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IMAGING ASTEROIDS: SOME LESSONS LEARNED FROM THE VIKING INVESTIGATION OF PHOBOS AND DEIMOS

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There is a good chance that the two small satellites of Mars really are captured asteroids and as such may be representative in many (but not all) ways of other small bodies in the asteroid belt. This paper discusses specific experiences from the study of Phobos and Deimos during the Viking mission and uses them to formulate three basic goals of any serious imaging study of asteroids. These are to obtain: (1) the highest possible resolution, (2) complete coverage of the surface, and (3) data over a wide range of phase angles.

I. INTRODUCTION

The recent investigations of the satellites of Mars by the Viking Orbiters provide some useful lessons on how to plan a detailed imaging study of an asteroid. After summarizing our current knowledge of the two asteroid-like moons of Mars, I will discuss three crucial requirements for any successful imaging study of asteroids:

1. The need to obtain the highest possible resolution of the surface.
2. The need for complete coverage of the surface.
3. The advantages of imaging over a wide range of phase angles.

These points are illustrated using specific experiences derived from the study of Phobos and Deimos during the Viking mission.

Phobos and Deimos in Summary (*cf.*, Veverka, 1978)

Phobos and Deimos are small, very dark grey asteroid-like satellites. They have geometric albedos of about 0.06 in V and B-V colors of about +0.6 (*i.e.*, they are grey). While both are irregular, their shapes can be approximated reasonably well by triaxial ellipsoids. Phobos is about 27 × 21 × 19 km across; Deimos is about half as big: 15 × 12 × 11 km. The two satellites have a similar shape; in each case the ratio of the longest to the shortest axis is about 1.4 to 1.0. The spin periods of both satellites are synchronous with their orbital periods, but it is interesting to note that the actual values are comparable to those of asteroids--7^h39^m for Phobos and 30^h17^m for Deimos.

Both satellites are heavily cratered and are completely covered with a regolith whose surface microtexture appears to be lunar-like, judging from its photometric, polarimetric and thermal inertia properties. On the scale of several hundred meters, the surface of Phobos is homogeneous in albedo, but that of Deimos is not. Bright patches (some 30% brighter than the surroundings) are conspicuous on Deimos. The surface density of craters on both satellites is similar to that in the lunar uplands suggesting that these may be equilibrium surfaces. Using current models of the past cratering rates at the orbit of Mars, one can estimate that the surfaces are at least 2.5 to 3.0 billion years old. The largest crater on Phobos, Stickney, is about 10 km across. The largest known crater on Deimos is about 3 km across.

The most surprising discovery made by Viking is that the surface of Phobos is covered by swarms of trough-like grooves which seem to be surface expressions of deep fractures within Phobos produced by the formation of Stickney. Grooves are not found on the surface of Deimos. In spite of the low surface gravity of the two bodies ($g \sim 10^{-3}$ g on Phobos, and about one-half less on Deimos), much ejecta-like material, including coarse blocks tens of meters across, are evident on the surfaces--especially on Deimos.

A recent mass determination for Phobos leads to a mean density of about 2 g/cm^3. This low mean density, the low albedo, and the Ceres-like spectral reflectance curve of the satellite, suggest that Phobos is made of a low density, water-rich material similar to that which makes up some carbonaceous chondrites. Information on the composition of Deimos is inconclusive. The data suggest that although Deimos is probably *not* identical in composition to Phobos, it may also be made of some sort of carbonaceous material. A mass determination by Viking Orbiter 2 suggests that the mean density of Deimos is similar to that of Phobos, but the determination is very uncertain since we do not know the volume of Deimos very well (see below).

The probable low density, water-rich carbonaceous chondrite composition of Phobos (and Deimos?) suggests that they may have formed in the asteroid belt and were captured by Mars during a comparatively early stage of its accretion (when Mars was still surrounded by an extensive primitive atmosphere) or were perhaps captured collisionally. Thus there appears to be a good chance that the satellites of Mars really are captured asteroids and as such are representative in many (but not all) ways of other small objects that we may encounter in the asteroid belt.

II. THE NEED TO OBTAIN THE HIGHEST POSSIBLE RESOLUTION

The Viking experience in studying Phobos and Deimos provides numerous examples of the need to obtain the highest possible resolution imagery of asteroid-sized bodies.

Discovery of Grooves on Phobos: Their Morphology and Age

While Mariner 9 resolution (several hundred meters) was adequate to show the irregular shape and the heavily cratered surface of Phobos, it took resolution of better than 50 m to discover that the surface of the inner satellite is crossed with grooves (Figure 1). At moderate resolution (∿40 m), the linear features--or grooves--appeared to fall into two distinct categories, first called "striations" and "crater chains" by Veverka and Duxbury (1977). The "striations" seemed to be trough-like depressions, while in many cases the "crater chains" seemed to show similarities to the "herringbone" pattern of secondary crater chains on the Moon (Figure 2). Still higher resolution imagery (<15 m) was needed to make it clear that there is essentially only one type of linear feature, or groove, although some of the grooves have been modified to various degrees by other processes. At the highest resolution achieved on Phobos (5 m) the simplest grooves appear to be fault-like troughs (Figure 3), although local segments are often modified by pitting and have a beaded appearance (Figure 4). Significantly, at these highest resolutions none of the grooves looks like a chain of impact craters. Even the "herringbone" patterns suspected in Figure 2 are ultimately resolved into beaded troughs (Figure 5) which bear no resemblance to chains of secondary craters.

Fig. 1. View of Phobos from Viking Orbiter 2 (Frame 039B84). The large crater at top (Roche) lies close to the north pole of Phobos and is about 5 km across. Range = 800 km.

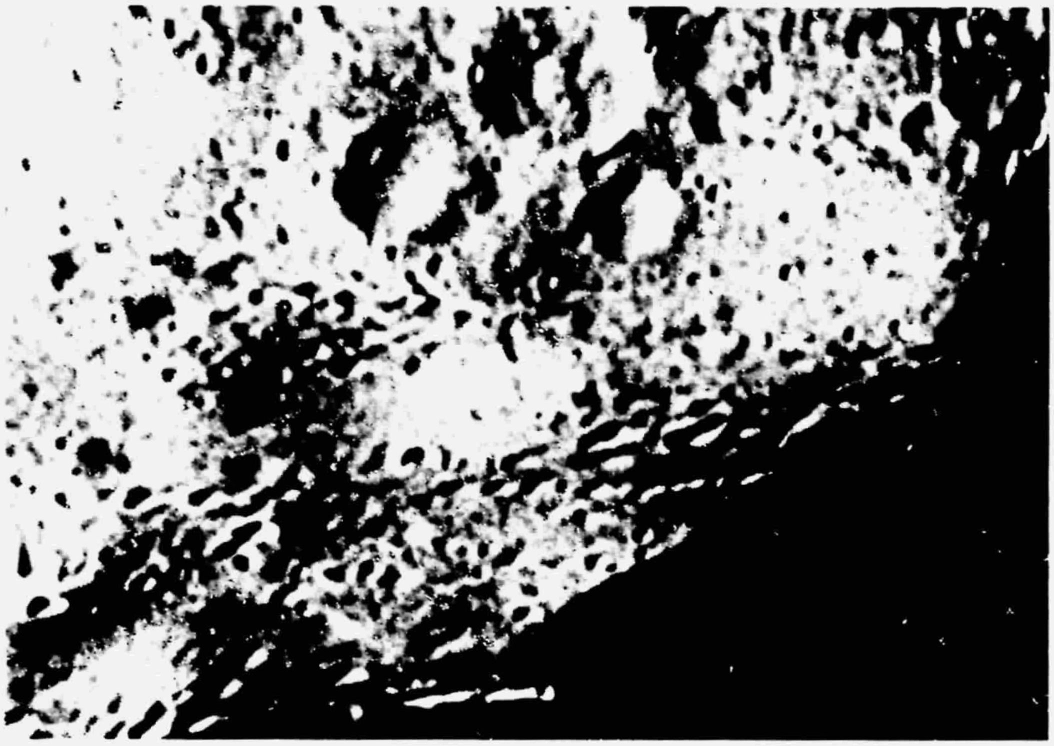

Fig. 2. Enlarged segment of Frame 039B84, showing apparent clusters of irregular depressions arranged in herringbone patterns suggestive of secondary effects.

From a detailed study of the morphology of the grooves, Thomas *et al.* (1977) conclude that they are probably surface expressions of internal fractures--fractures which as we will see below (Section III) appear to be intimately connected with the formation of Stickney, the largest crater on Phobos (*cf.*, Figure 12). This study of groove morphology using the highest resolution imagery available (5-15 m) established the following facts:

a. Grooves are typically 100-200 m wide and 10-20 m deep.

b. They are largest and best developed in the neighborhood of Stickney and taper out toward the point antipodal to Stickney (Figure 12). Some of the grooves near Stickney are 700 m wide and several hundred meters deep.

c. Many groove segments are modified by pitting (Figure 4) and have a beaded appearance.

d. A few segments may have slightly raised rims (Figure 6).

e. At the highest resolution available, no groove segment has the appearance of a chain of impact craters.

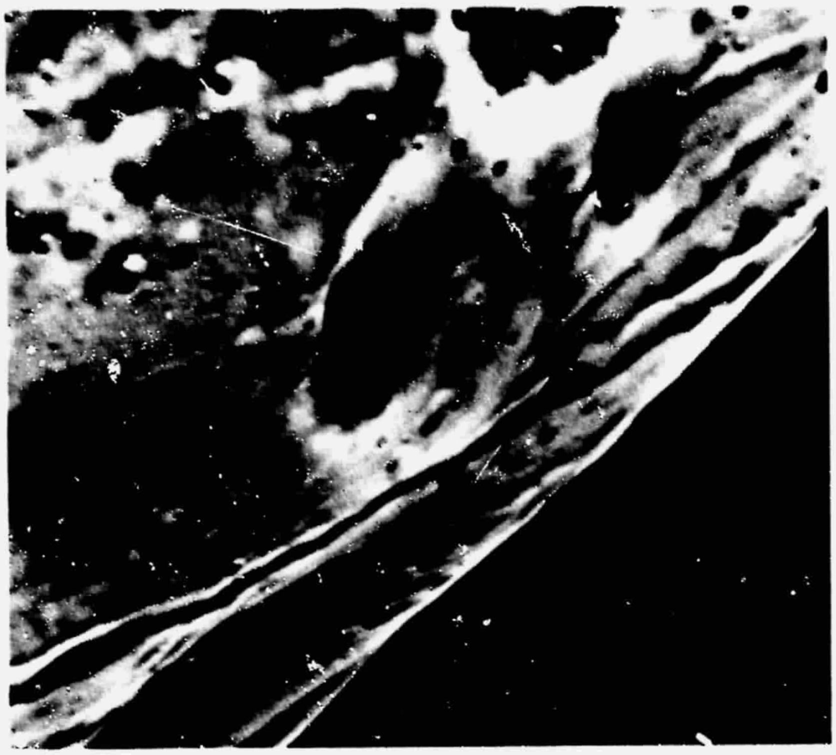

Fig. 3. Close-up of Phobos grooves obtained by Viking Orbiter 1 during February 1977. Range = 137 km. The picture is about 3 km across and shows detail as small as about 5 km. The triplet of large craters is the same as that in Figure 2 (Frame 244A08).

The pitting and the possible raised rims can be explained in terms of a modification of the grooves by internal processes. Veverka *et al.* (1977) suggest that the large impact which produced Stickney not only cracked Phobos, producing the grooves, but heated up portions of the interior enough to outgas some water vapor. It should be recalled that the low albedo, the spectral reflectance curve, and the mean density of Phobos suggest that the satellite is made of a material similar to water-rich low-density carbonaceous chondrite material (Veverka, 1978). By raising the temperature locally to slightly more than 400°K during the formation of Stickney, water vapor should be driven off. It is likely that this vapor will tend to come out along fractures, possibly accounting for the pitting and the possible raised rims on some of the grooves (Veverka, 1978).

Very high resolution imagery has also made it possible to estimate the age of the grooves by counting small impact craters within them. In this way Thomas *et al.* (1977) find that the grooves are probably at least 3 AE old and thus cannot be attributed to any recent event, such as the tidal stretching of Phobos by Mars. This mechanism, proposed by Soter and Harris (1977) should have been most effective during the past hundred million years (Pollack, 1977). Thus, the old age of the grooves is inconsistent with a tidal origin, but is consistent with an origin associated with the formation of Stickney (Thomas *et al.*, 1978).

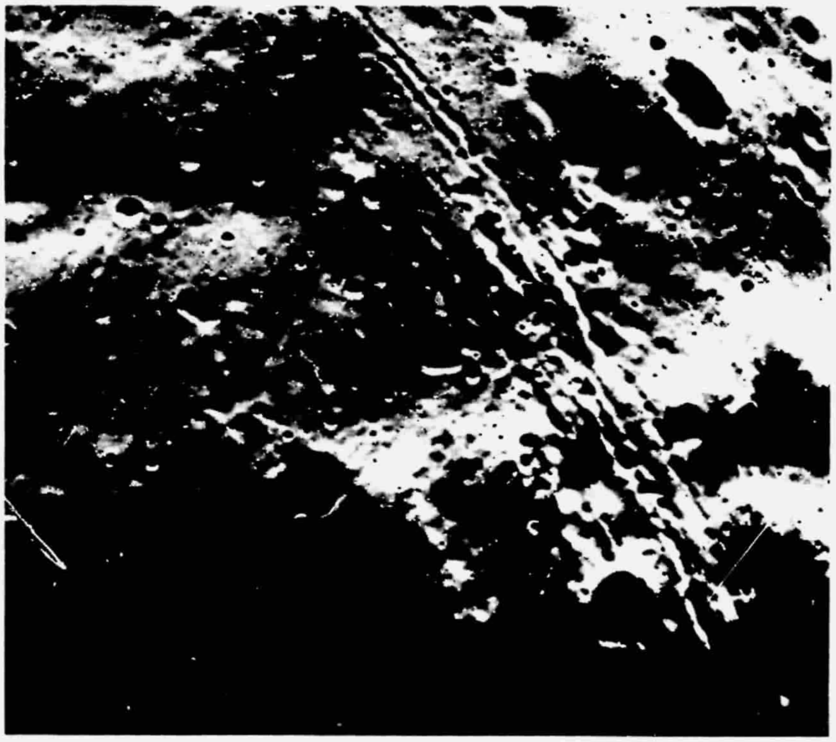

Fig. 4. Portion of Viking Orbiter 1 Frame 246A05 taken from a range of about 260 km. Note the conspicuous pitting of the grooves. The grooves are typically 100-200 m wide.

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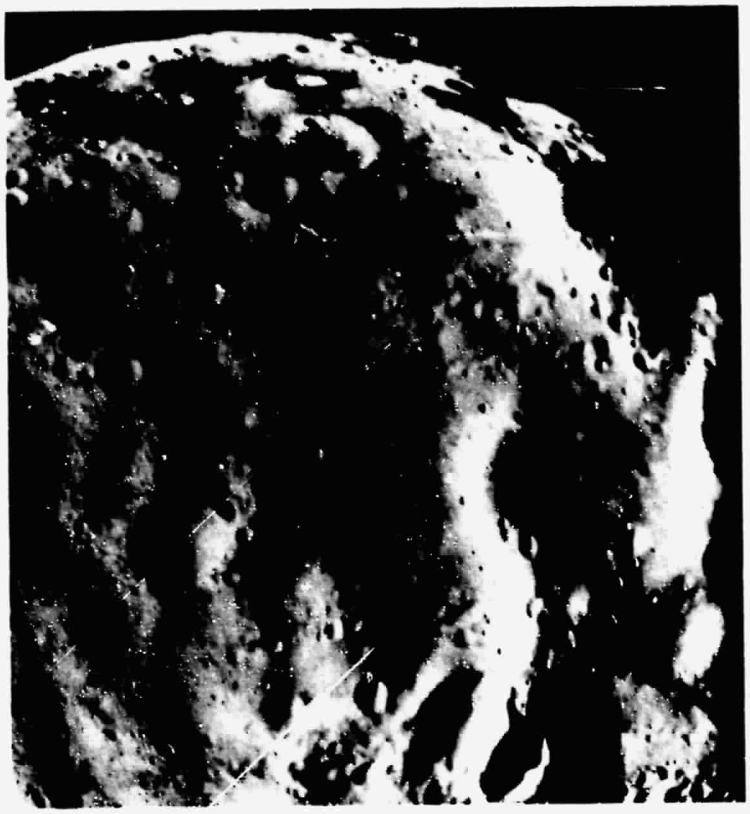

Fig. 5. Viking Orbiter 1 image of Phobos taken from a range of 530 km. The triplet of craters shown in Figures 2 and 3 is seen at center top. Note the different appearance of the groove just below the crater triplet in the three views. Raised rims are visible on some of the craters at top (Frame 243A71).

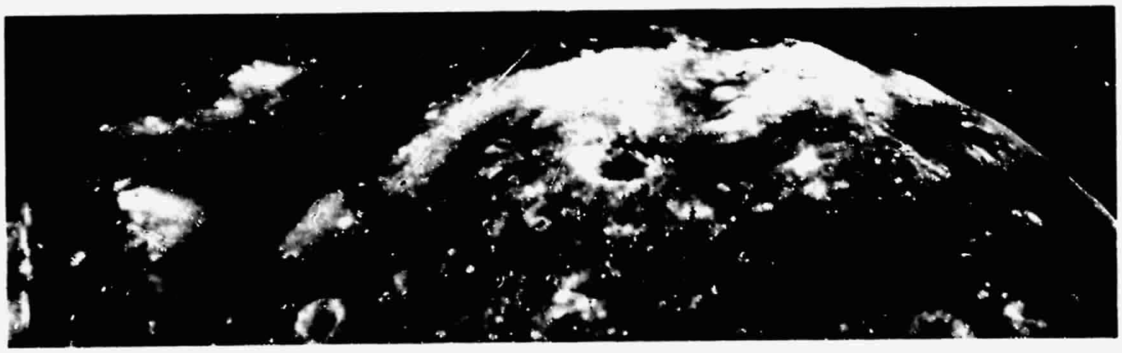

Fig. 6. View of Phobos from a range of 440 km at a phase angle 11°. Several grooves, showing possible raised rims, are seen on the limb (Frame 252A16).

Fig. 7. Viking Orbiter 1 view of Phobos from a range of about 310 km. Note the conspicuous dark marking in the 2 km crater at upper left (Frame 248A01).

Evidence of Small-Scale Surface Inhomogeneities on Phobos

While the surface of Phobos is generally homogeneous both in texture and in albedo on lateral scales of several hundred meters (Noland and Veverka, 1977a), higher resolution imagery does reveal several interesting localized anomalies. For example, at large phase angles, many craters show prominent dark markings on their floors (Figure 7), which have been interpreted as deposits of impact melt (Section IV). Also, in the vicinity of Stickney there occurs a patch (about 3 × 6 km across) of hummocky material whose origin is at present unclear, but which could represent some type of ejecta associated with the formation of Stickney.

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Fig. 8. View of Phobos from about 160 km obtained by Viking Orbiter 1. Note the dark layer in the crater wall at top. The frame is about 3 km across (Frame 244A03).

Layering Within Crater Walls on Phobos

One of the highest resolution pictures of Phobos (~5 m) shows an oblique view of a crater wall which contains evidence of layering (Figure 8). A dark layer, about 50 m thick and some 150-200 m below the surface, demonstrates that there are at least shallow inhomogeneities with depth and may provide evidence for a very deep regolith. Similar evidence should be looked for on asteroids. An effective resolution of better than 10 m is needed.

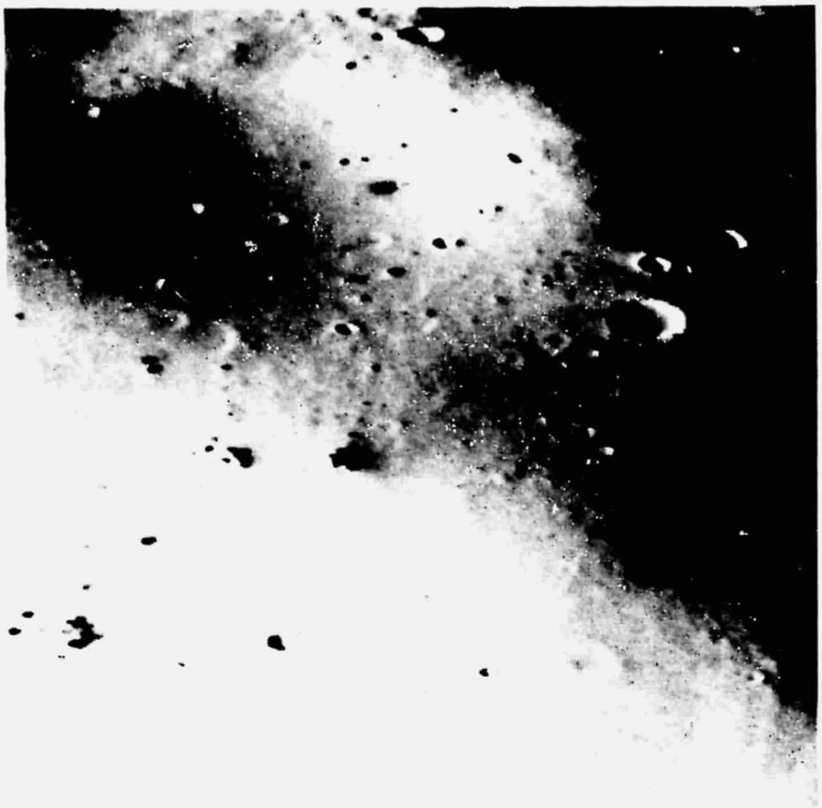

Fig. 9. Viking Orbiter 2 close-up of Deimos from a range of about 60 km. The picture is about 1.3 km across. The smallest visible detail is about 2-3 m. Note the conspicuous dark halo crater near top center (Frame 423B61).

Dark Halo Craters

Another noteworthy discovery made using the highest resolution imagery is that very small (d ≈ 10-20 m) *dark halo* craters appear to be common on both Phobos and Deimos (Figure 9). These craters appear to be similar to their lunar and martian counterparts. Their ubiquitous presence on very different bodies suggests that they may not involve the excavation of dark, subsurface material, as has been proposed in the lunar context, but may instead be attributable to certain characteristics of the impacting body (*e.g.*, composition, high velocity, etc.)

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Fig. 10. Viking Orbiter 2 mosaic of Deimos from a range of 60 km. Each frame is about 1.3 km across. Two different enhancements are shown (Frames 423B61-63).

Blocks and Ejecta Deposits on Deimos

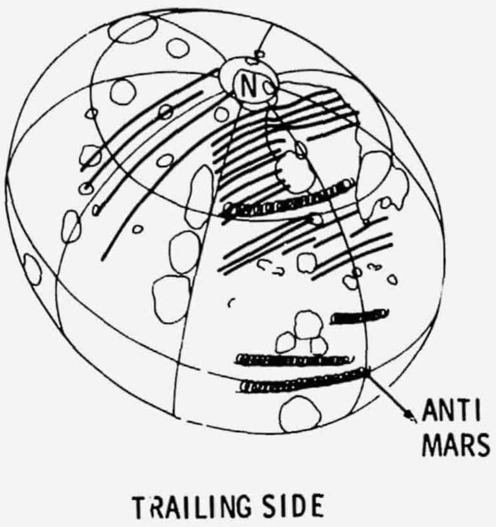
Low resolution images (100-200 m resolution) show that the surface of Deimos has bright patches, and that, compared to Phobos, Deimos appears to be very smooth. The latter observation remained a puzzle for a long time inasmuch as crater counts indicated that Phobos and Deimos have equal surface densities of impact craters. The very high resolution images (resolution about 3 m) obtained by Viking Orbiter 2 in October 1977 have resolved this puzzle and have provided convincing information as to the nature of the bright patches (Figure 10).

The bright patches appear to be deposits of fine-grained ejecta which, in many cases, partially fill craters on Deimos--thus accounting for the relatively smooth appearance of the outer satellite. (Similar bright patches do not occur on Phobos, and there is less evidence of craters being filled in by ejecta.)

The high resolution images also show that the surface of Deimos is littered with numerous isolated, roughly equidimensional positive relief features (typically ~10 m in size) which have the characteristics of ejecta blocks. How so much ejecta is retained on such a small satellite, and why the process seems to be so much more efficient on Deimos than on Phobos, remain unresolved puzzles.

The high resolution images also show a new, and as yet unexplained surface feature: bright streak-like markings behind positive relief features such as crater rims and blocks. These markings appear to be concentrations of fine-grained ejecta, and it is conceivable that they may be analogous to certain deposits formed by near surface flows that are seen in some parts of the lunar surface, but it must be admitted that the detailed resemblance is not very close.

Fig. 11. Old sketch map of the distribution of grooves on Phobos based on incomplete surface coverage (from Veverka and Duxbury, 1977). Compare with Figure 12.



III. THE NEED FOR COMPLETE COVERAGE AT HIGH RESOLUTION

One of the crucial requirements is that complete coverage of the surface be obtained at the highest possible resolution. Complete coverage of the surface is needed to look for global patterns and to search for regional anomalies. For all missions, the angle of the subsolar latitude determines the extent of the surface that is illuminated. Given the short rotation periods of most asteroids, full coverage at a useful resolution could be realized even for a flyby mission. Rendezvous missions offer an opportunity for higher resolutions with complete coverage.

The Viking investigation of Phobos provides a striking example of the need to have global coverage in order to understand important phenomena on small bodies. As soon as the enigmatic grooves were discovered, many possible explanations were proposed. At first the coverage of Phobos at the resolution needed to see grooves was very limited (Veverka and Duxbury, 1977) and it was impossible to determine the true distribution of the grooves on the surface of Phobos, or their possible connection with other major topographic features. One early and clever suggestion by Soter and Harris (1977)--that the grooves are fractures due to martian tides--was consistent with the then available information (Figure 11). However, as soon as more complete high resolution coverage was obtained, it became evident, from the pattern of the grooves and from their intimate association with the crater Stickney (Figure 12), that the grooves could not be due to martian tides but were probably expressions of fractures associated with the formation of Stickney (Thomas *et al.*, 1978).

As far as regional variations are concerned, none were found on Phobos (other than that in the distribution of grooves). Specifically, there are no significant variations in the surface density of impact craters; thus no large-scale cratering or spallation event has occurred in "recent" times. The entire surface of Phobos, like that of the lunar uplands, has reached an equilibrium state in terms of cratering.

Complete surface coverage is also needed to derive an accurate density from a mass determination. For irregular objects such as Phobos, Deimos, or most asteroids, accurate volumes can only be determined by imaging all of the surface. There is no reliable way of extrapolating beyond the limb. In the case of Phobos, for which our surface coverage is essentially complete, the current uncertainty in the volume is still comparable (about ±10%) to the uncertainty in the mass determination. While further analysis will improve

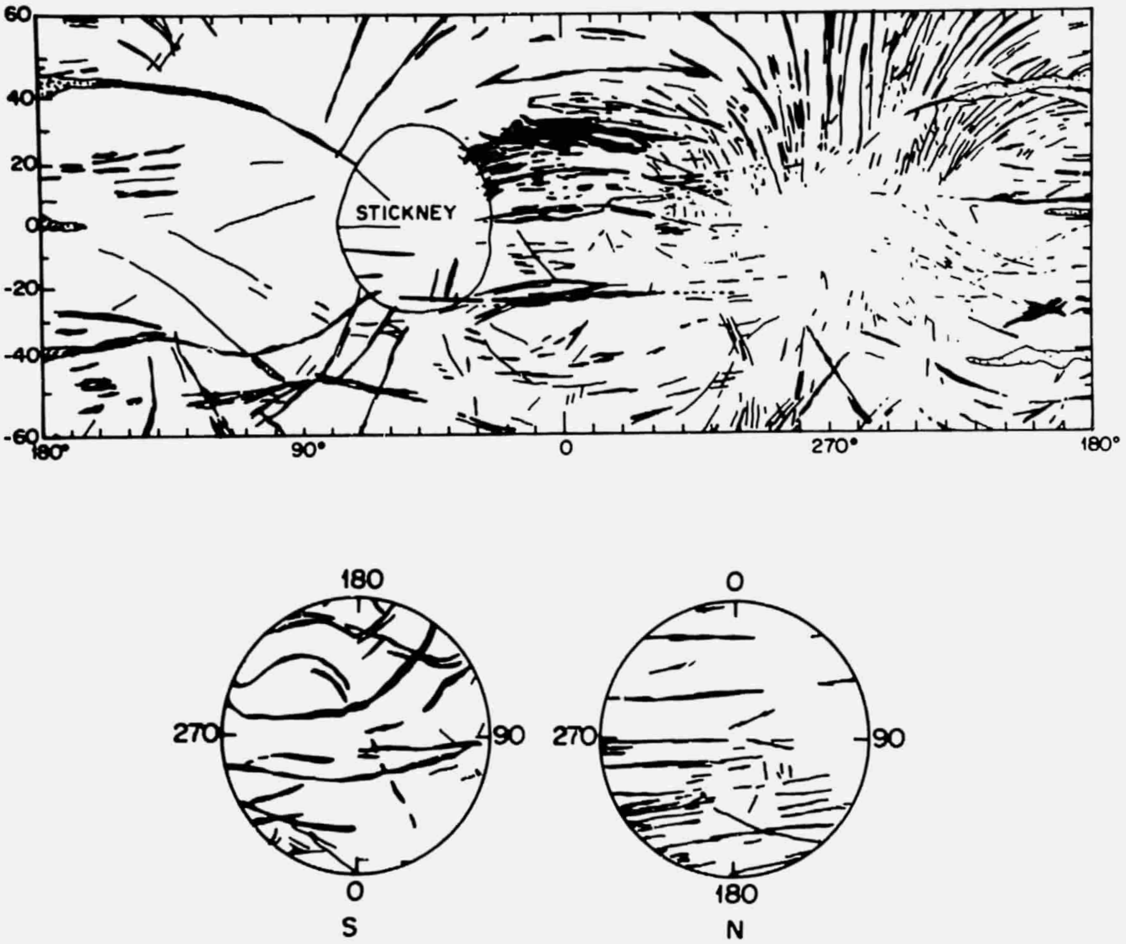


Fig. 12. Sketch map of Phobos showing the location of the grooves and of the largest crater, Stickney. Stippled areas represent hummocky topography within grooves (after Thomas *et al.*, 1978).

our knowledge of the volume, accurately determining the volume of an irregular object is still a difficult problem, even when essentially complete coverage of the surface exists. In the case of Deimos, Viking has imaged only about 50% of the surface, and the volume remains very uncertain. Thus while we know the mass of Deimos about as well as that of Phobos, we cannot determine the mean density of the outer satellite reliably until more extensive coverage of its surface is obtained.

The incomplete coverage of Deimos not only plagues attempts to determine the density, but also makes it difficult to resolve some other important questions. For example, we now know that there are no grooves on Deimos. Why? One possible explanation is that there is no crater large enough (say >5 km) on Deimos to have fractured the satellite. While we know that there is no crater larger than about 3 km on the part of Deimos that has been imaged, it is important to show that there is no much larger crater on the remainder of the surface.

Fig. 13. Viking Orbiter 1 view of Phobos at a phase angle of 14°. The conspicuous bright rings around many of the craters probably represent areas of unusually intricate texture. Range = 370 km (Frame 250A14).

IV. ADVANTAGES OF IMAGING OVER A LARGE RANGE OF PHASE ANGLES

While the optimum phase angle for studying surface morphology (craters, grooves, blocks, etc.) is close to 90°, much significant information about surface texture can be obtained by imaging over a wide range of phase angles. From such data it is possible to construct phase curves for various parts of the surface and search for textural differences. It is possible to determine whether the regolith is laterally homogeneous, and whether or not there are extensive exposures of bare, uncomminuted rock. For example, in the case of Phobos, Noland and Veverka (1977a) used such data (obtained by Mariner 9) to show that the regolith on the inner satellite is essentially homogeneous in texture on scales of several hundred meters.

Recent high resolution Viking images show that significant differences in surface texture do occur over smaller distances on Phobos. For example, near opposition (phase angle $\alpha \simeq 10°$), narrow bright rings are seen around many of the craters (Figure 13). At low phase angles these features are about 5-10% brighter than their surroundings; but they are inconspicuous at larger phase angles. They are best explained as regions of circumcrater ejecta whose texture is rougher than that of the surroundings.

Fig. 14. Viking Orbiter 2 view of Deimos from a range of 1000 km. The resolution is about 50 m. Note the absence of grooves and the conspicuous bright markings (Frame 428B60).

Phase angle coverage allows one to distinguish differences in albedo effects from differences in phase function effects. That is, one can determine *why* a certain region appears brighter than another under a given illumination geometry. Is it because the material is intrinsically brighter (*i.e.*, has a higher normal reflectance), or is it because it has a different phase function (*i.e.*, a different texture or surface roughness)? Two interesting examples can be given:

a. By constructing relative phase curves Noland and Veverka (1977b) proved that the conspicuous "bright" material on Deimos (Figure 14) actually has a normal reflectance about 30% higher than the surroundings, but has a comparable texture (since its phase function is essentially identical to that of its surroundings).

b. By a similar procedure, Goguen *et al.* (1977) have demonstrated that the "ultra-dark" material which is conspicuous on the floors of many Phobos craters at large phase angles (Figure 7), appears darker (contrast ~100% near α = 90°) because it has a steeper phase curve (*i.e.*, is much rougher) than its surroundings, and not because it has a significantly lower normal reflectance. Goguen *et al.* found that the normal reflectance of the "dark" material differs by less than 10% from that of the surroundings. Its coarse texture and its location on the bottoms of craters is consistent with its being solidified impact melt which, judging from terrestrial experiments, often has a coarse, vesicular texture.

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DISCUSSION

MATSON: How would you describe the blocks on Deimos? Do they tend to lie on their sides or to stand on their ends?

VEVERKA: We have looked at the block height versus block width distribution on Deimos and what is interesting about this is that if the blocks were equidimensional then the data suggest that they are buried in something. Typical blocks are like 10 m or so in dimension.

MORRISON: Do you want to say anything about which of these kinds of features or lessons apply most directly to asteroids? As you pointed out, asteroids have a somewhat different environment.

VEVERKA: In the next session, I am going to talk about imaging objectives and their importance. The best answer to your question is that you are really not smart enough to know what you are going to see on asteroid surfaces. That should be the lesson of these two objects. In neither case were we able to anticipate what we should see at high resolution and the two objects are really very different. Therefore, we should not pretend we can predict what will be seen on any particular asteroid and we must plan our strategy so we can take advantage of whatever is there. That involves doing the best you can to get high resolution, complete surface coverage, and complete phase angle coverage. I left color measurements out of this discussion for a number of reasons. In the case of Deimos, the bright patches, to our 5% sensitivity, don't really have colors different from the surroundings. I am sure they do have smaller color differences and that would be interesting information. If we had only global or hemispheric measurements, we would probably think that Deimos is very homogeneous, but when you get there you do notice these albedo differences.

CHAPMAN: This is entirely right. One does not want to view these observations as saying "let's think about whether we will see grooves on asteroids, etc." If we had Earth-based observations of Phobos and Deimos similar to those we have of asteroids (we don't because of their closeness to Mars), we would have concluded a number of things about these objects having to do with composition, for instance, but not with geology. Then, we go there and look at them and find features that are mysterious, unexpected and different between the two bodies. These features will cause people to think about these bodies in a way they have never been thought of before. Ultimately, this just proves once again that at least as much is going to come from serendipity as can be anticipated and planned for in advance. I think similar comments could probably be made about other scientific methodologies and not just imagery. We may think we know all the questions to address. We may think we have theories that explain what asteroids are all about. But we have never had the intelligence to really know for sure what we are going to find when we go to a planet or a small body. This is an important lesson.

MORRISON: This is perhaps saying the same thing. Once we have spacecraft data from other planets, we deal with a whole universe of questions we never would have asked from the ground. We have less data on individual asteroids now than we had on Mars or Mercury or Jupiter before the first missions to these planets. Surely the same dramatic widening of our perspective will apply to an asteroid mission.

SHOEMAKER: I hope no one in this room thinks that because we have seen the beautiful pictures of Phobos and Deimos, we now know what asteroids look like. There are some very important differences in the environments of Phobos and Deimos and the environments of the asteroids.

VEVERKA: Once we actually look at several comparable size objects, I think there will be a whole host of investigations to be done relating observations to differences in environments, composition, etc. I think we will learn a lot of things from that.

WETHERILL: I agree with what others have said. You have no idea before you go there what you are going to find. One great advantage of imaging is that it allows you to get answers to questions you didn't know enough to ask in advance. Imaging definitely isn't just for public relations. But I think it is worthwhile to make predictions before a mission. It was shocking that so many people were surprised by craters on Mars. And even after finding craters on Mars, I remember arguing with some members of the Mariner 10 imaging teams about whether there would be craters on Mercury. Some of these people were convinced there would not be craters on Mercury because Mercury was too far from the asteroid belt.

SHOEMAKER: It is necessary not only to think about what will be discovered and to try to make predictions, but also to take time to find out what others have predicted. There is a prophetic statement in Öpik's 1951 paper on Mars-crossing asteroids to the effect that it would be worthwhile looking for craters on Mars! Unfortunately, only a few of the predictions in the literature are as well-grounded.