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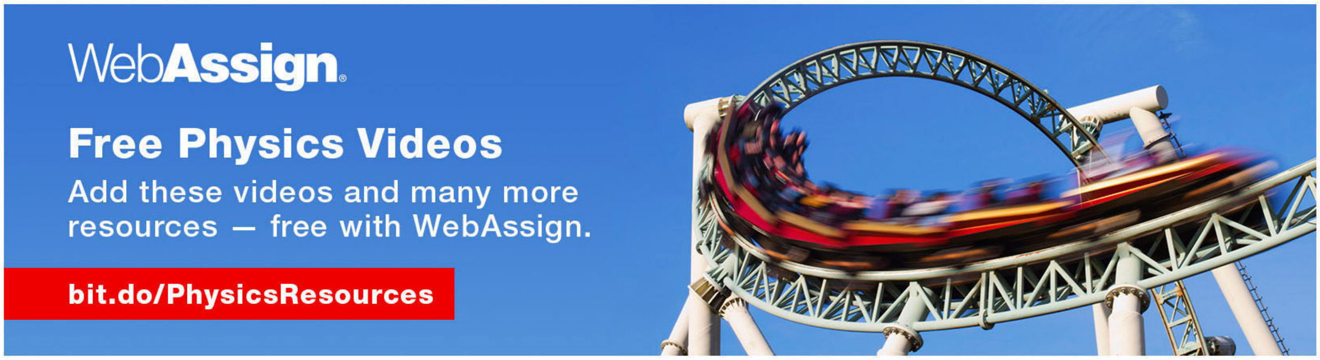

Ice rafts not sails: Floating the rocks at Racetrack Playa

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We suggest that the existence of many of the rock-carved trails at Racetrack Playa in Death Valley National Park is predominantly due to the effect of arbitrarily weak winds on rocks that are floated off the soft bed by small rafts of ice, as also occurs in arctic tidal beaches to form boulder barricades. These ice cakes need not have a particularly large surface area if the ice is adequately thick—the ice cakes allow the rocks to move by buoyantly reducing the reaction and friction forces at the bed, not by increasing the wind drag. The parameter space of ice thickness and extent versus rock size for flotation is calculated and found to be reasonable. We demonstrate the effect with a simple experiment. *© 2011 American Association of Physics Teachers.*

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I. INTRODUCTION

Among the many geological attractions[1] in Death Valley National Park in California is Racetrack Playa. The playa is a 4.5 km × 2 km lake bed at an elevation of 1130 m, which is only occasionally flooded. It is exceptionally flat (the south end is only a few centimeter lower in elevation than the north) and composed of mixed sand-silt-clay, usually with striking but small desiccation polygons. It is distinguished by the unusual presence of some dozens of rocks (usually cobbles or small boulders), which are very distinct against the very uniform playa (see Fig. 1), and often appear at the end of trails or furrows in the playa surface. These trails suggest that the rocks have moved across the surface when the playa was wet.

Much attention[2–5] has been given to documenting the rocks and their movements and to speculating on the mechanism by which they are induced to move.[6] Actual motion of the rocks has not been observed.

The idea that ice is involved was first reported by Stanley[7] in 1955. As also discussed by Reid *et al.*,[4] the motivation for this idea is that unreasonably strong winds would be required to move rocks by drag alone, and the observation that many trails—even curved ones—are congruent or at least parallel (see Fig. 2), suggesting that the rocks may have been mechanically connected when they moved. The involvement of ice has prompted much discussion (see, for example, Ref. 8), but beyond the requirement that the playa be wet, and that wind is not zero, the conditions for movement are not clear. The extent to which exceptional winds are needed and the amount of ice that may facilitate motion likely varies on a case-to-case basis. There are documented cases of rock movement where ice was not observed, for example, the report by Clements at nearby Bonnie Claire Playa.[9]

However, a key factor of the potential involvement of ice has been neglected, or at least not been made explicit in literature. All the discussions involve a sheet of ice acting as a means of increasing the area on which wind can act (for example, Ref. 4 refers to ice sheets 20 m × 20 m and 500 m × 850 m) without reference to ice thickness or buoyancy. We will argue that the principal effect of ice is to buoyantly reduce the normal force on the base of the rock, and therefore to reduce the drag force required to overcome friction.

In this paper, we calculate the influence of ice rafts (plates or cakes of ice around a rock lifting it up from the mud) of various geometries in reducing the wind speed needed to cause motion. We report on field measurements of the (high) coefficient of friction of rocks on well-soaked playa mud and note some observations that support the rafting idea such as sitzmarks (depressions in the mud showing how deep a rock was embedded before it moved), which suggest that rocks had to be plucked out of the playa mud before sliding. We also note examples of rock flotation in other geological settings.

II. MECHANICS OF RAFTED ROCK MOVEMENT

The playa is an exceptionally flat surface, with the northern end only 5–10 cm higher in elevation than the southeast.[5] On such a horizontal surface, the fundamental requirement for motion is that the wind drag force D acting on a rock of size h (we assume, for simplicity, that the rock is a cube with volume h^3) must exceed the friction force holding it in place. The latter is given by the product of a friction coefficient μ and the normal force N (see Fig. 3). This condition is expressed as

$$D = 0.5\rho_a V^2 (S_s C_{ds} + S_t C_{dt}) \geq \mu N. \tag{1}$$

The drag force has two components, the bluff body drag due to the wind acting on the side of the rock and the skin friction drag acting on the top of the rock and on any attached

Fig. 1. A rock on the regularly cracked floor of Racetrack Playa. The trail behind. The rock is about 15 cm across. Some faint streaking is visible on the playa surface to the upper right of the rock. It is believed that this streaking is due to smoothing by drifting ice sheets.

ice sheet. Both are proportional to the dynamic pressure $0.5\rho_a V^2$, where ρ_a is the density of air $\approx 1.2\ \text{kg/m}^3$ at this elevation and V is the relevant wind speed. Their contributions are determined by the side drag area $S_s \sim h^2$ (the use of S to denote area is the convention in aeronautics) and drag coefficient $C_{d,s} \sim 0.5-1.2$. This range of values for $C_{d,s}$ is known from the aerodynamics of nonstreamlined bodies in flow at the relevant Reynolds and Mach numbers (see, for example, Ref. 10). These values were used in the previous studies.[4] For a single rock, the top drag area S_t is zero because the drag on the top and sides is included in the definition of the drag coefficient and, in any case, because the drag coefficient for flat plates in transverse flow is so small, $C_{d,t} \sim 0.002$ (also assumed in Ref. 4), the contribution from these surfaces is 200–600 times smaller than the bluff body drag. Hence, the two paradigms of motion are the extremes, $S_t = 0$ for no-ice, and $S_t C_{d,t} > S_s D_{d,s}$ and $S_t \gg S_s$, denoting a large ice sheet or "sail." In the no-ice case, we appeal to a high enough V to overcome whatever friction μN is present, whereas in the presence of ice, we seek a sufficiently large S_t instead.

In some instances, the force on the side of a rock might be augmented by the change in momentum due to a wind-blown spray and/or by drag due to water currents that were generated by the wind.[11] However, these contributions are usually small.

Fig. 2. A picture from a small digital camera lofted on a kite at the south end of the playa, near the dolomite cliff (upper left), which is the source for many of the rocks. Note that many trails are parallel to each other. The kite string is faintly visible at the upper right, pointing toward the first author.

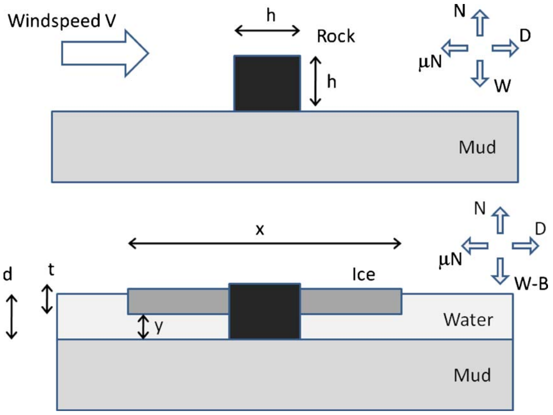

Fig. 3. Schematic of the forces and dimensions of a solitary rock and a rock frozen into an ice raft.

In the previous works,[2,3] the normal force N was assumed to be the weight of the rock W_r. However, the ice sheet floats and if it grips the rock (see Fig. 3), the normal force can be as low as zero, and is given by the sum of the weight of the rock and the ice, minus the buoyancy B due to the immersed volume with a density of water ρ_w,

$$N = W - B, \tag{2}$$

where W is the sum of the weight of the rock plus ice.

The weight of the rock (assumed to be a cube of linear dimension h) is $W_r = g\rho_r h^3$, where $\rho_r \approx 2700\ \text{kg/m}^3$ is the density of the rock, and the ice cake (assumed square) has a thickness t and a horizontal dimension x. Thus, $W_i = g\rho_i t x^2$ with the ice density $\rho_I = 900\ \text{kg/m}^3$. The displaced volume V depends on the water depth d and density $\rho_w = 1000\ \text{kg/m}^3$. In the idealized case of water that is just deep enough $(d = t)$, $B \sim [(\rho_w - \rho_i)/\rho_w] W_i \approx 0.1 W_i$. [Although the ice volume is $t(x^2 - h^2)$, the immersed volume of the rock th^2 also contributes to the buoyancy.] Small corrections to these expressions can be made for cylindrical or spherical rocks and cylindrical ice sheets.

Because a rock has a density of $2700\ \text{kg/m}^3$, it can be floated by ~ 20 times its volume of ice (it displaces its own volume of water at $1000\ \text{kg/m}^3$, and the rest of the buoyancy must be supplied by ice, which differs in density from water by about $100\ \text{kg/m}^3$). If the ice raft is nearly as thick as the rock $(t \sim h)$, then the raft need only be about 4.5 rock diameters across. In connection with this, we should reconsider the experiment of Sharp,[3] which is often used to argue against an ice sheet mechanism. He placed a corral or a ring of stakes into the playa (which is now not permitted by park regulations) and one of the two rocks moved out of the corral, whereas the other did not.[2] This observation demonstrates (assuming that intervention by humans or animals did not anomalously displace the rock that moved) only that a large ice sheet linking the two rocks was not involved. However, this inference relies on the "sail" paradigm in that an ice sheet large enough to meaningfully assist the motion of one rock would surely also be anchored by the stakes and/or cause the other rock to move. But this is not the case if buoyant rafting occurred. Specifically, of two stones about 10 cm across, one moved between the stakes, which were 64–82 cm apart. As we discussed, an ice raft 50 cm across could float the rock and yet slip between the stakes. We

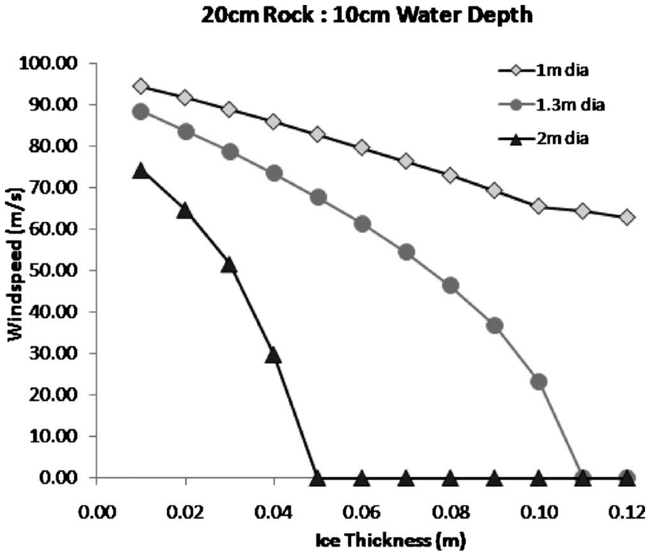

Fig. 4. Wind speed required to move a rock 20 cm wide and 20 cm high, immersed in water 10 cm deep as a function of ice raft diameter and ice thickness. For the 1 m raft, the thickest ice blocks some of the side of the rock. More generally, the buoyancy of the raft facilitates motion by reducing friction.

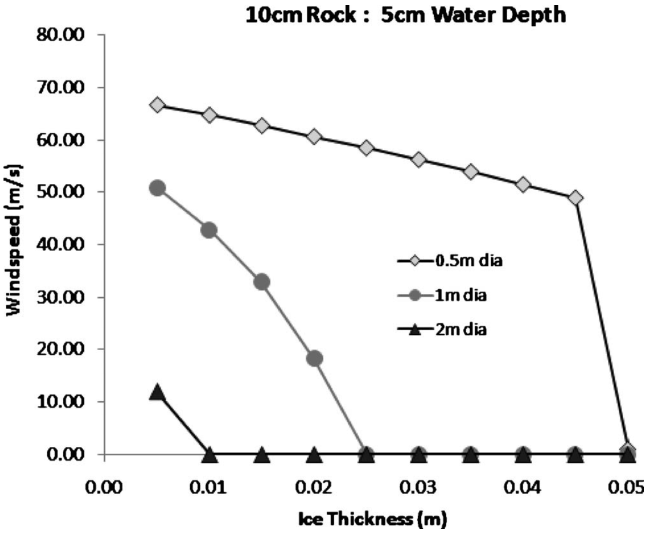

Fig. 5. The same as in Fig. 4, but for a smaller rock.

cannot evaluate here how probable such a raft might be, and note that it must be several centimeter thick, but we can show that rafting (floating) of this rock is possible.

For simplicity, we assume the coefficient of friction $\mu=0.5$. This value is at the low end of the values measured by Reid *et al.*[4] and consistent with measurements at another playa (see Sec. III). It has been claimed (see, for example, Ref. 8) that the coefficient might be lower due to a very fine size fraction of clay particles that did not have time to sediment in the measurements of Ref. 8, or due to the influence of gelatinous biofilm produced by cyanobacteria. However, no existing measurements support the contention that the value of μ is much less than 0.5 in any circumstances.

The wind speed that applies in Eq. (1) may not be the free stream wind speed measured at the conventional anemometer height of 10 m, or even the more practical field height of 2 m. Bacon *et al.*[12] suggested that the wind speed is only fractionally reduced because the playa surface is so smooth that the aerodynamic roughness length (the distance scale over which the wind speed near the surface declines by a factor of e) is very small. In documenting the motion of an instrumented beach ball ("tumbleweed rover"), we measured an aerodynamic roughness length of 5 mm at Willcox Playa in Arizona.[13] Because the value of this length changes our results only by 20%, we simply express the wind speed needed to move a rock in Figs. 4 and 5 as the wind speed at rock height, recognizing that the free stream wind speed is likely somewhat higher. Whether the free stream speed is 20% higher than at rock height (as with low aerodynamic roughness values[12]) or 200% higher as for more typical values[4] may be important when strong and therefore rare winds are considered. But because we claim that arbitrarily weak winds can move rafted rocks, the question of the near-surface wind gradient is irrelevant.

Immersion in water reduces the rock's effective bluff body area by a factor of $(h-t)/h$. In most cases, the reduction in the normal force will more than compensate, and Fig. 4 shows the results of an example calculation. (An additional parameter, y, is included in Fig. 3 for completeness. In principle, ice could float with its top surface above the water surface and contribute a bluff body drag area of its own, which may exceed the loss of the rock's drag area.) It is seen in Figs. 4 and 5 that modest sized rafts of a few centimeters in thickness and a few tens of centimeters in horizontal extent can reduce the wind speed needed to move a rock to arbitrarily small values. Over a single night at a few degrees below freezing, ice several centimeter thick should be able to form. This mechanism may offer more opportunities for rock motion than playa flooding and excessive wind speeds.

III. SOME EXPERIMENTAL SUPPORT FOR THE RAFTING MECHANISM

We measured the coefficient of friction of a small basalt rock (400 g) at nearby Bonnie Claire Playa where rock movements have been recorded in the past. This playa is outside Death Valley, and thus park regulations that prohibit rock-moving experiments at Racetrack do not apply. The experiment was conducted in a pond[14] several days after the last recorded rainfall, allowing processes to occur that might reduce the friction below previously measured values, namely, settling of the finest silt fraction and/or the development of gelatinous biofilms by cyanobacteria.[8] We found (see Fig. 6) that although the mud was very soft and slippery (wheel spin sprayed the mud on the side of a vehicle), the horizontal force F measured by a spring balance to drag the rock was still >2 N, and the irregular texture of the bottom could still be "felt" through the soft mud. Because $F>\mu W$ for motion to occur, this measurement indicates a coefficient of friction $\mu\sim0.5$, a result consistent with similar observations of $\mu\sim0.6-1$ on a 12 kg dolomite boulder in Ref. 4. It seems that even though the mud surface feels slippery underfoot, the microtexture of a rock abrades on the solid bottom through a lubricating layer of mud.

We have observed that the dolomite rocks (which form the bulk of the Racetrack Playa rocks) are typically rough or fractured more than the basalt cobble we measured, and thus dolomite rocks likely have an even higher coefficient of friction.

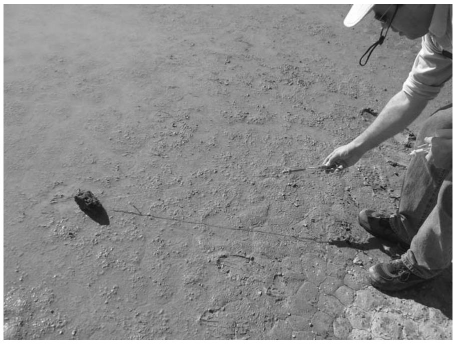

Fig. 6. Measuring the drag on a rock at Bonnie Claire Playa. Even though the mud felt extremely slippery underfoot, the weight of the rock causes it to sink through this lubricant and grip the rigid mud beneath, resulting in a measured coefficient of friction of 0.5 or more.

We can demonstrate the ice-rafted trail formation mechanism in a tabletop experiment. We froze a 64 g basalt pebble in a layer of water in a plastic food container, allowing one corner of the pebble to project above the flat ice surface. This approach was simply to form a suitable volume of ice with the rock embedded in it rather than to explicitly simulate the raft formation. The ice raft (≈3 cm thick, 20 cm across) was floated in a baking tray filled with water with a layer of coarse sand at its base and the rock projected downward into the sand layer. We found that a very gentle push (estimated to be a few mN) or blowing across the surface was enough to make the raft move, and a clear rock trail was formed in the soft sand (see Fig. 7). It would be instructive to compare different ice geometries and wind speeds experimentally. (It is useful to wash the fine material out of the sand to improve the visibility of the base. However, the use of fine material, such as clay or limestone powder instead of sand, might reduce the force needed to push the raft.) The depth of the impression and the frictional drag can be adjusted somewhat by changing the level of water in the tray.

IV. DO ROCKS ACTUALLY FLOAT AND DOES THE PLAYA ACTUALLY FREEZE?

We have posed a simple physical model to demonstrate that floated rock movement is possible, but does it occur in nature? So far, there are no observations of rocks moving at Racetrack, although recent efforts to study the playa with time lapse cameras[14] are making progress in documenting the conditions on the playa to evaluate how often it floods and/or freezes. It is well known that rocks and gravel can be found in ocean sediments thousands of kilometers from shore, to where it must have been rafted while frozen in icebergs during glaciations. More relevant for the present discussion, there are two known settings for rock flotation.

Sainsbury[15] noted tracks in sediments of the Thorne River Delta at Wales Island, Alaska. Here, the rocks, which are up to 1 kg, were rafted not by ice, but by kelp, which has air sacs that allow the seaweed to float (presumably an evolutionary adaptation to facilitate dispersion by wind). He noted that the trails were roughly at right angles to the tidal currents, suggesting that force due to wind was the likely cause of motion. Although the source of buoyancy and the appearance is different from the playa, the physics is fundamentally the same.

Tidal inlets in arctic and subarctic regions sometimes feature boulder barricades, elongate lines of boulders that follow the coastline but are separated from it by a tidal flat. These have been long recognized to be an ice-deposited landform.[16] As discussed by Rosen,[17] these boulder barricades form by the grounding of boulder-laden ice rafts near low tide. With low rock density, a broad boulder flat might be formed, but because the presence of a boulder increases the probability that a subsequent ice raft will be trapped nearby, a self-organized boulder barricade forms. (It is interesting to speculate that if the rock density at Racetrack Playa was higher, similar self-organized rock arrangements might occur.)

The playa is known to freeze. The movement of discrete (10 cm–10 m) plates of ice on the playa has been documented[3] by the shallow and wide trails without associated rocks that can often be seen on the playa surface. These trails are presumably caused by ice sheets (see Fig. 1). The impressions of ice crystals[3] can also be seen in the playa mud. We further observed in time lapse camera images[14] of the playa that after the playa was flooded in February 2009, it remained frozen for much of a day.

Rosen[17] noted that variations in the level of the water facilitate the lifting of boulders from the bottom. This variation is usually supplied by tides in marine settings, but at Racetrack Playa wind stress on the shallow water may provide a mechanism for local changes in the water level. The movement of large puddles of water across the playa has been documented anecdotally[18] and time lapse imagery[12] shows rapid changes in the water level and extent. However, because the ice sheet grows downward from the surface, it may be possible to lift rocks off the bed without changes in the water level too.

A visit to Racetrack in Spring 2009 also provides some evidence of "plucking," where a sliding rock was lifted ver-

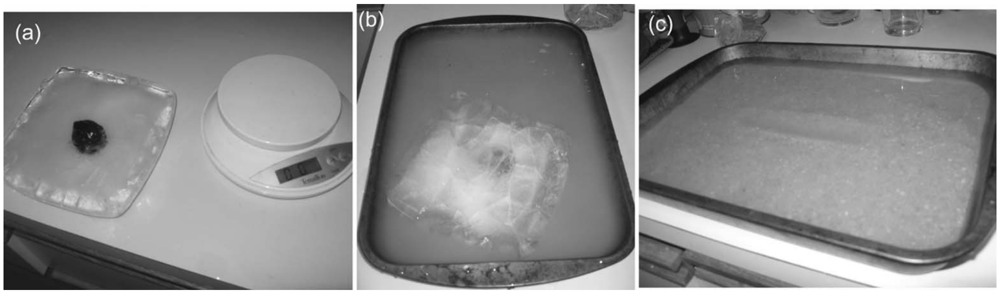

Fig. 7. A tabletop experiment showing trail formation with rafted rocks. A roughly cubical 4 cm rock was frozen (a) in ice (the assembled raft had a mass of 950 g) and is floated, rock-downward in a baking tray (b) with sand and water. (c) It is easy to form a trail.

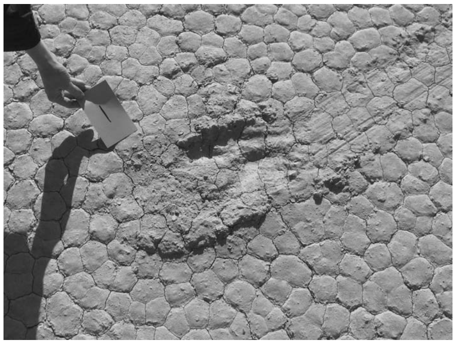

Fig. 8. The sitzmark of a rock is believed to have moved during Winter 2008–2009. Note that the trail is much shallower than the original depression.

Fig. 10. A view of the playa from the dolomite cliffs, looking north during a December morning. Note the shadow in the foreground, where the rock density is higher.

tically before being dragged horizontally. A rock (with corner-to-corner dimensions of 23 cm × 24 cm) was found at the end of a 14 m shallow trail. At the start of the trail was a depression that was deeper than the trail, with some deposits around it (see Fig. 8). The exact mechanism of the deposit formation is not known, but may relate to ice formation. The steep edge of the depression suggests that the rock was not simply pushed out of its partly buried starting point, but instead was lifted out. The very shallow striations (see Fig. 9), defining a track only 0.12 m across (about two-thirds as wide as the rock itself), also seem inconsistent with simple sliding on mud, but suggests instead that the rock was held somewhat above the mud. These indications are consistent with an ice raft forming around the rock and lifting the rock up, allowing it to be dragged by wind or currents to form a shallow trail.

The one-dimensional freezing rate of ice is well known (the "Stefan problem"[19]), and thus the rate of ice growth in cold water can be calculated as a function of air temperature (typically a few centimeters over the course of a winter night). However, the ice-raft formation process around a rock is not well understood (e.g., the raft required to float Sharp's corralled rock[3]). It is common in winter to see collars of ice around rocks in puddles or rivers, but why this happens is not obvious. There may be a role for the crystallographic nucleation of ice on the rock, its thermal inertia (the effective heat capacity of the rock, which depends on the timescale involved and thermal conductivity as well as mass and specific heat capacity) may play a role, or there may be purely mechanical processes at work such as the rock trapping floating needles of ice. Exploration of the ice-raft formation process may be a fruitful area of future research, although it is not clear whether laboratory work would easily capture all the processes that may occur in the field.

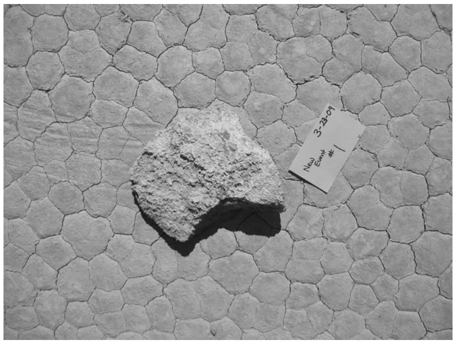

Fig. 9. The rock that originated at the depression in Fig. 8. Note the very shallow striations, forming a trail narrower than the rock itself. The card is 7.6 cm × 12.7 cm.

V. CONCLUSIONS

With the caveat that no single set of criteria may define the conditions under which all rocks may move (that is, although ice facilitates their motion, motion may sometimes occur in its absence), we have argued that ice rafting provides a mechanism that requires only circumstances at the playa that have been observed to occur, both there and elsewhere, and allows motion to be driven by modest winds. This mechanism avoids the problem that the exceptional winds or large ice sails, which would otherwise be required, would lead to effects that are not observed.

We have calculated the ice thickness and the extent needed to move rocks either by sailing, floating, or both, and discussed construct scenarios where the wind speed needed to push the rocks can be arbitrarily small. We have noted that the rock floating occurs in other real-world settings and that freezing occurs at the playa. We have observed, as have others, that the friction on rocks in the playa mud is ~0.5 times the normal force. We have also observed some evidence that rocks can be plucked upward, an action more consistent with ice lifting than wind pushing.

The facilitating effect of ice explains in part why moving rocks are not more commonly seen on the playa surfaces. For there to be playa surfaces at all requires evaporation rates to substantially exceed precipitation, which favors the midlatitudes where downward motion in the atmosphere's Hadley circulation brings dry air from the upper troposphere to the surface and thus causes low humidity (which is why most terrestrial deserts are 30° from the equator). These midlatitude regions are generally too warm for ice to be common at sea level, and therefore playa, which must be closed depressions in order to trap the sediment (that is, they are local topographic minima) must be at a high enough elevation for temperatures to be low enough to permit freezing. Another condition for moving rocks, namely, a cliff immediately adjacent to the playa to act as a rock source, further increases the rarity of the phenomenon. The fact that the dolomite cliffs at the edge of Racetrack Playa are at its southern edge likely explains why most rocks and trails are found there, although it is tempting to speculate (as did Reid *et al.*[4]) that shadowing by the cliffs (see Fig. 10) may also increase the probability or duration of freezing during the winter months when the sun is low in the sky.

Consideration of the rafting mechanism suggests a possible means of testing the hypothesis apart from direct observation. Even a shallow increase in the height of the lake bed will increase the probability that a rafted rock will become grounded. Thus, the resting location of rocks should be preferentially on topographic highs (relevant slopes are too small to affect whether wind without ice can cause motion). The strength of this correlation may depend on the variation in water depth (that is, a rock may become fixed because its raft melts, because it becomes grounded on a topographic high, or because the lake level drops). Measuring the topography of the playa to a subcentimeter accuracy may be challenging. Further field studies, and perhaps laboratory work, might be fruitful in understanding the mechanisms and rate at which ice cakes can form around rocks.

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