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Modes of Sediment Transport in Channelized Water Flows with Ramifications to the Erosion of the Martian Outflow Channels

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Depending on their grain sizes (settling velocities), sediments are transported in rivers as bed load, in suspension, or as wash load. The coarsest material rolls or bounces along the bottom as bed load whereas finer material is placed into suspension by the water turbulence. The finest sediments are transported as wash load, evenly distributed through the water depth and effectively moving at the same rate as the water. The criteria for quantitatively determining which grain-size ranges are being transported in terrestrial rivers as bed load, suspended load and wash load are applied to an analysis of sediment transport in the large Martian outflow channels, assuming their origin to have been from water flow. Of importance is the balance of the effects of the reduced Martian gravity on the water flow velocity versus the reduction in grain settling velocities. Analyses were performed using grain densities ranging from 2.90 g/cm^3 (basalt) to 1.20 g/cm^3 (volcanic ash). The results show that the Martian flows could have transported cobbles in suspension and that nearly all sand-size material and finer would have been transported as wash load. Wash-load transport requires little or no net expenditure of the water-flow power, so the sands and finer could have been carried in nearly unlimited quantities. A comparison with terrestrial rivers indicates that concentrations as high as 60–70% by weight of wash-load sediment could have prevailed in the Martian flows, resulting in the very rapid erosion of the channels.

INTRODUCTION

Sediment transport in rivers occurs as a combination of bed-load, suspension transport, and a fine-grained wash load. The coarsest sediments are transported as bed load, rolling, and bouncing (saltating), always remaining close to the river bed. Finer sediments are lifted well above the bottom by the water turbulence and comprise the suspended load. The wash load consists of sediments that are sufficiently fine grained that the river is able to transport them at uniformly high concentrations and at nearly the same rates as the water flow itself. The ranges of sediment grain sizes that are transported, respectively, in these three modes are governed by the stream-flow velocity and by the settling velocities of the grains. The criteria that are commonly used to distinguish these transport modes will be summarized, and then applied to presumed channelized water flows on Mars, the flows that may have eroded the large outflow channels (Milton, 1973; Sharp and Malin, 1975; Carr *et al.*, 1976; Masursky *et al.*, 1977). Because the reduced gravity on Mars affects both the flow velocity and the settling velocities of the transported grains, it can be expected that the proportions of bed load, suspended load and wash load would have differed in such water flows from that in terrestrial rivers. Sediments that comprise the wash load are sufficiently fine grained to require little or no net expenditure of the river's power, the presence of the sediment perhaps even contributing to the flow's power (Bagnold, 1962). As a result, rivers or water flows on Mars are able to transport nearly unlimited quantities of this fine-grained wash load. Due to the possible catastrophic nature of the flows that eroded the Martian outflow channels (Baker and Milton, 1974), large quantities of wash load may have been present in these flows. Thus rapid erosion of the channels could have occurred, at least until solid bedrock was

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reached, having proceeded at much faster rates than the erosion of terrestrial river channels and possibly even more rapidly than the erosion due to the Lake Missoula floods. An important consideration is the question of how much of this fine-grained sediment the flows could have transported before the flow turbulence becomes damped and the flows become more akin to pseudolaminar mud flows than to turbulent rivers.

This paper will first summarize the criteria that have been employed to distinguish between bed load, suspended load, and wash load in terrestrial rivers. These criteria will then be applied to channelized water flows on Mars to determine which grain sizes would have been transported in these three modes. The ramifications of the results to the erosion of the channels and the deposition of sediment from the Martian water flows will then be discussed. Included in the analyses will be an examination of threshold of sediment motion under water flows on Mars. This is important in order to evaluate whether the rate of channel formation might have been erosion limited or limited by the rate at which the sediments were transported away.

MODES OF SEDIMENT TRANSPORT

Bed-Load Versus Suspension Transport

Bagnold (1966) and Francis (1973) make the clearest distinction between bed load and suspension transport in rivers; grains moving as bed load slide, roll, and jump (saltate) along, with frequent contacts with the bottom or with other grains, whereas grains transported in suspension are supported above the bottom by the turbulence field of the flowing water. In principal this distinction is sound, in practice the distinction is more difficult and somewhat arbitrary. The interest here is that the coarser-grained bed load is transported in close proximity to the bottom and so moves at much slower rates than the mean water flow, whereas the finer-grained suspended load can be found far above the bottom, being transported at much higher rates than the bed load but at lower concentrations.

It has been of interest to engineers and geologists to determine a cutoff sediment grain size between bed load and suspension transport, the coarser sizes moving principally as bed load, the finer grain sizes transporting primarily in suspension. Desired was a means of relating this cutoff to the known river flow rate (velocity, stress, or discharge). The approach was to compare the grain settling velocities tending to move them toward the bottom with the upward components of the turbulent eddy velocities (Bagnold, 1966). This approach leads to the ratio

$$w_s/u_* = \mathrm{k}, \tag{1}$$

where w_s is the settling velocity of the cutoff grain size between bed load and suspension, and u_* is the so-called frictional shear velocity, given by

$$u_* = (\tau/\rho)^{1/2}, \tag{2}$$

where τ is the stress between the flowing water and bottom and ρ is the water density. The dimensionless k in Eq. (1) is the value of the ratio which will be employed to distinguish between bed load and suspension transport. For a given u_*, grain settling velocities greater than w_s of Eq. (1) are transported as bed load, those with smaller w_s values move in suspension. Various values of the critical k have been used: $k = 1.00$ (Lane and Kalinske, 1939; Inman, 1949; Francis, 1973; Middleton, 1976), $k = 1.20$ (Einstein, 1950), $k = 1.25$ (Bagnold, 1966) and $k = 1.79$ (McCave, 1971). This range of k values is in part due to the rather arbitrary nature of the distinction between bed load and suspension transport. In the analyses to follow, an intermediate value $k = 1.25$ will be used in Eq. (1) to differentiate between bed load and suspension transport.

The frictional shear velocity u_* of Eqs. (1) and (2) can be determined by measuring the stress τ directly or in the case of uniform or near-uniform flow it can be determined from the flow depth h and channel slope S through the relationships

$$\tau = \rho g h S, \qquad (3)$$

$$u_* = (ghS)^{1/2}, \qquad (4)$$

where g is the acceleration of gravity (981 cm/sec^2 for Earth and 372 cm/sec^2 for Mars). Combining Eqs. (1) and (4) gives

$$w_s = k(ghS)^{1/2} \qquad (5)$$

relating the cutoff between bed load and suspension directly to the flow depth and channel slope. In Komar (1979) it was shown that the mean flow velocity $\bar{u}$ is given by

$$\bar{u} = \left(\frac{1}{C_f} ghS\right)^{1/2}, \qquad (6)$$

where C_f is a dimensionless drag coefficient for the channelized water flow. In Komar (1979) I discussed the relationship between C_f and the dimensioned Manning-n and Chezy coefficients applied to river flows by engineers. From Eqs. (5) and (6) it is seen that

$$w_s = kC_f^{1/2}\bar{u} \qquad (7)$$

and

$$\bar{u} = C_f^{1/2}u_*. \qquad (8)$$

so that the cutoff can be related directly to the mean flow velocity $\bar{u}$ so long as C_f is approximately known. In general, due to the uncertainties involved in selecting a value for C_f (Komar, 1979), it is better to analyze the flow in terms of u_* than $\bar{u}$, and this will be the procedure mainly followed in this paper. Corresponding values of $\bar{u}$ will be given as for many these are more easily visualized than u_* values; these corresponding $\bar{u}$ values are obtained from Eq. (8) with $C_f = 0.005$, a C_f value which is equivalent to Manning-n values in the range 0.038 to 0.052 on Earth (Komar, 1979, p. 178). It should be remembered, however, that the u_* values given are more reliable than the $\bar{u}$ velocities.

From all of the above relationships it is apparent that the greater the combination of flow depth h and channel slope S, the greater will be the flow velocity $\bar{u}$ and shear velocity u_*, and hence the coarser the grain size (of which the settling velocity w_s is a measure) at the cutoff between bed-load and suspension transport. These relationships also begin to show the importance of the gravitational acceleration g so that the cutoff would be different on Mars than on Earth, other factors being the same. This difference will be examined later.

Wash-Load Transport

The wash load of a river consists of the finest-grained portion of the total sediment load with settling velocities so low that there is essentially no vertical concentration gradient through the flow depth. The analysis of the wash load has proved difficult in that, unlike the bed and suspended loads, the concentration and total transport rate of the wash load do not always relate to the river-flow parameters ($\bar{u}$, u_*, discharge or flow power) (Einstein *et al.*, 1940; Colby, 1963; Guy, 1964). Instead, the concentration depends more upon the geology of the river's drainage basin and upon the climate. Concentrations tend to be high if there is a ready source of fine-grained sediments in the drainage basin, either derived from geologic formations or where chemical weathering promotes clay formation. The very highest concentrations are found in semiarid regions with a ready fine-grained source; there, torrential rains result in amazingly high concentrations of wash load. Some of these will be discussed later when we consider the concentration limits one can place on catastrophic flows such as carved the Channeled Scablands (Baker, 1973) in eastern Washington and may have eroded the large Martian outflow channels.

Unlike the division between bed load and suspension transport, there has been very little consideration given to the cutoff between suspension and wash load. The only proposed criterion I could find in the literature on rivers is the equation of Kresser (1964) [see discussion in Graf (1971, p. 204)], which has the form of a grain Froude number, $\bar{u}^2/gD = 360$, where $\bar{u}$ is the mean flow of the river and D is the cutoff grain diameter between suspension and wash-load transport. However, application of this formula to the Mississippi River data of Jordan (1965) and other data sets yields much too high values for D, grain diameters that can be expected to be part of the bed-load rather than the onset of wash-load transport.

The fact that a river can transport nearly unlimited concentrations of wash load suggests that the transport mechanism may be via autosuspension, a concept introduced independently by Bagnold (1962) and Nordin (1963). This approach compares the energetics of the river flow and sediment transport system. It was found that when $w_s \leq \bar{u}S$, S being the channel slope, the sediment suspends itself in the sense that it needs no net expenditure of energy by the flowing water. The autosuspended sediment actually provides more energy or power to the flow. The mass of this autosuspended load may therefore rise to an indefinite value, limited only by the availability of the material (and perhaps ultimately by the damping of the turbulence by the sediment). Because this autosuspension concept appears to explain many of the properties of the wash load in a river, I initially used the $w_s \leq \bar{u}S$ formula to calculate the cutoff between suspension and wash load. However, the autosuspension concept has never been adequately tested in rivers, and when applied to the Mississippi River data of Jordan (1965) it gives grain diameters that appear to be too small for the onset of wash load. Therefore this criterion was also abandoned.

There is an extensive engineering literature on the pumping of various suspensions through pipes. Of importance to this practice is maintaining the granular material in true suspension, not allowing it to settle onto the bottom of the pipe. For this reason engineers have sought criteria for maintaining complete suspension. The terminology they employ is heterogeneous flow, which is analogous to our suspension transport, and homogeneous flow, comparable to our wash-load transport. Carleton and Cheng (1974) reviewed 55 equations that have been proposed, but most of these were for the onset of heterogeneous flow (suspension), which is of chief concern in transporting granular materials through pipes. As in rivers, little work has been done on the onset of homogeneous flow (wash load) in pipes, but what considerations have been undertaken do provide a useable criterion. The approach suggested by Task Committee (1970) and taken by Stevens and Charles (1972) is application of Eq. (1) but with a much lower value for k than used for the bed load versus suspension cutoff. Task Committee determined a value $k = 0.076$, and Stevens and Charles obtained $k = 0.13$. My analysis of the data of Jordan (1965) from the Mississippi River indicates approximately $k \simeq 0.03$ for the onset of wash load, a somewhat lower value than indicated by the pipe-flow data. The value of w_s/u_* governs the concentration gradient of the suspended sediment in a river (Graf, 1971, p. 173), and this range of k values indicates the concentration would be essentially uniform through the flow depth, further indicating their appropriateness as a criterion for the onset of wash load. Other proposed formulas based on pipe-flow data indicate that this critical w_s/u_* value may depend on the flow Reynolds number or Froude number, but this evidence is unclear so such refinements will not be attempted here. Instead, Eq. (1) will be employed to calculate the development of wash-load transport, where the range $k = 0.05$–0.10 is employed to indicate the degree of uncertainty in the calculations.

EARTH-MARS COMPARISONS

The effects of gravity g in the suspension and wash-load criteria are complicated by the fact that g influences the grain settling velocity w_s as well as the fluid flow ($\bar{u}$ and u_*), and the effects are in opposite directions. The lower gravity of Mars tends to produce lower $\bar{u}$ and u_* values than for comparable flows on Earth, which would result in smaller grain sizes for the cutoffs of the suspension and wash-load criteria. But the lower g also results in the settling velocity w_s on Mars corresponding to a larger grain size. Figure 1 presents curves for the settling velocity versus grain diameter for quartz-density (ρ_s = 2.65 g/cm^3) particles in water on Earth and Mars and for basalt grains (ρ_s = 2.90) and volcanic ash (ρ_s = 1.20) settling in water on Mars. These curves are calculated from standard drag coefficient curves as described in Graf (1971, p. 43–44), curves based upon the drag of a fluid flow around a sphere, data which are applicable to Mars as well as Earth.

In the calculations to follow, this density range ρ_s = 1.20–2.90 g/cm^3 will be utilized as it should encompass any materials that could conceivably form the loose surface materials of Mars, even if the material is not precisely one or more of these three density values. Basalt or a slightly more basic rock type is of course likely to be an important rock on Mars. Volcanic ash is similarly a likely component in certain areas, giving us the lowest density in our range under consideration. Calculations are also carried out with ρ_s = 2.65 g/cm^3 to provide a more direct comparison between Mars and the transport of quartz-density sediments on Earth. Quartz is a very unlikely component of the materials on Mars, but this intermediate density could approximately correspond to the iron-rich clay minerals that appear to form the fine-

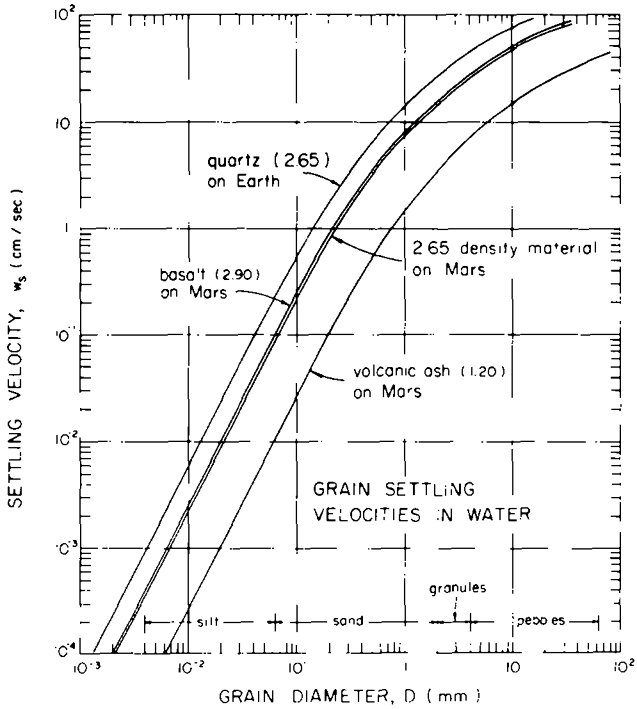

FIG. 1. Grain settling velocities of basalt and volcanic ash grains in water on Mars, and quartz-density grains on Mars and on Earth.

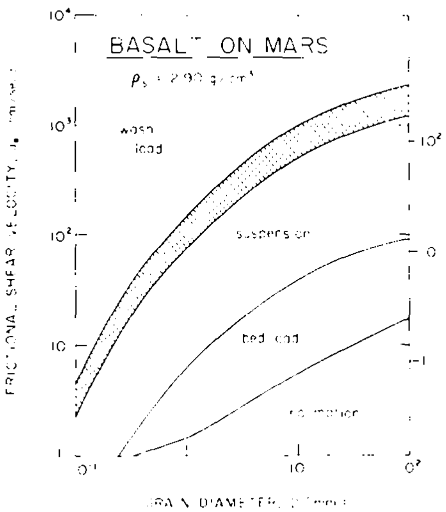

FIG. 2. Fields of modes of transport of basalt grains on Mars as a function of the shear velocity u_* and the grain diameter D. The divisions between bed load, suspension, and wash load are based on Eq. (1) with, respectively, $k = 1.25$ and $k = 0.05$–0.10 (yielding the shaded zone).

grained fraction found at the Viking Lander sites and perhaps also the aggregates (Arvidson *et al.*, 1978; Toulmin *et al.*, 1977).

Figures 2, 3, and 4 apply the suspension and wash-load criteria, discussed above, to the transport of the 1.20–2.90 g/cm^3 density range material on Mars. Each figure graphs an expected range of u_* values for the water flows on Mars [Komar (1979) and Table I] versus the grain diameter D. The corresponding $\bar{u}$ velocities are given on the right-hand margins of the graphs, calculated with Eq. (8) as discussed.

Each figure is divided up into regions where wash-load, suspension, and bed-load transport prevail, depending upon the combination of u_* and D. Each figure also provides a threshold curve, below which no sediment motion takes place and directly above which the particular grain size moves as bed load. These threshold curves are based upon the data reanalysis of Miller *et al.* (1977), in particular upon their Fig. 2, the so-called Shields curve which is the most general form for presenting sediment threshold data, and as discussed by Miller and Komar (1977), can be applied to environments such as Mars and to a range of sediment densities.

Figure 3 also shows the corresponding curves for the transport of quartz-density sediments on Earth. It is seen that the Earth curves are displaced toward higher u_* values from those for Mars. This shows the net effect of the reduced gravity of Mars. For a given u_* or $\bar{u}$ value, coarser material can be moved (threshold) and transported in suspension and as wash load on Mars. These gains due to the reduced gravity alone are fairly modest, however. More important it turns out are the steeper channel slopes of the Martian outflow channels that yield higher u_* and $\bar{u}$ values than generally exist in larger terrestrial rivers such as the Mississippi.

Direct comparisons between expected water flows in the Martian outflow channels and large-scale water flows on Earth are contained in Table I. These computations continue the comparisons of the flows made in Komar (1979). Results of the analyses of Table I are for Mangala Channel using an average bottom slope $S = 0.003$ determined by Milton (1973) and for Ares Channel with

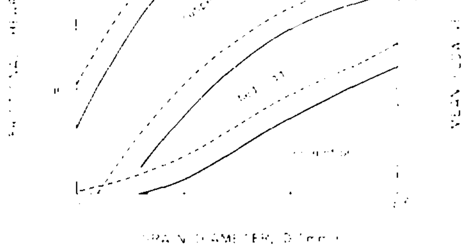

FIG. 3. Modes of transport of quartz-density grains on Mars and Earth, showing the effects of the reduced Martian gravity.

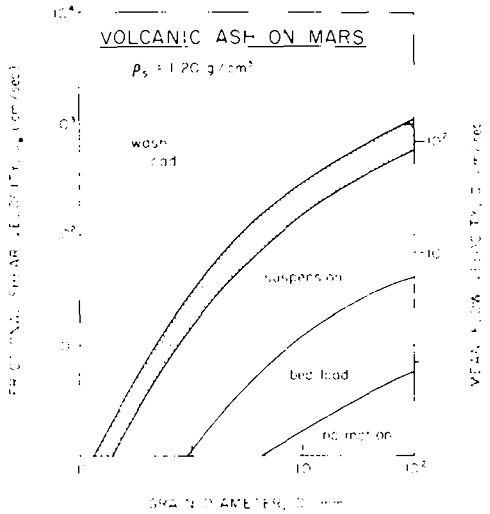

FIG. 4. Modes of transport of volcanic ash on Mars, with the divisions based on Eq. (1) as in Fig. 2.

$S = 0.01$ given in Masursky *et al.* (1977). These estimates of channel slopes are highly uncertain, which is unfortunate since that parameter is important to the analysis (Eq. 4). On the other hand, the actual channel slopes would have to be some two orders of magnitude smaller than these estimates to seriously change the over-all conclusions arrived at in this analysis.

Computations have been made in Table I for a range of possible flow depths, h, a range that spans modest, ordinary flows to more catastrophic flows that are comparable to the Lake Missoula floods. For each flow are given the grain diameter D_t that could be set into motion (threshold), the diameter D_s corresponding to the cutoff between bed load and suspension, and the diameter D_w for the onset of wash-load transport.

Because of the combined effects of the reduced Martian gravity and large slopes of Mangala and Ares Channels, it is seen in Table I that even for the basalt-density material the flows would have been able to move very large material, D_t ranging from 14 mm for the smallest flow to boulder-sized clasts for the intermediate to large flows. Still larger blocks of the lighter-density materials could of course be transported. The flows are generally so competent that the results go well above the range provided by the standard Shields threshold diagram. But in this range the trend is linear so that reasonable estimates can be made. These results indicate that the rate of channel erosion would probably not have been limited by the development of a lag deposit of clasts too large for the flows to transport. Channel erosion rates would instead have been first controlled by the rate at which the sediments could have been transported away, and then perhaps ultimately by the erosion into bedrock as in the case of the Lake Missoula Floods (Baker, 1973). An analysis of erosion into bedrock is beyond the scope of this paper. Baker (1973) has shown that plucking and cavitation could be active processes, but the erosion depends on the bedrock structure (bedding, jointing, etc.). The rates of these processes for the Martian flows are unknown. Once blocks of bedrock are eroded, they will be transported as bed load or in suspension, depending on their sizes. The analyses of this paper therefore do not apply to the bedrock erosion but do apply to the transport of the eroded material.

The results of Table I also indicate that coarse material would have been transported in suspension and in wash load, much coarser than in terrestrial rivers such as the Mississippi. The cutoff between bedload and suspension transport, D_s, is in the pebble-sized range except for the small h = 1-m flow where it drops into the coarse sand. For more catastrophic flows comparable to the Lake Missoula Floods (h = 50–100 m), large pebbles and even cobbles could have been transported in suspension. Calculations of the grain diameter for the development of wash load, D_w, indicate that most sand-sized basalt grains would have been in the wash load rather than in the suspension and bed loads as is the case for the Mississippi River.

EROSION OF THE MARTIAN CHANNELS

The views and samples obtained by the

TABLE I

CALCULATED VALUES FOR RANGES OF DIFFERENT MODES OF SEDIMENT TRANSPORT

	Bottom slope, S	Depth, h (m)	Shear u_* (cm/sec)	Velocity $\bar{u}$ (m/sec)	Basalt			Quartz-Density			Volcanic ash		
					D_t[a]	D_s	D_w	D_t	D_s	D_w	D_t	D_s	D_w
Mangala Channel	0.003	1	6.3	0.89	12.5	1.0	.11– .17	14	1.1	.12– .19	1.1×10^2	4.6	.36– .56
		5	23	3.3	1.7×10^2	4.2	.22– .36	1.9×10^2	4.8	.24– .40	1.4×10^3	27	.80– 1.4
		10	33	4.7	3.4×10^2	7.1	.29– .48	4.0×10^2	8.0	.30– .50	3.0×10^3	52	1.0 – 1.9
		50	75	10.6	1.7×10^3	42	.54– .96	2.1×10^3	64	.56–1.2	1.5×10^4	372	2.0 – 4.2
		100	105	14.9	3.5×10^3	[200][b]	.70–1.4	4.2×10^3	[250]	.76–2.0	3.0×10^4	729	2.9 – 6.2
Ares Channel	0.01	1	11	1.6	37	1.8	.16– .23	42	2.0	.16– .25	3.4×10^2	9.0	.50– .82
		5	43	6.1	5.7×10^2	11	.35– .60	7.0×10^2	13	.36– .64	5.0×10^3	110	1.3 – 2.5
		10	61	8.6	1.2×10^3	24	.45– .81	1.4×10^3	32	.48– .85	1.0×10^4	246	1.7 – 3.5
		50	136	19	4.6×10^3	[800]	.90–1.8	7.2×10^3	[1000]	.97–2.2	5.0×10^4	1224	3.8 – 8.5
		100	193	27	9.4×10^3	$>10^3$	1.2 –2.6	1.5×10^4	$>10^3$	1.3 –2.9	1.0×10^5	2464	5.6 –14
Mississippi River (Jordan, 1965)	0.000075	4.7	5.8	0.61				4.4	.52	.07– .11			
	0.00014	17	15	2.3				28	1.3	.12– .18			
Missoula Floods (Baker, 1973)	0.003	70	106	15				1.3×10^3	[45]	.41– .73			
Turbidity Currents (Komar, 1979)	0.003	100	70	10				6.5×10^2	8.5	.30– .51			

[a] D_t threshold grain diameter, D_s cutoff between bed load and suspension, D_w grain diameter at onset of wash load. All grain diameters are in millimeters.

[b] [ ] signifies a large uncertainty in the value given.

Viking Landers provide us with our most direct indication of the type of material the flows might have had to erode away to form the outflow channels. This evidence indicates a great abundance of fine-grained material estimated to be less than 0.1 mm in diameter (Mutch *et al.*, 1976; Moore *et al.*, 1977). Also abundant are pebble- and cobble-sized clasts. But no sand-sized grains have been identified at the Lander sites. Sagan *et al.* (1977) have suggested that sand-sized particles would quickly break down to silt and clay-sized grains due to collisions at the high wind speeds characteristic of Mars. This is confirmed by the laboratory experiments of Krinsley *et al.* (1979) using basalt and quartz grains. If this is the cause of the absence of sand in the surface at the Lander sites, it does not preclude the possibility of the presence of sand at depth beneath the immediate surface, so the flows may have had to erode and transport an extremely wide spectrum of grain sizes.

If the Viking Lander sites are at all representative of the areas into which the outflow channels were eroded, then the flows would have had an extreme abundance of fine-grained sediment that would have been transported as wash load. As indicated by the terrestrial rivers, this wash load material could have been transported at very high concentrations, permitting the rapid erosion of the channels. The question becomes, how much of this sediment could the flow have transported before the turbulence becomes damped and it becomes a pseudolaminar mudflow rather than remaining as a turbulent flow.

Extremely high concentrations of wash load are a common occurrence in the rivers of the semiarid southwestern United States. Beverage and Culbertson (1964) used the term "hyperconcentrations" for streamflow samples that exceed 40% sediment by weight (that is, the weight of dry sediment to the weight of the water–sediment mixture exceeds 0.40). They tabulated the hyperconcentration measurements obtained by the USGS river-sampling program, finding measured values as high as 65% sediment by weight. That weight concentration corresponds to a volume concentration of 41% (volume of sediment to the total volume); thus it is seen that in hyperconcentration flows an appreciable portion of the stream discharge constitutes sediment rather than water. This could also have been the case for the water flows on Mars.

Measured discharges in the data compilation of Beverage and Culbertson range from 1.1 to 6270 cfs (8.6–49,300 cm^3/sec); as shown in other studies of wash load, there is no definite relationship between the river discharge and hyperconcentration levels, the sediment concentration instead depending only upon its availability. All of the data of Beverage and Culbertson are seen to have come from relatively small rivers. Large terrestrial rivers seldom reach hyperconcentration levels because their sizeable drainage basins do not supply adequate fine-grained material. However, Todd and Eliassen (1938) mention that the Yellow River in China once carried a concentration of 40% at a discharge of 812,000 cfs (6.4×10^6 cm^3), indicating that high concentrations can occur even in large rivers if a source is available [in the case of the Yellow River, extensive loess deposits provide the source].

Mud-flow concentrations have been placed at 79 to 85% by weight (Sharp and Nobles, 1953), so it is seen that some of the hyperconcentration measurements in rivers are approaching a mud-flow level. Mud flows generally lack turbulence, being pseudolaminar in character. The available evidence indicates that rivers with hyperconcentration sediment levels are still turbulent, although the considerable sediment concentrations most certainly must be affecting the turbulence spectra (Pierce, 1917; Lane, 1940; Bondurant, 1951). Nordin (1963) discusses the flow of streams with extreme hyperconcentration sediment loads, basing his observations on the Rio

Puerco in New Mexico. He makes the important point that at the concentrations of fine material involved, the settling velocities of still coarser grains would be so reduced that this coarser material would also become a part of the wash load. This indicates that the above calculations (Figs. 2, 3, and 4 and Table I) are very conservative, and that due to the reduced settling velocities resulting from the abundance of fine-grained material, still coarser sediments could have been transported as wash load and in suspension.

From this comparison with terrestrial rivers, it would appear that water flows on Mars could have reached hyperconcentration levels of wash-load sediments. Considering the abundance of fine-grained sediments available, it is conceivable that the flows could have progressively coverted into dilute mud flows, especially if water were also lost by evaporation or percolation. Nummedal (1978) has suggested that the channels may have been eroded by mud flows. His suggestion differs from the present proposal in that he invisions that the flows were mud flows right from the onset, while I am suggesting that an initially turbulent flow of water could have eroded a sufficient quantity of wash-load sediments to be converted into a pseudolaminar mud flow. However, most of the available evidence indicates that viscous mud flows were not the principal agent of channel erosion. Baker (1978) discusses the morphological evidence indicating that channel erosion was by a turbulent agent rather than by a laminar flow such as lava, ice, or a mud flow. In addition, mud flows are not noted for their ability to cause channel erosion unless travelling over a very incompetent bottom (such as the submerged portion of a delta). Mud flows also "freeze" to form a deposit looking much like a lava flow, rather than spreading over the wide flat areas terminating most outflow channels. Thus the evidence indicates that the turbulent flows with hyperconcentration levels of wash load did not convert into laminar mud flows.

The results of this analysis considerably modify the estimates presented in Komar (1979) of sediment transport rates in the Martian flows and times required for channel erosion. Those calculations did not take into account that a large portion of the eroded sediment would have been transported as wash load at very high concentrations. Making a rather conservative assumption of concentration levels at 40% by weight (volume concentration = 0.20), order-of-magnitude estimates indicate that a flow of average depth $h = 50$ m would have taken only 8 days to remove the wash-load material from the Mangala Channel site, assuming it formed half of the total volume of material to be eroded. A flow of 10-m depth would have taken some 120 days. It is difficult to judge the reasonableness of these calculations and results. The rate at which the flow could have carved Mangala Channel may have been governed more by the transport of the suspended and bed loads. As discussed above, the flows are competent to transport extremely large material so it is doubtful whether a nonmoving lag would have developed to inhibit further erosion. However, the formation of a protective bed-load cover might have slowed the erosion process and the stripping away of the fine wash load. It would probably require full numerical models of the water flow, channel erosion, and sediment transport to refine this evaluation of time required for channel formation. Noting in Table I that if the Martian flows were catastrophic and thus similar to the Lake Missoula floods, the flows would have been more competent and could have transported coarser material in suspension and as wash load than did the Lake Missoula floods. Thus, like the Lake Missoula floods, the water flows on Mars probably were able to rapidly strip away the loose sediment cover, the erosion only being slowed when bedrock was reached. As discussed above and by Baker (1978), at that stage the erosion processes are very complicated and depend upon the structure of the bedrock.

Two objections that have been raised to

the water-erosion origin of the Martian channels can in part be answered by a high proportion of wash load in the flows. One objection deals with the relatively small sizes of the source areas as compared to the volumes of channel erosion achieved (Blasius *et al.*, 1978). If the above analysis is correct, the wash load becomes an inherent part of the flow rather than being passively carried along by the water. If Bagnold's (1962) concept of autosuspension is correct, then this wash load would have contributed to the flow power, enhancing its ability to carve the channels. In a sense then, the material from the channel itself was a part of the flow source area. In that the wash load could have formed more than half of the flow by weight, in principle only half as much water was required.

The second objection that has been made to the water-erosion origin of the Martian channels involves the lack of readily apparent depositional areas at the ends of the channels. This absence has been discussed by Sharp and Malin (1975) and Blasius *et al.* (1978). But again, if a large portion of the sediment load was wash load, and particularly if it was autosuspended, the sediment would not immediately have deposited upon entering a basin of much lower slope than the channel. Instead, the flows would have spread out over the basin and the sediment would have only gradually been deposited. An analogous situation occurs in the channelized flow of turbidity currents in the deep sea (Komar, 1979); even when the turbidity currents leave the confines of the main channel they spread out widely, depositing sands over an extensive area rather than as a "delta."

It is seen in Table I that this analysis also indicates that the Lake Missoula floods were able to transport pebbles in suspension, and most of the sand as well as the finer-grained material would have been in the wash load. Many of the above comments concerning the erosion of the Martian channels apply equally to the Lake Missoula floods and the erosion of the Channeled Scablands. In that region thick deposits of loess (the Palouse Formation) overly basalt (Baker, 1973). Once eroded, the loess would have been part of the wash load and could have been transported away at high concentrations and at rapid rates, leaving more time for the waters to erode the underlying basalt. The sands also having been part of the wash load may explain their nearly total absence in land deposits laid down by the floods (Baker, personal communication, 1979), not having been deposited until the flows reached the Pacific Ocean.

SUMMARY OF CONCLUSIONS

Application to Martian water flows of the criteria that quantitatively determine which grain-sized ranges are transported as bed load, suspension, and wash load indicates that nearly all sand-sized material and finer would have been transported as wash load and that basalt pebbles and even cobbles could have been transported at rapid rates in suspension. An analysis of the threshold of sediment motion on Mars further indicates that the flows would have been highly competent, the larger flows having been able to transport boulder-sized material.

Comparisons with terrestrial rivers which transport hyperconcentration levels of sediments suggest that the Martian water flows could have achieved sediment concentrations as high as 60–70% by weight. Although it is possible the flows could have picked up enough sediment to convert to pseudolaminar mud flows, they probably remained at hyperconcentration levels and fully turbulent in flow character.

High concentrations of wash load would have permitted the rapid erosion of the channels. Although calculations are highly uncertain, order-of-magnitude estimates indicate that the channels could have eroded in a matter of a few days, much shorter time periods than estimated in Komar (1979) based upon bed-load and suspension transport alone.

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