

Sailing Stones on Racetrack Playa¹

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ABSTRACT

Racetrack Playa in Death Valley, California is home to a group of stones which have, on occasion, slid hundreds of meters across the dry lake bed. New data on wind shear from a similar playa, Owens Dry Lake, about 80 km SSE of Racetrack Playa, and data on the velocities of wind gusts across these playas are consistent with threshold coefficients of static friction that allow for the motion of 30 of the 31 rocks for which data are available.

Introduction

The sliding stones on Racetrack Playa in Death Valley, California have attracted much scientific speculation because, under extremely rare conditions, rocks ranging from a few hundred grams to hundreds of kilograms are known to have slid upward of hundreds of meters across the dry lake bed, or playa. Adding to the mystery, there has never been a first-hand observation of the rocks in motion. These conditions have led to much speculation as to the nature of the force that drives the rocks.

Currently, the most widely accepted explanation for the motion of the rocks suggests a fine layer of clay deposited after the playa has been flooded creates a slick surface, which allows the rocks to slide under the force of the wind (Sharp and Carey 1976). However, when one performs an experiment to determine the force of the wind needed to push the stones across the wet playa (Schumm, 1956; Sharp 1960), the results suggest that the playa surface is too rough or that the wind velocity is too small to allow the rocks to begin their slide. Once the rocks are moving, however, they easily overcome the coefficient of kinetic friction, which is about half that for static friction (i.e., based on the equations given below a 320 kilogram rock that would need a 600 Newton force to be set in motion requires only a 300 Newton force to keep it moving).

Recent investigations of wind shear on Owens Dry Lake playa, approximately 80 km SSE of Racetrack Playa, have discovered an interesting and previously overlooked fact about the velocity profile of the wind on these playas (Cahill et al. 1994; Barone et al. 1981). Due to the smooth, flat surfaces of playas, the wind velocity near the surface has a very thin boundary layer and is appreciable down to millimeters above the ground. Second, recent data from the USGS Desertland Project have documented that extreme wind gusts of up to 40 m per sec (144 km per hr) regularly occur on the playas, due in part to the extraordinary vertical relief of the Basin-Range topography (Cahill et al. 1994). Using these data, reasonable values of the threshold coefficients of static friction can be found that allow the motion of 30 out of the 31 rocks for which data are available.

Results

The velocity distribution of the wind above the surface is shown schematically in figure 1. Within the boundary layer, the velocity varies as a function of the height above the ground. On a non-moving surface, the velocity decreases to zero at the surface (non-slip boundary condition). The Z_0 roughness displacement height at Owens Dry Lake was measured to be 0.1 mm, while the maximum wind gust reached 41 m per sec (Cahill et al. 1994). The playa is unique among terrains in that the flatness, smoothness, and the coupling of the air to the ground cause a small boundary layer. These

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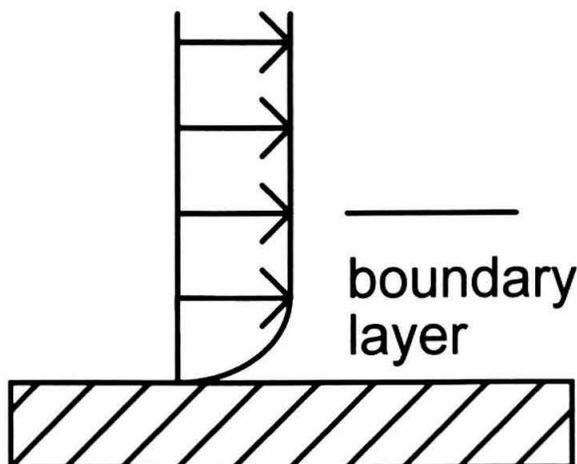


Figure 1. The velocity profile of the wind above the ground. The velocity of the wind drops from some upper air velocity down to zero at the ground over a region called the boundary layer. On Racetrack Playa and similar playas such as Owens Dry Lake playa, the velocity profile is abnormal in that the boundary layer is only a few centimeters high.

same conditions produce some of the highest fine dust levels recorded in the United States (Barone et al. 1981). According to the wind profile measurements on the dry playa surface, the velocity 4 cm from the ground is still 90% of the velocity measured 1 m above the surface. This allows us to assume that the wind velocity is at least 80% of the upper air speed over all but the smallest rocks. Previously, experiments in a wind tunnel (Schumm 1956) were done using very small pebbles on the order of 1–2 cm height, and extrapolations were made from these results. Clearly, these pebbles would have a much harder time moving because most of the pebble would lie in the slower moving portion of the wind; hence, the results of the wind tunnel experiments (Schumm 1956) cannot be used to conclude that large rocks will not slide (see figure 2).

According to Sharp and Carey (1976), the stones on Racetrack Playa probably move 12 hrs to a few days after a rainstorm. They base this assumption on the fact that most of the tracks seem to be made in a layer of fine clay that according to their experiments settled 12 hrs after the rain (see figure 3). It is not unreasonable to infer that there existed a fine layer of water on top of the clay when the rocks moved (as discussed in Sharp and Carey 1976); the existence of fine sheets of roaming water is well documented (Torgersen 1984). Such a layer would most surely move under the influence of a strong shearing wind; thus, the velocity of the

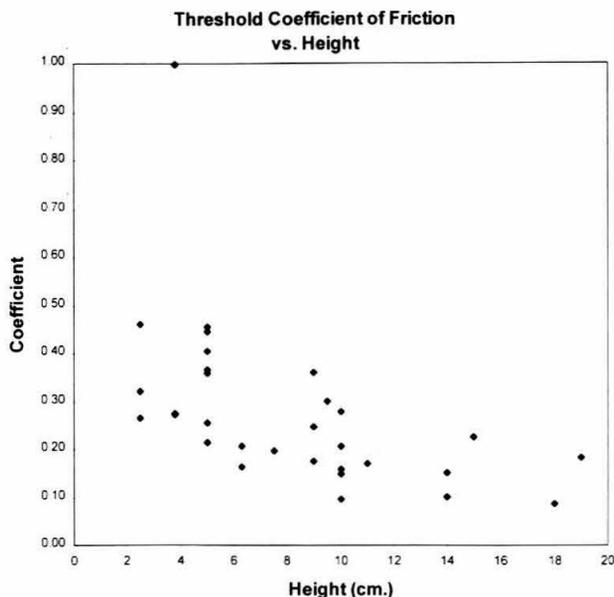


Figure 2. The threshold coefficient of static friction needed to move the rock versus the height of the rock. The taller rocks have a lower calculated threshold coefficient because they protrude higher into the wind profile. Likewise the smaller rocks are calculated to have a higher threshold coefficient. For a constant threshold coefficient of friction, this graph indicates that the wind velocity must be increasing as a function of height below approximately 5 cm and can be constant above, thus indicating that the wind's boundary layer is very small.

wind at the surface would not be zero and an even steeper velocity profile would be possible. So, although the movement of this layer of water definitely would not be able to push the rock, it would create a more favorable wind profile. (A mechanism for rock motion in which the rocks are imbedded in wind-driven ice sheets has been shown in Sharp and Carey [1976] to be incapable of explaining the movement of the rocks listed here, although it certainly has been observed in other circumstances).

Consider the drag produced by this wind velocity distribution across a rock. For the idealized case of a solid rectangular rock of height h , width w , and mass m , with a wind velocity V , the force on such a rock, $F_{|d|}$, is given by (Daugherty and Franzini 1977):

$$F_{|d|} = \frac{1}{2} C_p V^2 A,$$

where C is the drag coefficient, A is the area of a cross section of the rock, and p is the density of air ($\approx 1.29 \text{ kg/m}^3$). The drag coefficient C is dependent

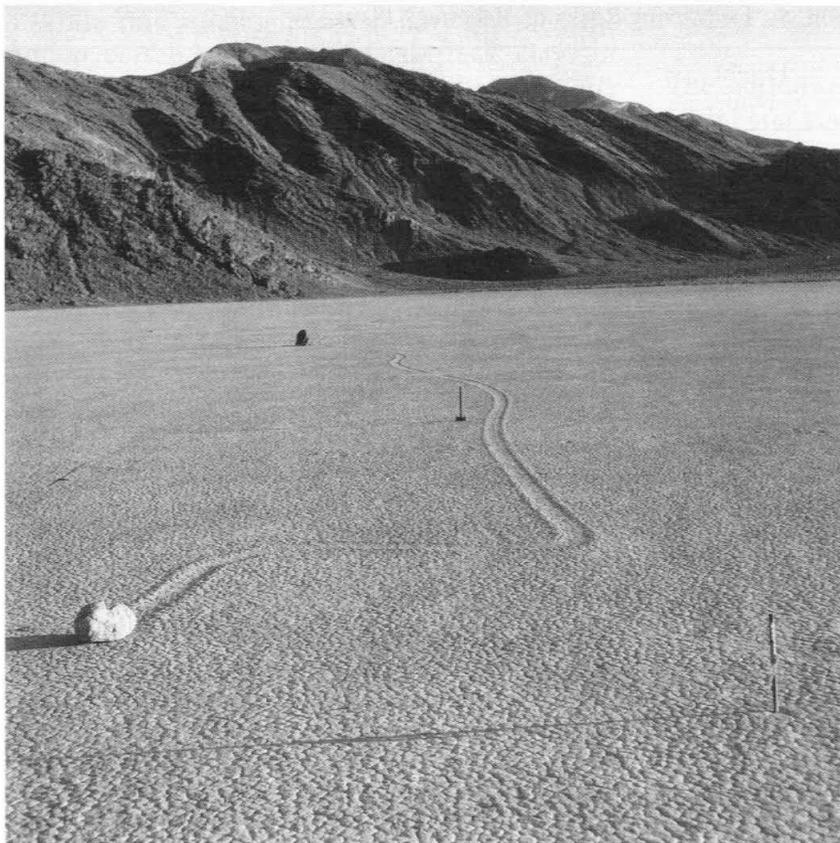


Figure 3. A 250 m track made on or about December 2, 1970, by stone R ("Hortense") photographed on January 23, 1971 (originally figure 4 in Sharp and Carey [1976]; used with permission of R. P. Sharp). The Cambrian dolomite ridge at the south shore of Racetrack Playa is in the background.

on the shape of the rock. In the case of a rectangular rock, it will be slightly >1 ; generally, it may vary between 0.5 (sphere falling through air) and 1.2. The frictional force has the form (Daugherty and Franzini 1977):

$$F_{|f|} = smg,$$

where s is the coefficient of static friction and g is acceleration due to gravity. That this force must be less than the drag force defines the threshold value of the coefficient of static friction for the rock being set into motion:

$$S_T = \frac{1}{2} \frac{C_p V^2 A}{mg}.$$

Using data obtained by Sharp and Carey (1976), we calculate the threshold values of S_T needed to move the rocks that are known to have slid on the playa. These data (i.e., the right hand side of the equation above) are assembled in column 7 of table 1. These calculations were done with $C = 0.8$, $V = 40$ m per sec, and the mean velocity assumed at 80% of

the upper air velocity. The cross sectional area is taken to be the mean cross sectional area, i.e.,

$$A = h\sqrt{lw}.$$

Almost all of the rocks (all but J, L, N, and S) have a threshold coefficient >0.15 . This is a very reasonable estimate for the static friction. To put this in context, ice on ice has a coefficient of 0.1, wood on snow has a coefficient of 0.19, and wood on wood has a coefficient of 0.25 to 0.50. Experiments in which the rocks were pulled across similar mud give a coefficient of friction around 0.145 for mud that has been thoroughly soaked under the rock and 0.26 for mud that is dry beneath the rock (Sharp 1960). The lower value, which assumes the layer underneath the rock is already wet, is likely to be more appropriate because of the time delay after a rainstorm suggested by Sharp and Carey (1976).

The exceptions (J, L, N, and S) are taller and thus are exposed to greater than the 80% wind speed experienced above 4 cm from the surface; thus, the last column in table 1, with the mean velocity as-

Table 1. Threshold Coefficient of Friction, S_T , for Moving Rocks on Racetrack Playa

Stone Ident.	Length (cm)	Width (cm)	Height (cm)	Mass (kg)	Area/Mass (m ² /kg)	S_T 80% ^a	S_T 100% ^a
A	20	16.5	10	6.6	.0028	.15	.23
B(a)	13	10	3.8	0.85	.0051	.28	.43
B(b)	18	16.5	11	6	.0032	.17	.27
C(1)	15	6.3	5	0.65	.0075	.40	.63
C(3)	7.5	5	2.5	0.18	.0085	.46	.72
C(4)	15	7.5	5	0.8	.0066	.36	.56
D(1)	25	18	9	5.9	.0032	.17	.27
D(2)	33	15	5	2.8	.0040	.21	.34
E(a)	18	10	10	4.55	.0029	.16	.25
E(b)	23	15	10	3.6	.0052	.28	.44
F(a)	23	18	9	4	.0046	.25	.39
F(b)	23	13	10	4.5	.0038	.21	.32
G(1)	23	14	7.5	3.7	.0036	.20	.31
G(2)	14	10	5	1.25	.0047	.26	.40
G(3)	12	7.5	5	0.7	.0068	.37	.57
G(4)	7.5	2.5	2.5	0.22	.0049	.27	.42
G(5)	12	9	9	1.4	.0067	.36	.56
G(6)	6.3	5	5	0.34	.0083	.45	.70
I	14	9	6.3	1.85	.0038	.21	.32
J	74	48	51	320	.0009	.05	.08
K(a)	10	6.3	3.8	0.6	.0050	.27	.42
K(b)	10	10	9.5	1.7	.0056	.30	.47
L	28	23	10	14.2	.0018	.10	.15
M	28	23	14	12.7	.0028	.15	.24
N	28	20	14	17.8	.0019	.10	.16
O(a)	7.5	6.3	2.5	0.29	.0059	.32	.50
O(b)	7.5	3.8	3.8	0.11	.0184	1.00	1.56
R	28	20	19	13.2	.0034	.18	.29
S	36	13	18	24.3	.0016	.09	.14
T	18	15	15	5.9	.0042	.23	.35
X	7.5	7	5	0.43	.0084	.46	.71
XX	18	10	6.3	2.8	.0030	.16	.26

^a Percentage of the upper air velocity actually used in the calculation.

Note. Upper air velocity of the wind, V , is 40 m/s. The drag coefficient, C , is 0.8. Data from Sharp and Carey (1976).

sumed to be 100% of the upper air velocity, would be more appropriate for the larger rocks. Excluding rock J, the mass of which was only estimated, the value that the threshold coefficient of friction assumes is ~ 0.15 .

If one singles out the incidents cited in Sharp and Carey (1976), in which subsets of the rocks were driven on approximately parallel trajectories, one finds that the range of threshold static friction coefficients is somewhat tighter—but not different from the trends of table 1. This subgroup has a wide range of masses, heights, and shapes, i.e., there is no single common feature that stands out. This is even true when we consider only those rocks that moved most often, e.g., A, F, K_b, N, O_b.

Conclusion

Why aren't sliding stones common to all playas? The reason for this lies in the geological conditions

in and around the playa. First, the playa must be extremely smooth and flat, which allows the boundary layer to be very small. Another factor is the surrounding mountains: the 2 km vertical relief near Death Valley is responsible for the high winds that are observed on the playa after a storm. Also, the playa surface must be of an ideal composition. Too much salt in the playa sediment will increase the surface roughness, causing the coefficients of friction to be raised significantly, hence impeding motion of the rocks. Finally, on Racetrack Playa an adjacent steep bedrock face not only provides the needed abundant source of rocks, but also provides a convenient method, i.e., in the form of rocks being shed off of the bedrock face, by which the rocks can be deposited on the playa without creating a sediment that has too many coarse particles. This is a unique aspect of Racetrack Playa; there is scarcely a rock 3 cm diameter on the Owens Lake Playa.

While this study appears to have clarified the motion of the rocks on the Racetrack Playa, it must be noted that the same wind shear over dry surfaces has generated extraordinary dust storms of potentially global scale. Thus, the importance of this phenomenon is not restricted to the mystery of the moving rocks, but is also major factor in other areas of science such as atmospheric studies. Although the rock motion itself is merely a curiosity, we feel that continued study of this phenomenon is relevant to a wide range of environmental contexts and deserves greater attention.

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