectacular, rectified, photomosaic panoramas produced by integration of the many imaging frames from the martian Viking lander sites of 1976–1977 (Levinthal and Jones, 1980) stimulated our interest in re-inspecting surface geological phenomena and relationships near the landers.

Those panoramas are too large to be effectively reproduced here. Copies of modest grade are available from the U.S. Geological Survey distribution branches in Arlington, Virginia, and Denver, Colorado, as Miscellaneous Investigation Series Maps 1-1243, 1366, 1367, 1368, and 1515 to 1518. Liebes’ (1982) report is also useful.

Principal Viking lander teams publications pertinent to this presentation can be categorized as follows: geology (Mutch and others, 1976a, 1976b, 1976c, 1977; Mutch and Jones, 1978; Binder and others, 1977); surface materials (Moore and others, 1977, 1979; Shorthill and others, 1976a, 1976b, 1976c; Sagan and others, 1977); geochemistry and petrology (Clark and others, 1976, 1977, 1978; Laird and others, 1976, 1977; Toulin and others, 1977); meteorology (Hess and others, 1976a, 1976b, 1977); summary (Snyder, 1979). In order to avoid repetitve citation of this group of papers, the phrase “Viking lander teams” will frequently be substituted. Specific citations to these and additional papers by individuals of the teams will be made where appropriate.

WEATHERING

Our concern is primarily with evidences of weathering directly observable on Viking lander images and less with models and hypotheses concerning the possible formation of clays, patinas, ferricrete, and secondary minerals such as carbonates, sulphates, and various oxides of iron plus other colored compounds, all described in an extensive published literature.

Viking lander photos suggest that current processes of martian weathering are slow and ineffective, regardless of what may have transpired in earlier times under different conditions. Most surface stones at the lander sites appear worn, but seemingly more by mechanical erosion than by chemical (Garvin and others, 1981, p. 385) or mechanical weathering. Spectral reflectance from a spot on stone Big Joe suggests an oxidized, fresh, rock surface (Guinness, 1981, p. 7990), and most other stones (Fig. 1) appear to be fresh (Jones and others, 1979, p. 804; Guinness, 1981, p. 7991; Laird and Clark, 1981, p. 43). When impacted by the sampler head, small stones near the landers did not crack, spall, crumble, or disintegrate, nor were their surfaces perceptibly scarred, as noted by the Viking teams. These tests have limited significance, because the sampler-head impact, owing to flexibility of the extendable arm, may be less than devastating, possibly an order of magnitude less than that of a rock hammer. Footpad 3 of VL-2 did not, however, crush or fracture a stone it impacted on landing (Hutton and others, 1980, p. 305).

The ground around stones is not littered with spalls (Fig. 1), the term “Spalling Valley” (Laird and others, 1977, p. 4610) being a misnomer, and fragments of disintegrated rock are not abundant near most stones, despite a statement to the contrary (Sagan and others, 1977, p. 4435). The Viking teams showed that pebble-sized fragments on the ground between stones near the landers are largely pellet-like aggregates of fine particles. Al-
though most pellets may be fragments of indurated fines, recent experiments suggested that a few pellet-like forms near the landers could have been created by roll-up of surface fines by retro-engine exhaust (J. Marshall, personal commun.). Abundant pellets clustered around the base of some stones are probably lag accumulations created by wind scour.

Some fracture-parted stones (Mutch and Jones, 1978, p. 112) look like the separated parts of previously jointed rock. Thermal or frost fracturing yields a more irregular and intimately shattered product. A few stones display fresh-looking fracture facets (Fig. 1). Fracturing probably occurred before emplacement of these stones, because the separated fragments do not litter the ground, and they were clearly of a size too large to be easily disposed of by weathering or eolian removal. Stones with fresh fractures could have been introduced, by nearby impact events, into a population of stones more deeply worn and modified by antecedent processes. Different generations of stones should be expected on the surface in view of the large number of nearby fresh craters shown on low-level orbiter photos.

Two phenomena displayed in lander photos, possibly produced by weathering, are pitted stones and a reddish coloration on some stones. Pits can be formed by differential weathering, and the uniform development and distribution of pits over the entire exposed surfaces of many martian stones invite consideration of that possibility (Garvin and Mouginis-Mark, 1981). If the pits are a product of weathering, inhomogeneities, even of microscopic scale, within the host stone would be implied. McCauley and others (1979, p. 8229–8230), however, argued that such pitting can be created on homogeneous rock by wind. Pitting is treated more fully in a subsequent section, with the conclusion that secondary martian pits are more likely the result of erosion than of weathering.

Color photos render seemingly fine-grained, homogeneous stones at the lander sites in a uniform reddish-brown color. Patination is an attractive explanation for this appearance (Strickland, 1979, p. 3071–3075; 1981), but the environmental requirements for currently forming such a coating, and the problem of maintaining it against eolian erosion, suggest that the lesser of two evils is to coat the stones with dust (Arvidson and others, 1983), which may adhere uniformly because of electrostatic charges (Greeley, 1979). Strickland's (1979, p. 3072) "green" coating is a different matter.

Most dust at the lander sites appears, under martian viewing conditions, to be reddish brown (Guinness and others, 1979, p. 8357). Dust-sized particles in themselves are not necessarily indicative of weathering, as they can be produced by other processes (Allen and others, 1982). No amount of mechanical breakup, however, is going to produce reddish material from dark martian rocks (Baird and Clark, 1981, p. 43), except possibly through high-pressure, impact-generated phase changes (Weldon and others, 1980, 1982). An extensive literature (see Huguenin, 1974, 1982; Gooding, 1978) advocates chemical weathering as the source of martian reddish-brown dust, or, alternatively, a coating of that color on dust particles (Clark and others, 1976, p. 1285–1286). Other speculations involving tephra or the products of hydrothermal processes (Toulmin and others, 1977, p. 4632; Newsom, 1980, p. 210; Kieffer and Simonds, 1980; Allen and others, 1981) appear less attractive.

WIND ACTION

Wind has long been regarded (McLaughlin, 1954a, 1954b, 1956) as one of the most effective exogenic agents on the martian surface, and that view has prevailed within the Viking lander teams. Evidence cited as indicative of eolian activity includes: wind-scoured drifts of eolian material, eolian-type cross-bedding, strongly deflated ground surfaces, ripple-like bed forms, lee-side tails, basal scours, ventifacts, erosion of constructed debris piles, and coatings of reddish dust on nearly everything. Inspection of surface images near the Viking landers quickly convinces most experienced observers that the ground has been subjected to effective wind scour and deflation. Many stones sit on the surface rather than being embedded in the substrate, and accumulations of lag particles have formed in interstone areas (Mutch and others, 1976a, p. 792, 795). Nonetheless, eolian erosional modification of tophographic features is said to have been slow, except on disturbed materials (Arvidson and others, 1983), and with possible paucity of sand-sized abrading materials is cited as one reason (Mutch and others, 1976b, p. 88; Arvidson and others, 1979, 1981; Greeley and others, 1982). We will refer to material transported in suspension as "dust" and to grains moving by eolian saltation and traction as "sand."

The Case for Sand at Lander Sites

The assumption that the grain size of essentially all eolian material at both lander sites is in the 10–100 μm range has become something of a martian dogma, which has led to labored explanations for a possible paucity of saltating grains (Mutch and others, 1976b, p. 88; Mutch and Jones, 1978, p. 42; Sagan and others, 1977, p. 4435; Smalley and Kinsley, 1979, p. 278), including destruction by impact during transport. Many sites on Earth clearly traversed by large quantities of sand moving by eolian saltation and traction harbor only trivial accumulations of sand. The same may be true on Mars.

The 10–100 μm size favored for fines at the lander sites comes from models and interpretations, not direct measurements. The smallest particle that can be determined by sampler-head screening is 2 mm. The screen on the biology experiment passed 1.5 mm particles. Wind driftage of material dribbled from the sampler head suggests particle sizes of 1.5–0.9 mm (Shorthill and others, 1976b, p. 93). Electrical current consumption by the sample grinder has been interpreted as indicating no lithic or mineral particles larger than 0.3 mm (Shorthill and others, 1976a, 1976c; Moore and others, 1977, and 1979, p. 8367). Even if valid, these data and interpretations still allow for considerable sand coarser than 0.1 mm within the surface fines on Mars.

The 10–100 μm figure appeared first in a table compiled by Shorthill and others (1976a, p. 95), without specific indication of its origin. The figure was subsequently adopted by others, who appear to have forgotten that the original citation allowed for as much as 30% sand grains of 0.1 to
2 mm diameter within Viking sampler materials. The 10–100 μ figure seemingly was favored because of the coherence, density, penetrability, and other physical properties yielding near-vertical trench walls in excavated fines. It is a reasonable figure, but its near-wholesale adoption as representative of essentially all fines near the landers has led to a conclusion that sand is at most only a minor constituent of surface materials on Mars. The possible fallacy of this interpretation, now addressed, has been scrutinized by others (Peterfreund and others, 1981a, 1981b; Thomas, 1981).

From ways by which particulate material might have formed on Mars—impacts, volcanic explosion, or weathering—it seems likely that sand-sized particles were originally a significant part of the product. Only unlikely deep chemical weathering of quartz-free rocks appears capable of producing principally clay-sized particles. Large martian dune fields displaying typical forms and patterns (Breed and others, 1979; Tsoar and others, 1979; McCauley and others, 1981; Thomas, 1982) suggest that the planet has abundant sand-sized particles, or aggregates, in those areas. Erosion by retroengine exhaust indicates that particles behaving like sand are reasonably abundant within the substrate at lander sites (Moore and others, 1979, p. 8376; Hutton and others, 1980, p. 304). Shorthill and others (1976b, p. 94) made a case for sand- and granule-sized lithic particles within material excavated at VL-1, and Arvidson and others (1983) repeatedly invoked saltation, which requires sand-sized particles. Thermal and surface properties of some areas of martian regolith are interpreted as indicating significant sand content (Christensen and Kieffer, 1979; Zimbleman and Greeley, 1982, p. 10188).

Martian sand-sized fragments could consist of glass, lava, pumice, tuff, or any lithic material likely to be exposed on the surface, or they may be aggregates of silt or dust (Moore and others, 1977, p. 4522, and 1979, p. 8376; Greeley, 1979; Nummedal, 1981a, 1981b). The possibility of aggregates has received much attention because of the coherent fine-grained pellets collected by lander samplers. The ability of such aggregates, especially those with possible electrostatic bonding, to survive saltation across stone-littered surfaces at martian saltation velocities is suspect however. Further consideration of aggregates comes in the next section.

Relationships recorded on lander photos also suggest the likelihood of significant sand within martian surface debris, an example being the eolian bed forms within a shallow trough 8 m north of VL-2 (Fig. 2). These ripple-like features, asymmetrical to an effective wind from west-northwest, do not compose a continuous train in typical sand-ripple style (Fig. 3). They are individual forms of different size, configuration, and spacing, and their amplitude of ~10 cm far exceeds that of normal terrestrial sand ripples. These are the characteristics of granule ripples (Sharp, 1963, p. 632) composed principally of particles up to several millimeters in diameter. Even the barchan-like form of the ripples in the martian trough (Fig. 2) is duplicated by terrestrial granule ripples (Fig. 3). On Earth, granule ripples are built by accumulation of coarse particles moved by the impact of saltating sand. The longer saltation leaps, the greater terminal velocities, and the lower impact angles of saltating particles on Mars (White and others, 1976; Greeley and others, 1982, p. 10014) suggest that impact creep and granule-ripple formation should be effective on Mars. The martian bed forms, if truly granule ripples, would indicate saltating sand near VL-2, currently or in the immediate past, for the forms are sharp. The possibility of preserving ancient ripples by case hardening seems less likely. Interpretation of these features as granule ripples dispenses of concerns earlier voiced (Mutch and others, 1976b, p. 87, and 1976c, p. 1280) as to their size, spacing, and configuration and the length of leap required of saltating particles (Bagnold, 1941, p. 149–151), which is not a controlling factor in granule-ripple genesis.

Another martian feature suggestive of sand is the previously recognized cross-bedding (Fig. 4) in drifts near VL-1. Erosional etching of this exposure reveals cross-bedding dips of 20° to 30°. Bedding in eolian deposits usually reflects differences in grain size and specific gravity of

Figure 2. Eolian ripples, probably composed of very coarse sand and granules (2–4 mm), lying in shallow trough ~7.7 m N6°E of VL-2. Wavelength of ripple pair to left about 80 cm, amplitude near 10 cm. Indicated local wind direction is west-northwest.

Figure 3. Granule ripples in midst of normal eolian sand ripples, Kelso Dunes, Mojave Desert, California. Wavelengths 30 to 60 cm; pencil for scale.
Drifts at VL-1

The most obvious seemingly eolian features visible from VL-1 are the fine-grained, homogeneous, bright, and at least superficially reddish, winds-carved deposits 10 to 20 m to the northeast and east (Fig. 6). Commendably, the Viking team applied the term “drifts” rather than “dunes” to these features (Mutch and others, 1976b, p. 87). The grooves, flutes, and hollows and the intervening sharp ridges composing the micromorphology of these deposits are characteristic of eolian scouring. The homogeneity, cross-bedding, and mantling nature of the deposits suggest an eolian origin, possibly as dunes, although the present forms are those of erosion, as noted above. The mantle was originally probably more extensive and at least 1–2 m thick.

The drift deposits are too distant for imaging resolution of particles smaller than many millimeters in diameter, and so conclusions concerning their particle size are necessarily circumstantial. The interpretation that the drifts may consist of dust and silt (Mutch and Jones, 1978, p. 39; Strickland, 1979, p. 3067; Gooding, 1981) in the 10–100 μ range or even finer (Guinness, 1981, p. 7988–7989) presumably is based on their coherence, brightness, and redness; the abundance of dust in the environment, and the presumed grain size of deposits sampled within 1.5 m of VL-1, which may or may not be comparable to drift material. The brightness and redness of the drifts may be due to a thin surficial covering of dust, and their coherence could reflect reworking and cementation rather than small grain size.

Previous discussions of a dark drift in midfoot east of VL-1 (Binder and others, 1977, p. 4442–4443) and of observed changes in its appearance (Jones and others, 1979, p. 801; Guinness, 1982; Guinness and others, 1979, p. 8357–8360) suggest that this drift consists of dark material locally mantled with a thin veneer of bright, reddish dust (Strickland, 1979, p. 3067–3068). As it seems unlikely that this drift is compositionally any different than the others, we conclude, with Mutch and Jones (1978, p. 42), that the drift deposits are dark and simply have a mantle of reddish dust. If dark, they are probably composed of lithic fragments or aggregates of lithic fines.

A small slump (Fig. 7) in drift deposits near stone Big Joe (Jones and others, 1979, p. 800–801) shows they are coherent enough, to a depth of at least 1 cm, to stand in a vertical face and to yield discrete chunks upon

Figure 4. Layering interpreted as cross-bedding in drift deposits, 8.5 m N89°E of VL-1. Separation of prominent layers about 35 cm.

Figure 5. Wind tail of Sponge stone before and after excavation. Stone is 25 cm across and lies 2.9 m N10°E (S7°E) of VL-1.
slumping. The base of the slump is a planar surface (Jones and others, 1979, p. 800), presumably representing a discontinuity within the deposits (Moore and Hutton, 1981, p. 159; Moore and others, 1981, p. 521), possibly cross-bedding or the base of a coherent crust. As eolian materials are porous, owing to good sorting, atmospheric gases can move easily into and out of such deposits with changes in wind velocity and diurnal, seasonal, or secular variation in barometric pressure. In and out flushing of atmospheric gases, containing at least some trace of water vapor and possibly other elements such as sulphur (Housley, 1981), might produce some cementation within the deposits, if continued long enough. Arvidson and others (1981, p. 7) estimated the drifts at VL-1 to be perhaps 10,000 yr old, which should be enough time to produce some cementation by atmospheric flushing.

Some images (Fig. 8) show forms suggestive of ripples on the surface of a drift, although Mutch and others (1976b, p. 88–89) interpreted those particular features as the outcroppings of cross-beds. The uniform spacing of these features makes them look more like ripples to us. If ripples occur anywhere on the surface of the drifts, they are almost certainly composed of sand-sized particles, for it is generally accepted (Greeley and others, 1976, p. 419) that the optimum particle size, that is, the particle that moves most readily under minimal wind velocity, is somewhat larger on Mars than on Earth. Even in terrestrial settings, ripples in true dust, not silt or fine sand, are extremely rare, if they exist at all.

In view of these considerations, we believe that the drifts east and northeast of VL-1 are most likely composed primarily of dark material, possibly lithic particles, not reddish dust, and were probably deposited as a dune sheet. The possibility that the drift deposits accumulated as aggregated sand-sized pellets of fine material (Moore and others, 1977, p. 452) is not easily evaluated. Electrostatically bonded pellets (Greeley, 1979) are probably too insubstantial to sustain much transport (Marshall and others, 1980), and it is questionable that even chemically cemented aggregates (Nummendal, 1981a, 1981b) could survive saltation across bouldery surfaces like those around the drifts. Clay dunes on Earth, built by accumulation of aggregated particles (Coffey, 1909; Blackwelder, 1934, 1946; Roh, 1966; Price, 1963; Bowler, 1973; Butler, 1974), are relatively rare, occur...
in unusual settings, and involved transport of the aggregates across smooth clay flats or soft ground. For those believing in a superabundance of clay on Mars, these arguments will carry little weight.

Wind Blasting of Surface Stones

Many stones near the landers display surface features suggesting intense wind blasting (Garvin and others, 1981, p. 385). Martian stones are pitted, etched, grooved, and possibly faceted, and their edges and corners are blunted. The physical soundness of these stones, previously described, suggests that some form of mechanical erosion, rather than chemical weathering, is responsible. Eolian wear is the most likely process, and the abundance of particulate material, including dust (Garvin, 1982, p. 262), indicates that the efficacy of erosion by pure air (Whitney, 1979a) need not be a point of debate. We believe that the deep and extensive fretting or etching (Fig. 9) of many martian surface stones is even more definitive evidence for effective wind blasting than are the pitting and faceting emphasized by others.

Any stone altered by eolian erosion is by definition a ventifact, but faceting is often regarded as a prima facie characteristic of ventifacts. Many martian stones have planar surfaces that could be either wind-cut facets or joint faces (Garvin and others, 1981, p. 386). It is not possible to see, on lander images, whether the smooth surfaces on martian stones are polished, fluted, or shallowly pitted, which are the characteristics necessary to distinguish wind-cut facets from smooth surfaces of other origins, even in terrestrial settings. Ventifacts are certainly abundant on the martian surface, but the effects of wind blasting are more definitively recognized by etching or fretting, pitting, and modification of vesicles than by faceting.

Stewart and others (1981) showed, by experiments, that sand is a more effective agent of eolian abrasion than is finer debris.

CRUSTS ON FINE MATERIALS

Viking lander images and team reports suggest that curbing is a near-abrupt phenomenon on fine materials of the martian surface. The only fines without significant crust development are transitory mantles of reddish dust (Guinness, 1982; Guinness and others, 1979; Arvidson and others, 1983) and the surficial layer of soft, fluffy debris near the landers, and presumably elsewhere (Ditton, 1982), into which pellets ejected by retrograde exhaust and particles dropped from the sampler have penetrated so easily (Fig. 10). This material was swept aside by retrograde exhaust to reveal an underlying, seemingly tough, coherent crust (Fig. 11) on older fine debris at the VL-1 site (Moore and others, 1977, p. 4499).

The fine substrate penetrated to a depth of 16.5 cm by footpad 2 of VL-1 (Shorthill and others, 1976b, p. 1314) has a weaker crust (Fig. 10), 1–2 cm thick, that was fractured by footpad impact and possibly pelletized by retrograde exhaust. Crusting may be a continuing process on the martian surface, with older deposits having thicker, tougher crusts (Arvidson and others, 1983, p. 467).

Use of the term “duricrust,” as practiced by the Viking teams and others (AGI Directory), to characterize the thin, relatively weak, surficial crusts around the landers appears undesirable in view of Wollnough’s (1927, p. 27) original definition of duricrust, which involves extended deep chemical weathering under conditions of abundant moisture. Fuller and Hargreaves (1978, p. 615–618) employed the term in its proper sense in postulating that strongly pitted surface stones at VL-2 may represent fragments of ferricrete, a true duricrust. The crusts described by the Viking teams are more akin to case-hardened rinds (Anderson, 1931, p. 56–60), and the mode of genesis suggested, involving surfacement movement of fluids and near-surface depositions of cementing material, is the classical case-hardening process. Recent studies by Conca and Rossman (1982) indicated, however, that much, perhaps all, of the cementing substance in some terrestrial case-hardened crusts comes from external rather than internal sources. Herein, we use the term “crust” in the sense of a case-hardened layer.

As previously noted, most small “pebbles” littering the wind-swept ground surface within the 1.5-m reach of lander samplers proved, upon sieving, to be aggregates of particles smaller than 2 mm. The clods, pellets, and aggregated grains among these “pebbles” have probably come, at least in part, from crusts, as suggested by the Viking teams. Flaty fragments visible around VL-2, however, may have been derived from thin, coherent layers of fines within the substrate (see Fig. 14 below).
Figure 11. Thick, coherent crust on fines (lower left) swept clean by exhaust from retroengine 2 of VL-1. Central stone, 15 cm across, looking like a crackle breccia, lies 1.2 m N134°E (S54°E) of VL-1. Discarded latch pin of sampler arm at lower right.

The relatively high content of sulphur and chlorine in pellets presumably derived from crusts close to the landers (Clark and others, 1976, p. 1288; 1977, p. 4589; 1982, p. 10003) suggests that cementation by compounds of those elements (Housley, 1981) is a major factor in crust formation. Solfatara fumes and volcanic "juices" might have formed crusts on fine martian pyroclastics, but cementing on eolian deposits is probably of atmospheric origin. If the martian regolith "breathes" on a diurnal, seasonal, annual, or secular basis (Hess and others, 1977, p. 4572; Toulmin and others, 1977, p. 4627; Fanale and Cannon, 1979; Fanale and others, 1982; Jakosky and Farmer, 1980), and if the air contains a supply of volatile chemicals (Fanale, 1976) or aerosols (Siegel, 1979), near-surface reactions involving such volatiles, possibly aided by solar radiation, might have created crusts on pervious fines of any origin.

PRIMARY VESICLES, SECONDARY PITS, OR BOTH?

Many stones near the landers have pitted surfaces, but some, lacking macroscopic evidence of inhomogeneities on a scale resolved by lander images (Fig. 1, and see Fig. 16 below), also lack visible pitting or etching. Pits can be primary, for example, vesicles in lava, or they can be secondarily created by exogenic weathering, leaching, or erosion. Primary pits are internal as well as surficial (Fig. 12A), but secondary pits are largely surficial, except for internal cavities created by leaching. The faces of vesicular rock fragments cut across vesicles at different levels—proximal, medial, and distal—yielding surface indentations of various depths and configurations, including overhanging lips (Fig. 12A). Assemblages of secondary pits on a rock do not usually display comparable configurations, although wind vortices are said to be capable of creating such geometries (Whitney, 1978, 1979a, 1979b, 1979c; McCauley and others, 1979).

Pits of secondary origin are formed primarily by differential weathering or erosion, which usually exploit inhomogeneities within the rock. In view of the seemingly fresh and sound condition of most martian stones, weathering seems unlikely to have played a major role in martian pit production, unless Mars once had an environment like that of the Dry Valleys of Antarctica, where weathering of macroscopically, seemingly homogeneous, fine-grained igneous rocks has produced pits strongly resembling those seen on many martian stones. Formation of internal cavities in martian rocks by leaching is so demanding, in terms of fluids, materials, and events, as to be unlikely. The development of ferricrete with internal cavities (Fuller and Hargraves, 1978, p. 615–617) is suspect because of drastic environmental requirements (Woolnough, 1927, p. 50–51). A strong case has been made for eolian erosion as the principal cause for surface pits on martian stones (McCauley and others, 1979, p. 8230–8231; Garvin and Head, 1981).

In spite of a hesitantly expressed conclusion favoring vesicles in lava as the predominant type of martian pitting (Mutch and others, 1977, p. 4453–4459), the Viking teams appear to have remained somewhat ambivalent owing to inconclusive evidence. It is our conclusion that both primary vesicles and secondary pits, the product largely of differential, eolian erosion, are present.

Observation of literally thousands of vesicles in pahoehoe and aa lavas in Iceland, on Kilauea Volcano, Hawaii, and in lavas elsewhere, convinces us that the size, shape, and pattern of primary vesicles in lava can duplicate anything seen among pits on stone surfaces around the

Figure 12. Cross-section sketches of differences between vesicles (A), pitted rock surface (B), and fretted or etched rock surface (C).
Viking landers (Aubele and others, 1981), particularly if allowances are made for secondary modification of vesicles by wind blasting. Vesicles come in all shapes, including rectangular, and in all sizes as large as many centimetres across. Although irregularity is the rule, especially in aa, wherein vesicle shape can be distorted by plastic flow (Macdonald, 1972, p. 88–89), groups of vesicles tend to be more uniform in size and shape than are secondary pits, over corresponding areas of rock surface.

Pitting of fresh fracture surfaces suggests that the openings are probably internal as well as surficial, hence primary. The Viking teams gave considerable attention to a metre-long block (Fig. 1), here informally christened “Minerva,” that lies 6.7 m N56°E from VL-2. On the basis of uniform size and shape, and particularly because of a banded arrangement, they concluded that the pits on the faces of this stone were primary vesicles (Mutch and others, 1977, p. 4453). Although banded arrangements of vesicles are common in lava, banding of secondary pits is not unknown, especially on layered rocks. To our eyes, that part of Minerva facing the lander displays fracture surfaces seemingly of recent origin, because they intersect in sharp edges. None of the freshest-looking facets with pits shows independent evidence of significant modification by wind erosion. An exception is the lowermost few centimetres along the front of the stone, which looks to be somewhat fretted by eolian erosion. This is within the zone of heaviest abrasion by salting particles, and there shallow pits of secondary origin appear to exist. The pits higher on the fracture surfaces of Minerva are small, relative to pits on nearby stones, less abundant, and of reasonably uniform size and shape. These characteristics, and especially their existence on what appear to be fracture surfaces, suggest to us that most of the pits on Minerva are primary vesicles in a block of lava.

Another rock, about 3 m N70°W from VL-2, informally christened “Orthogonal stone” (Fig. 13), displays similar relationships. The planar faces and the sharp rectangularity of this stone are shown on several images from differing viewing angles under diverse lighting conditions. The top surface and the edges of the block display some suggestion of modification by secondary erosion, presumably eolian, but this stone appears to be a joint-controlled block (Mutch and Jones, 1978, p. 111). The planar faces are extensively pitted (Fig. 13), yet they do not show other independent evidence of significant wind blasting. We regard the pits on the surface of Orthogonal stone to be primary vesicles, possibly modified a little by wind blasting.

Other pitted stones near the landers, especially VL-2, probably have primary vesicles considerably eroded and modified by wind blasting. Among the likely examples are the highly pitted outer stone near footpad 3 of VL-2 (Fig. 14), other groups of stones 2–5 m northeast of VL-2, and Sponge stone near VL-1 (Fig. 5). In these examples, especially the footpad stone (Fig. 14), modification by wind blasting is suggested by the seemingly polished smoothness, fluting, and grooving of the rock surface between pits. Although Whitney (1978, 1979a), McCauley and others (1979), and Garvin (1982) showed that wind is capable of producing pits on the surface of dense, homogeneous stones, it is far easier for wind to
modify pre-existing pits by enlarging, elongating, and integrating them. The elongation and integration of vesicles by intense sand blasting of terrestrial vesicular lavas produce patterns (Fig. 15) similar to that on many martian stones.

A distinction between pitting and eolian fretting is worth making. In the ideal state, a pitted surface is one indented by closed depressions (Fig. 12B). A fretted surface, although irregularly pitted, is characterized more by projecting points, knobs, and ridges (Fig. 12C). Fretted surfaces are more ragged, uneven, and rougher than purely pitted surfaces; compare Figure 14 (pitted) with Figure 9 (fretted). In terrestrial settings, most stone surfaces etched by eolian processes strongly reflect internal inhomogeneities involving centers of differing resistance to erosion. Most of the Egyptian desert stones offered (McCauley and others, 1979; Garvin and Head, 1981) as analogues to martian pitted stones are deeply fretted as well as pitted. None corresponds closely to the VL-2 footpad stone (Fig. 1), for instance, which we regard as a vesicular lava altered by wind blasting.

Preoccupation with the ability of wind to create pits in dense, fine-grained, homogeneous rocks has caused neglect of the influence that lithological inhomogeneities can have on eolian pitting of rock surfaces. Many terrestrial ventifacts cut on dense, homogenous material, such as chert and bull quartz, showing major eolian erosion in the form of facets, flutes, and grooves but no pits (Sharp, 1949), suggest that pitting is not an inevitable product of eolian erosion.

Mixed with extensively pitted stones, within some areas around the Viking landers, there are scattered, dense, seemingly unpitted stones (Fig. 16). If these stones are not indented by pits too small for Viking image resolution, and if pitting of dense homogeneous rocks is ubiquitous, these stones could have experienced a history wholly different from that of the associated deeply pitted stones. Possible explanations include burial or recent emplacement, but most unpitted stones are regarded as faceted ventifacts by Viking team members and other investigators (Garvin and others, 1981, p. 386), an interpretation inconsistent with recent exposure or emplacement. We are inclined to the view that the unpitted stones are simply dense, homogeneous, fine-grained rocks that resisted pitting.

We conclude that most pits on surface stones around the martian landers are either primary vesicles, usually considerably modified by wind blasting, or pits etched out by eolian erosion acting largely upon lithologically inhomogeneous rocks.

LITHOLOGY OF STONES ON THE MARTIAN SURFACE

Geologists are accustomed to picking up, fondling, hefting, scratching, fracturing, and even smelling rock specimens to aid identification. It is frustrating to stare at the image of a martian stone and not be able to pick it up. This problem is expressed in the wide range of lithologies tentatively identified by various Viking team members. Garvin and others (1981, p. 377–378) differentiated martian stones on the basis of size, shape, and
Surface morphology, parameters easily determined from Viking photos. They found that VL-1 stones are on the average smaller, more uniform in size, differently faceted and fluted, more shallowly and uniformly pitted, and less rod-like than VL-2 stones.

One approach to identification of martian lithologies is to define expectations based on the currently known or inferred geology of Mars (Mutch and others, 1976; Carr, 1978). Evidence for volcanism on orbiter images is so clear and widespread that volcanic rocks are almost certainly represented among surface stones at lander sites (Strickland, 1979, p. 3073). In texture, structure, constitution, and composition, terrestrial volcanic rocks are highly variable, but lunar volcanics appear to be more homogeneous. The possibility of subsurface water substance (ice) on Mars suggests that textural and structural variations within martian volcanic products, including pyroclastics, may be considerably greater than on the Moon, even though chemical differentiation is probably less than on Earth (Head and Solomon, 1981, p. 68–69; Francis and Wood, 1982; Clark and others, 1982, p. 10065).

A rock abundant on the lunar surface, and almost certainly present on Mars, is breccia, a coherent aggregate of angular fragments of pre-existing rocks. Breccias collected from the lunar surface are thought to be the product of meteoritic impact, and the large number of impact textures on Mars suggest that impact breccias should be abundant there. Volcanic activity, especially if explosive, also produces breccias.

Present knowledge of martian surface features and processes suggests that eolian, alluvial, colluvial, slide, and debris-flow materials are the most likely types of martian sedimentary deposits. Of these, only eolian accumulations are identified with confidence in the vicinity of the lander sites. The possibility of debris-flow deposits, of impact origin, at VL-2 has been advanced (Carr and others, 1977; Guinnness, 1978), and similar material may exist at VL-1 (Allen, 1979). The eolian deposits at lander sites are not coherent enough to form the surface stones, but debris-flow material might be. In view of the widespread evidence of fluvial flooding (Milton, 1973; Baker and Milton, 1974; Baker and Kochel, 1979; Sharp and Malin, 1975; Carr, 1979), alluvial deposits should exist. They have been tentatively identified in Chryse Planitia and Lunae Planum from orbital images (Theilig and Greeley, 1979, p. 8000). Garvin and others (1981, p. 384) concluded, however, from sphericity data, that surface stones around the lander sites were probably not emplaced by fluvial processes.

The Case for Vesicular Lavas

The likelihood that vesicular lavas compose some surface stones near the landers is best evaluated at VL-2, where pitted stones are more abundant. On many extensively pitted stones at VL-2, the rock between pits is seemingly fine-grained and homogeneous, for example, the outer stone near footpad 3 (Fig. 14). Here, the stone surface between pits has been fluted, grooved, smoothed, and possibly polished, presumably by wind blasting, but has not been visibly roughened by differential etching. The relatively uniform size, configuration, and distribution of the differing depths of pits on this footpad stone, and others like it in the immediate vicinity, look more like primary vesicles, modified by wind blasting, than pits in stones eroded by terrestrial eolian processes (McCave and others, 1979; Garvin and Head, 1981). The surface between pits on these latter stones is for the most part deep and irregularly etched.

The case for vesicles in other VL-2 stones (Figs. 1 and 14) has been made in the preceding section. If the pits on these stones are vesicles, then the rocks are almost surely lavas. The possibility that they are vesicular mud (Johansen, 1980, 1981) seems unlikely, as such mud, produced by impacts, would probably be a breccia and thus subject to strong differential etching. It is also doubtful that mud could survive intense wind blasting.

The case for vesicular lavas near VL-1 is more tenuous. Sponge stone (Fig. 5), judging from its strong resemblance to intensely sand-blasted terrestrial vesicular lavas (Fig. 15), could be of that nature. A few other stones around VL-1 appear to be of similar character, but vesicular lavas are seemingly less abundant than at VL-2.

Dense Stones

Scattered among the surface rocks at both lander sites there is a number of small to medium-sized, largely angular stones (Fig. 16), with smooth surfaces lacking visible evidence of pitting or etching within lander image resolution. These stones appear to be homogeneous, of fine uniform texture, and structureless. Mutch and Jones (1978, p. 95) noted that some of them display curved fracture surfaces, usually concave, a characteristic of dense homogeneous rock. The association of such dense stones with what are probably vesicular lavas at VL-2 suggests that they may simply be fine-grained, nonvesicular lava (Garvin, 1982, p. 279). The shape, size, and jointing characteristics of these stones moved Garvin and others (1981, p. 355, 366, 381) to speculate they might be anhedral basalt. Dike rocks would be the next most likely possibility (Mutch and others, 1976b, p. 87). Volcanic tuffs, although often fine-grained, are usually not sufficiently homogeneous or indurated to qualify.

The Case for Breccias

Despite earlier statements that breccias are probably only minimally represented within the population of lander stones (Binder and others, 1977, p. 4447; Mutch and others, 1977, p. 4453), we present arguments to the contrary. Many lander stones, especially those around VL-1, appear to have the coarse granular texture of a large-grained igneous rock (Binder and others, 1977, p. 4447–4448) or of a clastic assemblage, such as breccia. We believe that the scale of vertical relief and the highly irregular configurations displayed on wind-fretted faces of many lander stones are more compatible with the heterogeneity of breccias than with the greater homogeneity of most coarse-grained igneous rocks. The projecting knobs and blunt ridges of these etched surfaces suggest a greater differential resistance to wind etching than is normally expected in nonquartzose igneous rocks, even those of porphyritic texture. In most breccias, the clasts are commonly many times more resistant than the matrix in which they are embedded. An exception would be volcanic breccias with clasts of pumice.

In addition to relief and configuration, the planimeter scale and pattern of projections on many wind-fretted martian stone surfaces are larger and more irregular in size and shape than is normally expected for plutonic igneous rocks. Even the phenocrysts of porphyries tend to be of more uniform size, shape, and distribution. Some terrestrial igneous rocks—pegmatite, for example—are totally coarse-grained on a scale comparable to martian fretted features, but the possibility that products of such extreme differentiation exist on Mars seems remote.

Stone Big Joe (Fig. 7), a 2-m rock lying 9.4 m N39°E of VL-1, has been provisionally identified as a breccia (Mutch and Jones, 1978, p. 39). We agree that the scale and irregular configuration of fretted features visible from the lander support that interpretation but believe that arguments are better made with respect to stones closer to the lander. One such is the 15-cm stone about 1.2 m southeast of VL-1 (Fig. 11). In some views, the fretted faces of this stone have the sharply angular mosaic-like appearance of a clacke breccia, a shattered rock that was recremented before the fragments became separated. Crackle breccias are abundant in terrestrial settings, such as rock falls and areas of impact or explosion, where shattering has occurred. Shattering is no problem on Mars, but recrementation by
Figure 17. Enigma stone, possibly a breccia, lying 6.8 m N25°E (S75°W) of VL-2. Stone is 75 cm across at base and may have, in center of deeply etched front face, a residual finger capped by resistant clast; sun to left.

something other than ice would require some unusual conditions. Nonetheless, this stone looks like a crackle breccia.

Another possible breccia stone lies 6 m N16°W from VL-1 (Fig. 9). Its surface is so deeply etched and linedated by grooves that the distinction between a deeply scoured vesicular lava and a breccia is not easily made. The dominance of positive features of relief such as projecting knobs and short blunt ridges on the stone, some seemingly defended by resistant parts of the rock, suggests it is a breccia, however. The similarity of a good many other stones within a few metres of VL-1 suggests to us that breccias are probably more abundant there than lavas, either vesicular or dense.

At VL-2, the case for breccias is less compelling. Attention is directed to a 75-cm rock, informally designated “Enigma stone” (Figs. 17 and 18), lying 6.8 m west of the lander. The irregularly etched surface of this stone facing the lander displays a number of blunt knobs and ridges rising above generally shallow swales and scattered pits. The configuration is that to be expected of a wind-blasted heterogeneous rock composed of harder parts within a softer matrix. Projecting from the center of the gently concave face of this stone is an apparent rock finger 3.5 to 4 cm long. The dark mark to the right of the hypothetical finger is a permanent dark spot on the rock surface, not a shadow. Any shadow cast by the finger is superimposed upon this dark area in one view (Fig. 17) and lies behind the finger in another view (Fig. 18). If the finger is real, its height gives a minimal measure of wind cutting on the rock face. The fact that the finger points more upward than directly into the presumed principal wind direction would argue against an eolian origin, unless the stone has been shifted. It is possible that the finger is an optical illusion, created in part by the adjacent dark spot.

If the finger is real, it suggests that Enigma stone is a breccia, and that eolian abrasion of this and possibly other similar stones is not minimal or trivial, as previously thought (Jones and others, 1979). Behind and to the left of Enigma stone there are a number of other stones with irregularly pitted and etched surfaces. It is not possible to tell whether these stones are deeply fretted vesicular lavas, or breccias, although they appear to have a groundmass that is more heterogeneous and more irregularly etched than that of rocks previously identified as vesicular lava at VL-2. They resemble Enigma stone, but if the finger of that stone is an illusion, the conclusion that it and these stones are breccia is weakened.

We conclude that vesicular lavas, dense lavas, and breccias are all represented within the population of stones littering the surface near the Viking landers. The possibility that stones of other lithologies are present is more speculative. Whether the breccias are of impact or volcanic origin, or both, cannot be determined from features seen on lander images. We would regard fluidized debris-flow breccias (Mouginis-Mark, 1979), thought by some investigators to be likely at VL-2, as a product of impact.

Figure 18. Enigma stone illuminated by sun from behind observer.

Figure 19. Substrate “bedrock” exposure, approximately 8 m south-southeast of VL-1.
Figure 20. Hypothecated columnar section at VL-1.

Figure 21. Hypothecated columnar section at VL-2.
THE SUBSTRATE

Exposures of “bedrock,” 8 m south-southeast and 10 m south-southwest of VL-1, were reported by the Viking teams. The conclusion that “bedrock” is exposed only at VL-1 depends upon what is considered to be bedrock on the martian surface. If the VL-1 exposures are lavas (Mutch and Jones, 1978, p. 55), no comparable outcrops seem to be visible at VL-2, but if some or all of the VL-1 exposures are a consolidated breccia, then some of the surface at VL-2 may also consist of “bedrock.” Accordingly, we believe that “substrate,” the consolidated base upon which the regolith and other unconsolidated surface materials rest, is a more suitable term. Garvin and others (1981, p. 366) were seemingly of similar mind.

The substrate exposures nearest VL-1 are low, ground-level areas of frayed, worn, etched material (Fig. 19) with a consistency and continuity over many square metres, suggesting that they are part of a coherent integrated mass. They resemble subdued, weathered, and eroded exposures of terrestrial bedrock, and they appear to be traversed by a set of steep northwest-southeast joints, which strengthens the “bedrock” impression. It is not impossible, however, for these exposures to be the tops of huge boulders in an impact breccia, judging from the size of surface boulders on the rims of distant craters (Morris and others, 1978, p. 555). The paucity of surface stones on the substrate exposures, compared to nearby areas, is puzzling, if such stones have been emplaced largely by throwout from nearby craters. If the “bedrock” exposures have positive relief, they might shed most of their stones, but stereo inspection and data from Liebes (1982, p. 24–25, 43) do not indicate significant relief. If, as seems likely, many surface stones are residually derived from the substrate, the “bedrock” exposures could simply represent resistant areas that have yielded fewer residual stones. This paucity of surface stones and the likelihood that the two “bedrock” exposures at VL-1 are different (Binder and others, 1977, p. 4443–4444; Mutch and Jones, 1978, p. 55) support the interpretation that the exposures are simply the tops of large boulders. For this reason, we speculate that the substrate at VL-1 is principally a breccia, which is consistent with the thought that this substrate is a sheet of crater ejecta (Shorthill and others, 1976a, p. 806).

PYROCLASTICS (?) AT VIKING LANDER SITES

Pyroclastics are materials fragmented by volcanic explosions and consisting of either or both chilled magmatic particles and fragments of preconsolidated volcanic or country rock (West and Williams, 1932; Schmid, 1981; Fisher, 1961, 1966) that are emplaced by air fall or flow. Most writings on martian volcanism spoke of lava plains and constructive forms, such as cones and domes composed principally of lava. The possibility of martian pyroclastics, although not totally ignored, has until recently received only modest attention (West, 1974; Reiners and Komar, 1979; Malin, 1979). Lately, the subject has been more affirmatively treated (Spudis and Greeley, 1981; Wilson and Head, 1981; Mouginis-Mark and others, 1981, 1982; Wilson and others, 1981; Peterson, 1981; Frey and Jarosewich, 1982; Scott and Tanaka, 1982; Morris, 1982), but with some dissent (Francis and Wood, 1981).

**Figure 22.** Interpretative cross sections in vicinity of VL-1.
Many terrestrial volcanic events involving explosive activity are phreatic and thus dependent upon the presence of subsurface water. If martian ground ice is as widespread and voluminous as postulated by some models (Simolukowski, 1968; Wade and de Wys, 1968; Maxwell and others, 1973; Wilson and others, 1973; Carr and Schaber, 1977; Judson and Rossbacher, 1980, p. 59), martian phreatic eruptions might have occurred frequently (Toulmin and others, 1977, p. 4632).

We wish to consider the possibility that the fine, crusted material near VL-1, as exposed in the walls of the depression made by footpad 2 (Fig. 10), denuded by retrograde exhaust (Fig. 11), and presumably sampled in trenches (Fig. 5), may contain considerable pyroclastic ash. The low bulk density of the sampled fines, 1.1 to 1.2 (Clark and others, 1977, p. 4589; Moore and others, 1977, p. 4511–4512), the estimated bulk density in the undisturbed state, about 1.4 to 1.6 (Shorrith and others, 1976a, p. 93, and 1976c, p. 1314), which is approximately comparable to that of lunar soils (Mitchell and others, 1972, p. 7–8, 7–22); and an estimated porosity of ~50% (Clark and others, 1976, p. 1286, and 1977, p. 4589) all indicate that the excavated deposit has an unusual particulate packing or contains exceptionally light particles. Random packing of solid particles usually produces porosities in the neighborhood of 25%, and if the particles have average specific gravity, terrestrial bulk densities of less than 2 are rare. Crib structures created by soil processes can have a lower value, but they are fragile and crumble easily, and the disturbed sample has a density higher than that of the undisturbed material, the reverse of that expected.

Air-fall deposition of fine dry clay can result in unusual packings yielding porosities as high as 60% and bulk densities as low as 1.1 (Ronald Scott, personal commun.). This seems to be the interpretation favored by some members of the Viking teams (Shorrith and others, 1976c, p. 1315–1316). An alternative is that the fines sampled at VL-1 may be composed of at least in part of abnormally light particles—chards of pumice, for example—which characterize many volcanic ashes. Evans and Adams (1979) and Singer (1982) found the reflection spectra of martian fines to be similar to those of terrestrial weathered pumice or basalt.

**MICROSTRATIGRAPHY AT THE LANDER SITES**

Except for schematic sketches bearing on the origin of surface stones at VL-2 (Mutch and others, 1977, p. 4466), graphic representations of stratigraphic relationships in near-surface materials at the lander sites have not been published, although Strickland (1979) described a detailed stratigraphy of "soil" layers at both sites, based principally upon color differences, supplemented by other physical characteristics. Figures 20 and 21 are speculative representations of a microstratigraphy that might be expected in exposures a few metres deep at both sites, and Figure 22 shows what might be seen in a trench of similar depth at VL-1. Although relationships depicted are highly tenuous, this sort of exercise is useful in focusing an integration of observations, interpretations, and speculations.

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