

**SIZE-FREQUENCY DISTRIBUTIONS OF ROCKS ON
MARS AND EARTH ANALOG SITES:
IMPLICATIONS FOR FUTURE LANDED MISSIONS**

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ABSTRACT

The size-frequency distribution of rocks at the Viking landing sites and a variety of rocky locations on the Earth that formed from a number of geologic processes all have the general shape of simple exponential curves, which have been combined with remote sensing data and models on rock abundance to predict the frequency of boulders potentially hazardous to future Mars landers and rovers. Rock data from the near field of the Viking landers where dimensions can be measured accurately in stereo images and estimates from the far field of Viking 1 have convex up curved shapes on log-log graphs of cumulative frequency per square meter or cumulative fractional area versus diameter. The rock data show a sharp drop-off at large diameters and a progressive approach to a plateau with decreasing diameter (approaching the total rock coverage), which can be fit well with simple exponential functions. Similar shaped size-frequency distributions of rocks are found at a wide variety of rocky surfaces on the Earth and can be fit well with simple exponential functions. This distribution is compatible with fracture and fragmentation theory, which provides a physical basis for its wide application. A combined fit to rock area data at both Viking sites was made with a general exponential function, in which the pre-exponential is the total area covered by rocks. Simple linear height versus diameter relationships were also derived from height-diameter ratios at the Viking sites, which suggest that rockier areas on Mars have higher standing rocks than less rocky areas. Height was then substituted into the general exponential function derived for diameter, yielding the cumulative fractional area of rocks versus height for any given total rock coverage on Mars. Results indicate that most of Mars is rather benign with regard to hazards from landing on large rocks. For total rock coverage of 8%, equivalent to modal rock coverage on Mars and the Viking 1 site without the outcrops, about 1 % of the surface is covered by 20 cm or higher rocks. A lander designed to accommodate landing on 0.5 m high boulders, such as the Mars Pathfinder airbag system, could land on a surface covered by about 20% rocks, similar to the Viking 2 site (which is rockier than 95% of the planet), with 1% of the surface covered by rocks of 0.5 m or higher.

INTRODUCTION

Predicting the size-frequency distribution of rocks at different locations on Mars is difficult owing to the limited data set (ground truth from only two small sites at the surface) and yet is critical for determining potential hazards for future Mars landers. In this paper, the size-frequency distribution of rocks are reviewed at the two Viking landing sites with special reference to larger rocks that could be hazardous to a lander. The data are described in terms of simple mathematical expressions which provide an approximate means of extrapolation to any location on Mars from relationships between the rock frequency curves and remote sensing data. The extrapolations provide a ready mechanism for predicting the size frequency of rocks at any location on Mars for which the total rock coverage is known, which can be used for calculating the probability of a hazardous landing for any proposed landing system. The size-frequency distributions of rocks at a variety of rocky sites on the Earth are also presented and it is found that there is considerable similarity to the distributions found on Mars. Results of this work imply that Mars is actually a relatively benign environment with respect to hazards of landing on large rocks for the Mars Pathfinder mission,

SIZE-FREQUENCY DISTRIBUTIONS OF ROCKS ON MARS

Background

Plots of the distribution of rocks versus diameter at the two Viking landing sites have been used to suggest a power-law distribution [Binder et al., 1977; Moore et al., 1979], which has been used historically in the analysis of crater and rock size-frequency distributions on the Moon [e.g., Shoemaker and Morris, 1969; Hutton, 1969; Moore et al., 1969]. Moore and Keller [1991] suggested that power-law functions could be used to describe rock populations for diameters greater than 0.1 m, in the absence of more detailed data on rock populations on Mars. As a result, the following relationships have been used by the engineering community to estimate

the size-frequency relation and fractional area covered by rocks on Mars [e.g., Moore, 1988; Moore and Jakosky, 1989; Moore and Keller, 1991].

$$N(D) = K D^{-2.66} \quad (1)$$

and

$$F(D) = C D^{-0.66} \quad (2)$$

where $N(D)$ is the cumulative number of rocks per square meter with diameter greater than or equal to a given diameter D (where D is in meters), $F(D)$ is the cumulative fractional area covered by rocks of a given diameter or larger and C and K are constants, which are derived from the cumulative number or area of rocks greater than or equal to 10 cm size. For the Viking 2 site, K is 0.013 and C is 0.0408 [Moore and Jakosky, 1989]. Moore and Keller [1991] even suggested that C could be fit to the thermal inertia rock abundance estimates by Christensen [1986] for any location on Mars.

Analysis of Viking Data

in general, the data on occurrence of various rock diameters may be plotted as histograms of number of rocks at each site at each diameter (diameters are average of length and width, measured to nearest cm) as shown in Figures 1 and 2 (data are from Moore and Keller [1990, 1991] for over 400 rocks over areas of $\sim 84 \text{ m}^2$ from stereo measurements at the Viking sites, without the large, flat and benign outcrops at the Viking 1 site). However, in this paper where we are primarily concerned with estimating potential landing hazards for future Mars landers, it is more valuable to deal with the cumulative number of rocks per square meter versus rock diameter and the cumulative fractional area covered by rocks versus diameter, integrating from the largest to smallest rock sizes. In this form, the number of rocks (or fractional area of rocks) greater than any diameter provide the critical information needed for landing hazard analysis and has been a common representation in the scientific literature [Moore et al., 1979; Malin, 1988, 1989].

Figures 2 and 3 show that Moore's equation 1 does a reasonably good job of fitting the number versus diameter relationship for rock diameters greater than about 0.2 m at the Viking 2

size, but the power law overestimates the number of rocks at smaller diameters. Even though the power law appears to fit the data for diameters greater than 0.2 m, closer inspection of the data for the larger rock sizes (diameters greater than 0.4 m at Viking 1 and greater than 0.6 m at Viking 2) reveals that the slope of these data points is much steeper than the power law function, so that extrapolating the power law function to larger sizes will overestimate the number of large rocks.

In Figure 4, the cumulative fractional area covered by rocks of a given size or larger is plotted against diameter along with the power-law function suggested by Moore (equation 2) for the Viking 2 site. The data for either landing site clearly do not follow a straight line and the misfit with the power-law of equation 2 is severe at large and small rock diameters. Over the range of rock diameters from 0.2 to 0.4 m, the power law function provides a reasonable fit to the data. However, the power law significantly overestimates the cumulative area covered by rocks larger than 0.4 m diameter, which is of primary importance in determining the probability of a hazardous landing, and overestimates the cumulative area of rocks smaller than about 0.2 m.

The shapes of the cumulative area curves described by the data appear real and cannot be made into a straight line; there are not enough small rocks and the area covered by them is too little to make up for the deficiency at small rock diameter, and there are too few large diameter rocks at the two Viking sites. Even adding smaller rocks (less than about 0.2 m diameter) potentially covering up to an additional 4% of the surface [Moore and Keller, 1991] or rocks potentially shadowed by large rocks beyond a few meters from the lander cannot steepen the curve enough to match a straight line. The disparity at small diameters is not important so long as the power law equation is not applied to small diameter rocks. However, the disparity at large diameters is very important because the rock areas associated with the large diameters predicted by the power law equation lead to significant areas covered by larger rock sizes. For example, the data for the Viking 2 site suggest less than 1% of the surface is covered by rocks of 1 m diameter or greater, whereas the power law function suggests almost an order of magnitude greater surface area covered by such large (and potentially hazardous) boulders.

Exponential Size-Frequency Distribution

The size-frequency data for rocks at the two Viking sites on log-log plots better describe a curve rather than a straight line defined by a power law [e.g., Malin, 1988, 1989]. These curves can be fit empirically with simple exponential functions, which appear to better describe rock populations in theory and practice (see later discussion),

$$N(D) = L \exp\{-sD\} \quad (3)$$

$$F(D) = k \exp\{-qD\} \quad (4)$$

as shown in Figures 3 and 4. In these equations, L represents the total number of rocks of all sizes per square meter, k represents the fraction of surface area covered by rocks of all sizes (total rock coverage), and s and q are exponents. Least square curve fits are excellent, with correlation coefficients of 0.96-0.99 for the Viking data, with values of L and s , or k and q given in Figures 3 and 4. These curves have properties which parallel the data: 1) $F(D)$ approaches a constant (k) as D approaches 0; 2) the slope of $F(D)$ increases continually downward as D increases; and 3) at large D , $F(D)$ drops off sharply with increasing D .

Comparison of the exponential curves and the actual data shows that the fit curves actually drop-off more slowly at large sizes than the actual data, and thus predict slightly more area covered by large rocks than is evidenced by the data (Figure 4). This demonstrates that the flexibility of the exponential function is limited. There are only two parameters; the pre-exponential measures the total rock coverage by rocks of all sizes, while the exponent determines the rate of drop-off at large diameters. Note that the fits to the curves indicate that as D approaches 0, $F_1(D)$ approaches 0.069 and $F_2(D)$ approaches 0.176, which provide estimates of the total rock coverage by rocks of all sizes. Comparison of the exponential fit curves to the data in non-cumulative histogram form show a reasonable fit to the actual number of rocks per diameter bin (Figures 1 and 2). A comparison with the power-law function for Viking 2 (Figure 2), actually shows a slightly better fit than the exponential curves to the data in this form for diameters larger than 0.2 m. Nevertheless, at diameters smaller than 0.2 m, the power-law function significantly over-predicts the number of small rocks present (even if the function is cut

off at 0.1 m diameter as suggested by Moore). Given that the utility of a simple mathematical representation must apply to the data equally well in histogram and cumulative number and fractional area form, the exponential functions more closely represent the rock size-frequency data at the two Viking sites than do power-law functions.

Relationships Between Cumulative Number and Area Functions

There is a certain mathematical inconsistency in fitting separate exponential curves to both $N(D)$ and $F(L)$ for any site. For any given mathematical form for the $N(D)$ curve, there is a corresponding theoretical $F(D)$ curve, and vice versa. If the dN/dD curve is exponential, it follows that

$$dN(D) = -1/s \cdot c \cdot s^D \cdot dD \quad (5)$$

$$N(D) = 1, c \cdot s^{-D} \quad (6)$$

$$dF(D) = -(\pi/4) \cdot 1/s \cdot D^2 \cdot e^{-sD} \cdot dD \quad (7)$$

$$F(D) = (\pi/4) \cdot L \cdot e^{-sD} \{D^2 + 2D/s + 2/s^2\} \quad (8)$$

If exponential curves are fit to the Viking $N(D)$ data as in equation 6, equation 8 can be used to predict the corresponding $F(D)$ curve. Using the results given in equation 8, we predict $F(D)$ curves as shown in equations 9 and 10.

$$F_1(D) = (3.82) \cdot e^{-10.98D} \{D^2 + 0.182D + 0.0166\} \quad (9)$$

$$F_2(D) = (3.79) \cdot e^{-6.98D} \{D^2 + 0.28611 + 0.0411\} \quad (10)$$

These curves fit the overall shape of the Viking cumulative area versus diameter data reasonably well as shown in Figure 4, although they slightly overestimate the cumulative area of rocks with diameters less than about 0.5 m.

Viking 1 Far Field

The areas over which accurate stereoscopic measurements could be made of the rock sizes near the sample fields of the robotic arms are very small, resulting in very small samples of rocks at large diameters [Moore and Keller, 1990, 1991]. At Viking 2, the surrounding terrain has fairly low relief, so that it is extremely difficult to extract additional data from the far field. In

addition, large rocks are present within the near field (up to 1 m diameter) and the near and far rock fields appear homogeneous (Figure 5). By contrast, the area surrounding Viking lander 1 slopes toward the lander, making it possible to examine the far field in some detail. In addition, rocks larger than 0.5 m diameter are not present in the near field and the near and far rock fields appear quite heterogeneous (compare the rocky area to the south of the lander in Figure 6 with the drift-covered area to the northeast in Figure 7), with many large rocks present in the far field (note "Big Joe", a 1.5 m diameter rock is only 10 m from lander 1, Figure 7). As a result, an attempt was made to estimate the sizes of rocks in the far field of the Viking lander 1 site to better characterize the number of large diameter rocks.

Estimates of the distances to several rocks in the far field have already been made [U.S.G.S., 1982; Liebes, 1982; Moore et al., 1987], particularly those rocks perched on the rims of nearby craters [Morris and Jones, 1980], as well as some notable nearby rocks such as those named "Big Joe" and "Whale". In addition, the distances of rocks in the near field are known and could be identified in the photographs. Using these far and near field distance estimates, rough radial contours of distance were drawn on the lander image mosaics and a visual search was made for all large rocks in the extended field. The distance estimate was used to determine the largest dimensions of rocks from their measured apparent angular widths. The apparent maximum angular width is the total width of the rocks in silhouette, and usually included more than one face of a rock. The actual dimensions of a rock depend on the angle at which the rock is oriented relative to the cameras. For example, for rocks oriented at 45° the apparent width will include 0.707 times the sum of the lengths of two sides, and for rocks oriented at 60° it is 0.866 times the length of one side plus 0.5 times the length of the other side. Because separate length and width could not be distinguished for far field rocks, rock "diameter" was taken as roughly 0.75 of the apparent maximum width. A total of 84 apparently large rocks were measured. Only the 17 largest rocks, with diameters greater than 0.8 m, were retained, as the survey is undoubtedly very incomplete for smaller rocks. The effective area covered is roughly 20,000 m² (Figure 8).

The location of large rocks in the far field of the Viking 1 site is shown in Figure 8. It can be seen that many of the largest rocks are concentrated near the rim of crater C, implying that the largest rocks in the far field are ejecta. Figures 3 and 4 show the cumulative number and area versus diameter data for both the Viking 1 near and far fields. Data were plotted for a 2000 m² rectangle surrounding the large rocks at the rim of crater C and the sum of the near field plus the remaining far field rocks in the 18,000 m² beyond the rim of crater C. To first order, given the inherent uncertainties in estimating the sizes of rocks in the far field (estimated error in angular width $\pm 5\%$, estimated error in distance $\pm 25\%$, estimated error in diameter $\pm 30\%$), the similarity between the estimated frequency and area of all large rocks is rather similar to that predicted by the exponential fit to the near field data at these larger diameters. The far field area data without the 2000 m² crater rim is even more similar to that predicted by the exponential fit to the near field data. Note that if rocks smaller than about 0.2 m diameter were added to the near field data (covering up to 4% area as estimated by Moore and Keller [1990]), a worse fit to the larger diameter rocks would result, which is the primary focus of this work. In any case, the distributions are far below those predicted by the power-law functions (equations 1 and 2) at these large sizes. The 2000 m² area around the crater rim appears to have a greater frequency and area of large rocks, but nothing is known about the frequency of smaller rocks in this restricted area, so it cannot be used to test the complete size-frequency rock distribution. At these large sizes alone, however, the rock distributions appear similar to those measured near large impact craters on the Moon (Moore et al., 1969; Hutton, 1969; Cintala and McBride, 1995).

EARTHANALOG ROCK SIZE-FREQUENCY DISTRIBUTIONS

In this section, the distributions of rock sizes found on Mars are compared with distributions of rock sizes for a variety of rocky sites on the Earth, including: the Elysiata Fan, in the Channeled Scabland of Washington; Mars 1 in Death Valley; and volcanic (Goldstone) and alluvial fan (Avawatz) surfaces in the Mojave Desert (data are summarized in Table 1). These surfaces are very rocky by nominal Earth standards. At each site a homogeneous area,

typically 10 to 15 m on a side, was surveyed (staked) and all rocks in the area were measured systematically (each measured rock was marked with chalk). Two or three sub-areas within each site were typically measured separately to look for inhomogeneities in the rock distributions; unusually large rocks relative to the areas measured were avoided for this reason (see GDB 1, MIHNE/NE/SE and NW/SE/SW where one or two large rocks slightly skew the distributions). At most sites, the length, width and height of each rock were measured down to a minimum dimension (typically ~1 cm). In general, there is a decrease in number of rocks at the smallest one or two diameters in the measured data, which may represent a selection deficit and is of no consequence, given that the cumulative size frequency data have reached a plateau before this diameter is reached,

One area extensively surveyed is the Ephrata Fan in eastern Washington, which is a large, 40 km long depositional fan where channelized (Grand Coulee) flood waters catastrophically released from Glacial Lake Missoula, debouched into the Quincy Basin at Soap Lake in the Channeled Scabland [Baker, 1973; Baker and Nummendal, 1978]. This channel-fan arrangement is analogous to Arcs Vallis and the Mars Pathfinder landing site, where the incised channel debouches onto Chryse Planitia about 100 km south of the landing site [e.g., Golombek et al., this issue]. Rock frequency counts reported in this paper are from the proximal coarse rocky surfaces of the Ephrata Fan, restricted to areas within about 10 km of Soap Lake (Figure 9); areas farther down the fan are predominantly sand and gravel. Four sites (sites EF 1-3 and 5) are from armored lag deposits in Rocky Ford Creek, in which rocks deposited in the fan are significantly concentrated by the removal of fines due to late stage drainage of the Quincy Basin [Baker, 1972]. The other three sites are less rocky surfaces on top of the fan and appear to have had more glacial loess deposited on them (silt mounds common).

A number of sites in eastern California were studied, particularly four areas of Mars Hill in Death Valley (Figure 10). Mars Hill is an abandoned alluvial fan on the eastern side of Death Valley that has had much of the surface fines washed away, leaving an armored rocky surface. Mars Hill (Figure 10) has long been referred to and used as a possible Earth analog since the

earliest Viking lander work [e.g., Mutch et al., 1977], even though virtually no data have been collected to support this assertion. Two areas were measured in the field (MINE/NE/SE and NW/SE/SW) with the length, width and height of all rocks >7 cm diameter cataloged. Approximately 1000 rocks (down to about 5 cm diameter) were measured on vertical air photos of roughly 1:100 scale at two other areas (MINE/SE/SW and SE/NE/NE).

Rocky surfaces at two other areas in the eastern Mojave Desert were also measured. Avawatz is from the apex of an active alluvial fan on the eastern side of the Avawatz Mountains, a currently uplifting range in the Mojave Desert. The Goldstone surfaces, in contrast, are from eroded volcanic surfaces in the JPL/NASA Goldstone Deep Space Network tracking facility. Sites GDB 1 (Figure 11) and GDB2 are from the top of a Miocene basalt mesa in which blocks have moved slightly with sediment and dust filling in between. Site GDT3 is a Miocene tuff breccia that was likely deposited as a debris flow, with large (up to 2 m diameter) rhyolite blocks (McConnell et al., 1994). The tuff has been preferentially eroded leaving the rhyolite blocks on the surface with sand and dust filling in between [D. McConnell, 1995, pers. comm.].

Figures 12 and 13 show the cumulative number and area of rocks versus diameter, respectively, for a representative subset of the rocky surfaces described above, as well as the Viking sites for reference. The total rock coverage varies from 2-60% for the Ephrata Fan, 7.5-25% for Mars Hill, and 10-60% for the eastern California sites. Even so, rock distributions for the Earth sites have very similar shapes to the Viking sites (convex up), with a shallowing in the cumulative number or area at small rock diameters and a sharp drop-off at large diameters. The data from Mars Hill indicate that it is indeed a reasonable analog for the Viking sites. Rocks at Mars Hill, however, have greater height/diameter ratios compared with rocks from the Viking sites on Mars (0.6 versus 0.36 and 0.5, see next section), so that Mars Hill actually represents a more severe testing environment for rovers than appears to be likely for similarly rocky areas on Mars. Data from all the Earth sites can be fit very well (correlation coefficients >0.90) with simple exponential functions (Table 1). The fits to all the sites combined at Mars Hill and the Ephrata Fan, indicate that the Ephrata Fan data tend to drop-off more slowly at large diameter

than do Mars 1 Hill and the Viking sites. This is due to the relative scarcity of smaller rocks at the Ephrata Fan sites compared to the Viking and Mars 1 Hill sites, which produces lower intercepts at small diameters for the Ephrata Fan (e.g., Figures 12 and 13). As a result, the curves for the Ephrata Fan sites appear to be shifted to the right (to larger diameter rocks), which can be explained by the loess covering most small rocks and partially covering large rocks of the proximal Ephrata Fan sites; note that height/diameter ratios support this interpretation, varying from 0.2 for the least rocky site (EF 6) to 0.5 for the rockiest site (EF 3).

Malin [1989] plotted rock size-frequency distributions from 6 different rocky surfaces on the Earth, including Icelandic catastrophic outflow deposits, Antarctic dry valley wall talus, and Hawaiian volcanic ejecta. All areas he counted show the same shaped distribution of cumulative fractional area covered by rocks versus diameter as was found at the Viking landing sites and the Earth sites described in this paper. Even though the geologic processes responsible for the formation of these surfaces appear to be different, the cumulative area versus diameter data on log-log plots show the same shallow slopes at small diameter followed by steeper slopes at larger diameters. The shape of the curves is real and not an artifact of the counting technique because Malin included sieve analysis of smaller rocks down to 1 cm diameter to accurately capture all size rocks.

EARTH AND MARS ROCK SIZE-FREQUENCY DISTRIBUTION RELATIONSHIPS

The similarity in shape of rock size-frequency distributions at a variety of rocky surfaces on the Earth and the Viking sites on Mars and the excellent fits of these distributions by simple exponential functions can be explained by simple fracture and fragmentation theory. A wide body of observational data has suggested that the size-distribution of materials (typically at small sizes) expected from fracture and fragmentation would follow an exponential [e.g., Rosin and Rammler, 1933; Gilvarry and Bergstrom, 1961]. This distribution results from the fragment sizes expected from Griffith's fracture criteria, in which failure occurs from propagation of ubiquitous flaws and/or cracks in the material [e.g., Gilvarry, 1961]. The theory predicts that the likelihood