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ABSTRACT

Sharply angular boulders as large as 320 kg sit on the Racetrack Playa, Death Valley, California; trails leading to them indicate that the rocks have moved large distances. The process has never been witnessed. Although high winds and a wetted surface seem necessary, controversy persists about the need for other conditions, especially ice sheets. On the basis of experiments with a wetted Racetrack surface (soft mud ~3 cm deep), we find the effective coefficient of friction to be surprisingly high, ~0.8. Movement by wind alone of moderate-sized (20 kg) rocks with cubic shape requires sustained winds close to the ground of ~80 m/s (~180 mph). Larger flat-lying rocks require much higher winds. To assess the ice-sheet hypothesis, we mapped a large number of tracks into a precise coordinate system with an electronic theodolite. Certain tracks, separated by <1 to ~830 m, have nearly identical curving patterns near their starts. The distance between a distinctive bend on one such track and its mate on another matches the distance for another mated pair of bends on these same tracks within several centimetres, even for tracks 830 m apart. As proposed by Stanley (1955), it seems that the rocks, resting on mud, were locked into a single floating ice sheet, in this case at least 850 × 500 m. Final resting places of these rocks are much more widely scattered than their starting points, suggesting that the sheet broke into smaller plates. Large ice sheets can move rocks even with light winds and may explain the gentle curvature of tracks hundreds of metres long, a pattern very unlikely with gusty high winds and no ice.

INTRODUCTION

Scattered on the surface of the 2.5 × 4 km Racetrack Playa, Death Valley National Park, California, are stones up to ~320 kg with trails indicating that the rocks have moved periodically on the lake bed surface (Fig. 1). Various mechanisms have been proposed, but no one has witnessed the process. Gravity sliding can be discounted. The playa is so nearly flat that a lake 5 cm deep on a calm day covers most of the surface. In a 500 m leveling survey in the southeastern sector of the playa where most sliding rocks are found, we found a maximum relief of 5 mm.

All investigators have concluded that the motive force is the wind after the playa has been wetted by rain (McAllister and Agnew, 1948; Shelton, 1953; Stanley, 1955; Schumm, 1956; Sharp, 1960; Sharp and Carey, 1976), but consensus is lacking about the need for additional conditions, particularly ice sheets. With winds (~20 m/s) generated by an airplane propeller, Shelton (1953) caused a small rock (~0.5 kg) to move ~30 cm on an artificially wetted Racetrack surface, but doubted that heavier rocks could be moved solely by the wind. Sharp (1960) investigated the force needed to move a slab of polished granite on playa mud and concluded that even if pore pressures in the mud beneath the rock reduced the effective friction, sliding still required sustained winds exceeding 50 m/s (110 mph).

Stanley (1955) first proposed the need for ice sheets. He noted strong similarity in the detailed signatures of neighboring tracks and with survey data concluded that rocks were moved within an ice

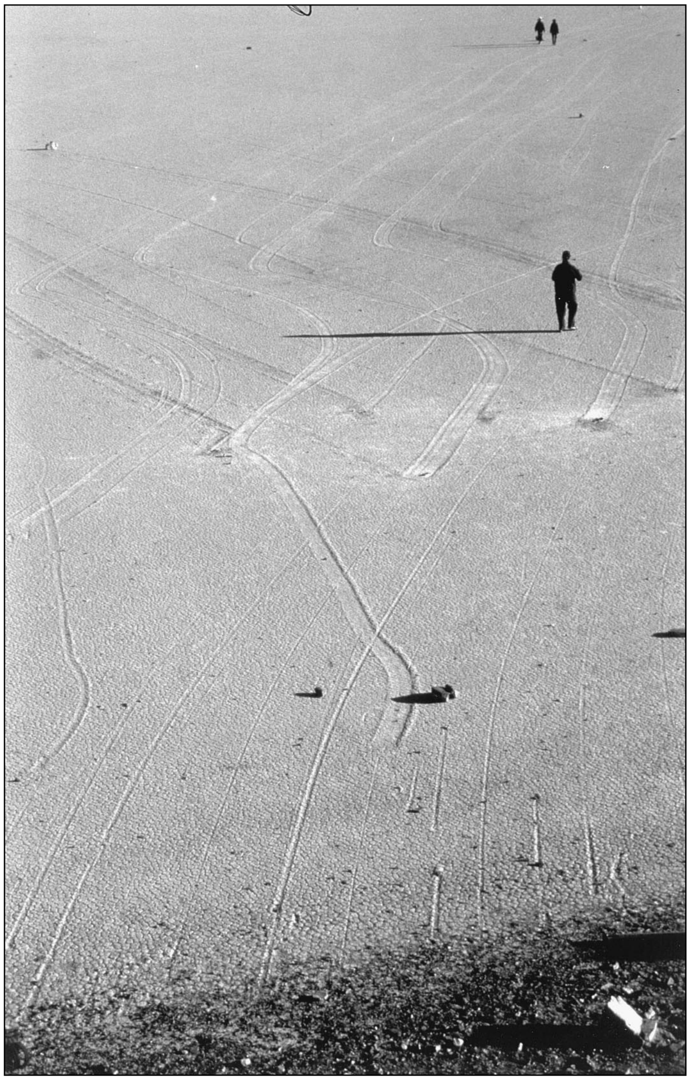

Figure 1. View of playa surface north of dolomite bluff, apparent source of most sliding rocks, at southeast corner of Racetrack; late 1980s tracks (dark trails angling to upper left) are superimposed by three 1992–1993 families of tracks. Some rocks began sliding in gravel at playa shore.

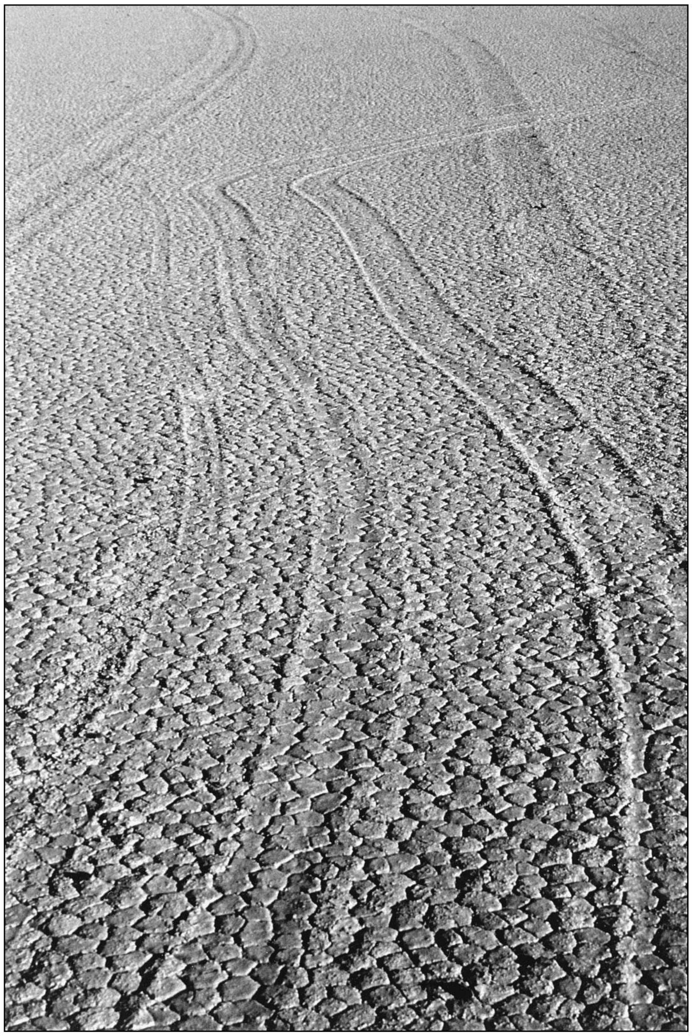

Figure 2. Three congruent 1992–1993 tracks, with differing widths, show distinctive wiggles used in determining intertrack separations. Wind alone is unlikely to have moved rocks of different masses around curves so similarly.

sheet floating atop a shallow lake. Because track lengths were not equal, Stanley felt that the ice sheet (~140 m in greatest extent) had rotated and fragmented when it snagged on large immobile rocks.

Sharp and Carey (1976) concluded that ice was not necessary for rocks to move. They placed two small test rocks within a circular cluster of steel reinforcing rods driven vertically into the playa ~60 cm apart. They later found that the smaller of the two rocks had escaped and concluded that a moving ice sheet could not have produced the observed result. As additional evidence, they noted that generally similar pairs of tracks did not maintain constant separation.

Our intent has been to assess these hypotheses by (1) direct measurement of the forces needed for sliding on the water-softened playa surface and (2) mapping of widely spaced tracks with similar signatures into a precise coordinate system with an electronic theodolite. Can the wind blow hard enough to move Racetrack rocks, and are their track patterns compatible with a mechanism involving wind alone?

RECENT OBSERVATIONS

On the basis of seven visits between 1987 and 1994, we have seen evidence for two major movement events, one in the late 1980s and another in late 1992 or early 1993. Two minor movements followed the main 1992–1993 event (Fig. 1). The largest rocks on the playa moved in the 1980s event, leaving deeply furrowed tracks with pronounced levees (still ~8 mm high in 1994), but did not move in the 1992/1993 event. The 1992/1993 tracks are more numerous and generally longer, but shallower and have smaller levees (~5 mm).

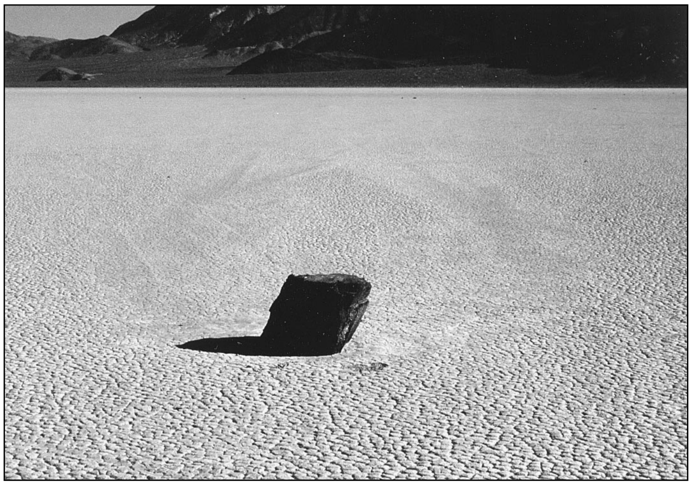

Figure 3. Largest Racetrack slider, stationary in 1992–1993 event, rests near scoured surface resembling wake of a boat. This texture may have been produced by breaking up of a northward-moving ice sheet.

The detailed descriptions by earlier authors generally apply to the current tracks. In many places, there is striking similarity in the signatures of neighboring tracks, despite wide differences in size (Fig. 2). Wind is unlikely to have moved rocks of differing masses around curves so similarly. Most rocks traveled more erratically near their final resting places than at the outset. An important point is that rocks generally did not spin as they traveled. Within the tracks are ridges and swales that generally parallel the entire track length (Figs. 1 and 2; Sharp and Carey, 1976, Figs. 10 and 16); these scars are commonly asymmetrically deep and reflect the uneven projections of the rock that made the track. Tracks of oblong rocks resemble calligraphy, varying in width as the rocks ranged from broadside to lengthwise sliding around curves.

Several small rocks with short tracks (bottom of Fig. 1) began moving not in slippery mud, but in imbedded angular gravel at the playa shore. They moved despite handicaps of minimal wind fetch (<10–15 m) and the elevated frictional drag of the gravel. Further from shore, we have found broad scour of the playa surface resembling the wake of a boat near the largest playa rock (Fig. 3). The pattern, possibly produced by the shredding of a northward-moving ice sheet, erases 1992/1993 tracks nearby.

ROLE OF ICE SHEETS

To assess the ice-sheet hypothesis, we mapped a large number of widely spaced tracks into a precise coordinate system, using an electronic theodolite. Figure 4 shows the initial parts of 1980s and 1992–1993 tracks, normalized to starts at (0, 0). Starting points for 1980s tracks span ~500 m; 1992–1993 tracks span ~300 m. Both sets show striking congruence, a pattern difficult to reconcile with the wind-alone hypothesis. Some rocks that moved during the late 1980s event ceased to maintain constant separation (Fig. 4A). Several 1992–1993 rocks (e.g., #27, Fig. 4B) apparently began moving after others that had moved as an integral unit from the start.

Evidence of synchronized motion exists on a broader scale. For 23 tracks of the 1992–1993 event, spanning 830 m at the south end of the playa, we determined coordinates for starting points (A) and the common tangent points (B and C) of two pronounced wiggles that each displays (Figs. 2 and 5). With the easternmost track as

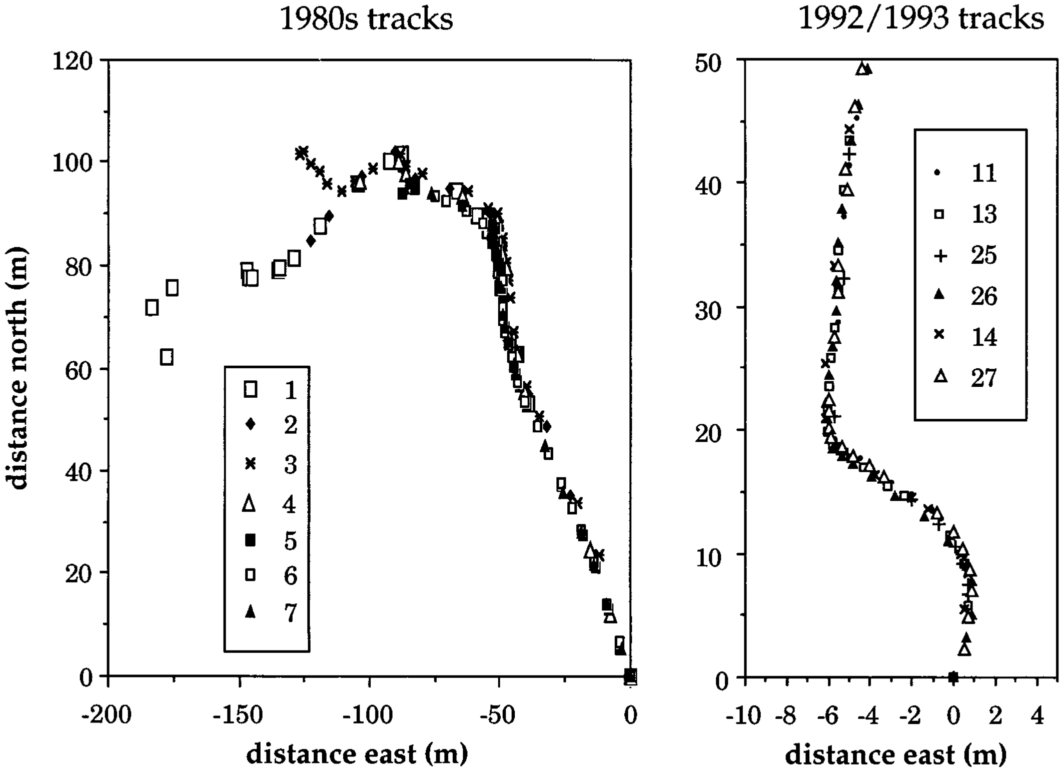

Figure 4. (A) Seven 1980s tracks with starting points spanning ~500 m and normalized to starts at (0, 0) show striking congruence of their initial motions. Note subsequent development of divergent pathways. (B) Six 1992–1993 tracks (spanning ~300 m) normalized to starts at (0, 0). All show congruence but only if 2.4 m are added to track 27 length at its start, suggesting that it resisted starting its travel with the others.

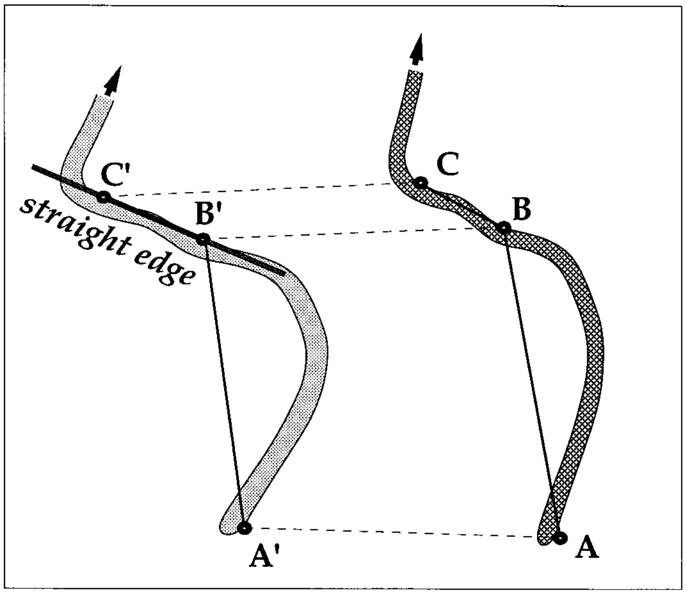

Figure 5. Schematic analogue to Figure 2, showing geometry of calculated intertrack and intratrack distances (Fig. 6). Six-metre straight edge was used to locate common tangent points, B and C, of gently curving tracks.

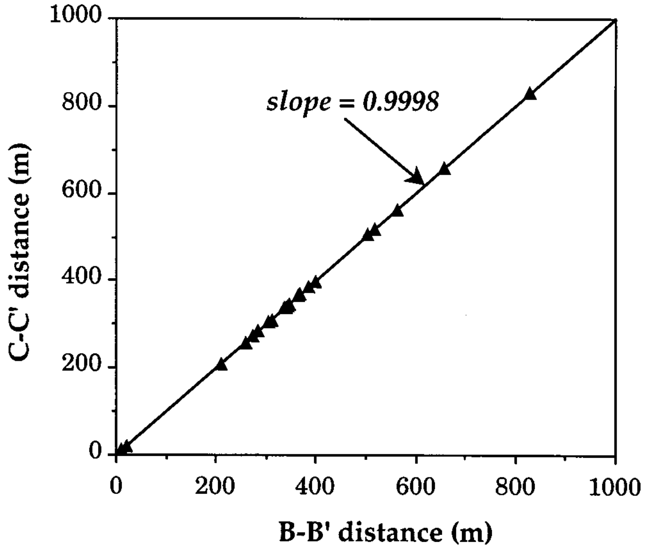

Figure 6. Comparison of intertrack distances for 23 tracks of 1992–1993 computed as shown in Figure 5. Distances B-B′ and C-C′ match very closely; average absolute difference for 23 tracks is 6.4 ± 5.6 cm. Slope of best-fit line is 0.9998.

reference, distances B-B′ and C-C′ generally match each other within centimetres even for pairs of tracks as much as ~830 m apart (Fig. 6). The average absolute difference is 6.4 ± 5.6 cm.

The data suggest that these rocks moved as Stanley (1955) envisioned, locked into large ice masses floating just above the lake bed. Except where shredded by stationary rocks (Fig. 3), the ice sheet protected the mud surface from disruption everywhere but where rocks slid. The sheet moved mainly by translation, with a component of rotation; A-B distances increase smoothly (from ~12 to 17 m) and B-C distances decrease (from ~6 to 4 m) eastward across the playa; the data suggest slight counterclockwise, then clockwise ice-sheet rotation consistent with the rocks' early S-shaped travel (Fig. 5).

The observation that rocks with similar signatures may not maintain constant separation was given by Sharp and Carey (1976) as support for the wind-alone hypothesis. This condition, however, may also be produced by rocks moving in the pieces of a disintegrating ice-sheet (Fig. 4A). They also felt that the escape of one of two rocks from an enclosure of metal stakes precluded involvement of ice. We have seen evidence, though, that ice sheets can be shredded by some objects (Fig. 3) while other objects may be moved by the same ice. With thin ice (~5–10 mm), steel rods may have shredded ice that was capable of moving the small (~1 kg) rock out of the enclosure. The immobility of Sharp and Carey's larger rock (~2 kg) may be consistent with this hypothesis.

Can any rocks slide without the aid of an ice-sheet sail? To determine the resistive forces involved, we surrounded a moderate-sized (~12 kg), angular, dolomitic rock with a wooden enclosure (~40 by 90 cm). The enclosure was caulked to the playa with mud, filled with water and covered with a sheet of black plastic to allow the surface to soften. Two hours at ~40 °C produced thorough wetting ~3 cm deep. Initial movement required a force, measured with a laboratory spring balance, about equal to the rock's weight, w, to break the rock loose. Continuous motion required an average force of ~0.8 w, though the force was not constant. As the rock moved, it alternately bulldozed and then slipped through mounds of mud, the resistance varying from ~1.0 w to ~0.6 w through such a cycle. Pronounced soft levees, initially ~10 mm high, had degraded to <5 mm six months later. On a less deeply wetted surface outside the enclosure, motion required ~0.5 w, but no levees were made. The sharply angular weathered surface of the dolomitic rocks is important in producing their surprising resistance to sliding; by constrast, we found that the effective (coefficient of friction) μ for bare feet on this surface was about 0.1. On a dry surface, angular 15 kg dolomitic rocks moved haltingly with forces of ~1.0 w to 1.2 w, despite their jagged undersides. Small rocks (less than ~0.5 kg) may roll or skid on a dry playa surface, but offer little exposure to the wind for sliding in mud without the aid of ice. We have measured a μ of 1.1 for the largest playa rock (Fig. 3) on a dry surface and 0.84 with 0.5 cm of mud.

WIND FORCES ON ROCKS AND ON ICE

The form drag exerted by wind on a surface normal to the air flow can be approximated by

$$F = 1/2\rho\, c_p A_{\mathrm{vert}} v^2, \tag{1}$$

where ρ = density of air (~1.3 kg/m^3), c_p is a form drag coefficient (ranging from about 0.1 to 1.0) related to the shape and surface texture of the object, A_{vert} = vertical projected surface area, and v = wind speed striking the surface (Ashton, 1986). Wind speeds are generally referenced to an elevation of 10 m above the ground, not to the near-surface height of a sliding rock. The reduction in air speed as the playa surface is approached is approximated by

$$v/v_0 = (z/z_0)^{0.2} \tag{2}$$

(Baumeister, 1987). Winds calculated to move low-profile rocks ($z \simeq 5$ to 10 cm) must be multiplied by factors of ~2 to 3 to correspond to winds at the 10 m reference elevation.

To move a cubic 20 kg (~0.2 m cube) rock where $\mu \simeq 0.8$, winds at the center of the cube must be ~78 m/s (~175 mph). This corresponds to winds, measured 10 m above the ground, v_{10}, of ~195 m/s (~440 mph). Moving a cubic 320 kg rock (~0.5 m cube) requires winds at its center of ~125 m/s (~280 mph); v_{10} would be ~260 m/s (~580 mph). Flat-lying rocks require even higher winds. These speeds are clearly unreasonable, even in microburst downblasts. Moreover, the long straight or gently curved tracks of nonspinning rocks suggest that sudden short-lived gusts cannot be the sole cause of the rocks' motions.

The frictional drag produced by wind on an ice surface is estimated as

$$F = c_\tau \rho A_{\mathrm{hor}} v_{10}^2, \tag{3}$$

where estimates of the air-ice drag coefficient, c_τ, range from $\sim 1.3 \times 10^{-3}$ (Andreas et al., 1993) to $\sim 2 \times 10^{-3}$ (Ashton, 1986) for smooth ice; ρ is the density of air; and A_{hor} is the surface area of the ice sheet. With 100 rocks—each 20 kg, resting in mud with $\mu \simeq 0.8$, and locked in a floating ice sheet 850 × 500 m in size—steady motion requires $v_{10} \simeq 4$ m/s (10 mph). If the ice sheet were dismembered, an individual 20 kg rock trapped in a 10 × 10 m ice sheet could continue to move with $v_{10} \simeq 27$ m/s (62 mph). Gusts like these are probably common at the Racetrack and, with small ice plates, might produce the erratic motions that rocks display near their final resting places. Andreas et al. (1993) noted that ice-sheet velocities are typically a few percent of the wind speeds driving them. Maximum speeds for Racetrack rocks, therefore, are on the order of a few tens of centimetres per second, but probably much less with large ice sheets and gentle winds. At these low speeds, drag on the ice by the water is negligible (Ashton, 1986).

Sliding is a relatively rare event at the Racetrack apparently because several unusual conditions must occur simultaneously. Sufficient rain for a lake must be followed by cooling and ice formation, but winds cannot blow too strongly before the ice is adequately thick to move rocks. The Racetrack, itself, is rare in the extent to which it displays rock sliding. It is higher in elevation (1130 m) than most playas in the region and cold enough in winter for ice formation. Bedrock outcrops lie close to the southeastern part of the playa where most sliders are found, and in winter, hills to the southeast provide shade into mid-morning, perhaps allowing ice to persist in just this region.

Because of the strong congruence of widely spaced tracks and the rocks' high resistance to sliding in mud, we conclude that ice sheets are necessary for Racetrack rocks to slide.

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