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COMMENT

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Warmest congratulations to John Reid and his students (1995) for demonstrating beyond a doubt that wind-driven sheets of ice have carried track-making stone over the Racetrack. They made the finest playa stone-track photo ever published. During seven years and more than 20 visits to the Racetrack, we (Sharp and Carey, 1976) never saw a comparable set of congruent tracks. We have only two bones to pick: their determination of the friction coefficient and the firm concluding statement ". . . ice is necessary for Racetrack rocks to slide" (p. 822).

Nobody has yet published a reliable measurement of friction between stones and a wet playa for two reasons. Track-making stones move on a surface much slicker and smoother than that used in the experiments of Reid et al., and the modes of propulsion employed are faulty. Playa tracks are engraved in the layer of finest clay that last settles from muddy playa water. Playas dry quickly, and this thin clay layer curls into cornflake chips, which winds export to the playa's edge. The deflated surface has approximately this composition: 25% fine sand, 40% silt, and 35% clay. W. E. Sharp's (1960) standard playa mud was probably of about the same composition. The clay-mantled playa surface was smoothed by a partial filling and bridging of the many polygonal cracks in its surface. In friction tests, stones were pulled or pushed unnaturally. Wind grips a stone on all exposed surfaces and exerts a slight lift owing to higher velocity over the top. After many trials, we concluded that a wind tunnel was required. Grove and Sparks (1952) made a commendable attempt, but results are partly compromised by use of an ice surface and an overly small size and flat shape(?) of test specimens. Unfortunately, most wind tunnel operators will probably close down when they see a geologist with a bucket of mud and a sack of stones headed their way.

The Reid et al. (1995) closing statement concerning the necessity of ice ignores many track configurations that are difficult, if not impossible, to explain by wind-driven ice. Even if, to parody an old U.S. Geological Survey Pick and Hammer song, "Every little cobble has an ice floe all its own." We feel that the behavior of many track-making stones requires a delicacy, selectivity, and flexibility beyond that expectable from wind-driven ice sheets or floes of any reasonable dimension.

For example, our work (Sharp and Carey, 1976) showed that a cluster of six monitored stones all slid contemporaneously for 5.2 to 36.5 m on mean paths ranging from N2°W to N27°E, in the winter of 1974. Only three of the tracks look modestly congruent when normalized in the manner of Reid et al. (1995). Heaviest stones moved the least and lighter stones the most. Within our 7 yr observation period, only one of these stones had slid before, a highly selective behavior. In the winter of 1970–1971, two large stones invaded separate parts of the study area without disturbing nearby monitored stones. Many stones experienced rotations of a few to more than 150° while traveling. Stones with rough bottoms steered straighter tracks than stones with flat, smooth bottoms, which wandered like sailing vessels without keels. A selection of five contemporaneous 1974 tracks with the most similar signatures had takeoff angles ranging from N4°W to N22°W, and only three showed modest congruency. A doublet of track-making stones, D_1 (5.9 kg) and D_2 (2.8 kg), that initially lay 1.2 m apart moved between January 14 and March 17, 1969, respectively 4 and 4.9 m, making similar tracks (Fig. 21, Sharp and Carey, 1976). The lightest stone, D_2, moved faster as shown by the greater length of corresponding track segments, and it caught up with D_1. The above behaviors are difficult to reconcile with stones frozen into ice sheets.

Reid et al. (1995) summarily dismissed our corral experiment. It consisted of a ring of iron stakes surrounding a 7 cm track making a 0.43 kg cobble. Between January 14 and March 17, 1969, this stone slid out of the corral and stopped 28 cm beyond, making a sitzmark, from which it moved 6.8 m farther northeast before March 17. Two heavier cobbles, 2.8 and 3.2 kg, were then placed in the center of the corral, 53 cm apart. In 1974, the 2.8 kg cobble escaped by moving 3.7 m N39°E. The 3.2 kg cobble remained undisturbed in its original seating. Reid et al. (1995) assumed that only the lightest, 0.43 kg cobble moved and attributed that to the reduced transporting power of ice shattered by the corral stakes. We feel that the events, particularly the lack of disturbance of the 3.2 kg cobble, indicate that ice was not involved.

Recent studies of winds blowing across flat smooth playas have revealed the remarkable compression, from about a metre to a few centimetres, that occurs within the boundary layer over a playa (Cahill et al., 1994). This results in intense shear almost down to the ground surface. Using this relationship, three physicists (Bacon et al., 1996) calculated that reasonable wind velocities can skid stones across a wet, clay-veneered playa surface.

None of the above detracts from the accomplishments of Reid et al. (1995). They capitalized on an unusual opportunity and showed without doubt that a sheet of ice moved track-making stones over the surface of Racetrack playa. This neat piece of Quaternary research merits consideration for a Kirk Bryan Award. It would have made Kirk's eyes sparkle, and he would have been especially pleased that students were involved. Our conclusion is that both wind-driven ice and wind alone can create stone tracks on playas.

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REPLY

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The question of how Racetrack rocks slide seems to belong in the first week of Physics 101. What is the resistive force and what forces can overcome it? Estimates of these forces, though, are elusive. The resistance depends on the playa surface conditions (duration and rate of rainfall, depth of wetting, presence or absence of a slippery clay coating and possible subsurface algae, and whether the mud surface is frozen) and the rock (type, mass, shape, angularity, and degree of pitted weathering). If wind is the driving mechanism, the motive force depends on the wind at standard height (10 m), its profile near the ground, the height and cross-sectional area of the rock, and whether ice sheets exist to magnify the wind's effects. Hypotheses must pass muster with the track record, and, if ice sheets were involved, their size, thickness, ice quality, and sun and shade history are complicating factors.

Sharp and Carey take issue (most graciously) with our findings in three ways. They feel that (1) detailed rock movements that they saw over time were too locally individualized to be explained as rocks welded into ice sheet(s), (2) that our friction experiments did not reproduce the very slippery condition of a fine clay veneer, and (3) with reference to studies at Owens Dry Lake (Cahill et al., 1994), that wind speeds within a few centimetres of the playa surface are higher than we estimated them to be.

Track Geometries. With 20 visits to the Racetrack in the 1960s and 1970s, Sharp and Carey (1976) saw behaviors of rock clusters that we agree are hard to reconcile with the ice hypothesis, especially those where individual rocks moved into or out of groups of other small stones that remained stationary. Also, closely spaced rocks began moving in fanlike manners with initial takeoff angles varying by >20°, and one but not both of two rocks within a corral of vertical steel rods escaped the enclosure.

To be sure, complex rock motion is to be expected with a fragmenting ice sheet. Like a dinner plate dropped on the floor and swept aside with a broom, ice sheet fragments may push one another as a jostling unit, with some fragments (those with larger rocks?) sticking more and causing chaotic rotational and strike-slip motion in neighboring pieces. With irregular rock placements in rotating and translating ice fragments, one might expect complex divergent or crisscrossing trails to be left on the playa. As the sun rots the ice (perhaps initially along its first-lit northwest edge), the sheet's edges may crush against "stuck" rocks and allow some degree of interpenetration of rock groups. Sharp and Carey feel, however, that no realistic ice sheet complex could have been selective enough to explain what they saw. We have to agree.

Coefficient of Friction (μ). Sharp and Carey feel our friction experiments did not duplicate the real conditions of sliding. There is probably a continuum between two track types (those with pronounced levees and those with none), implying a spectrum of surface conditions. Nearly all the current tracks have well-developed levees and central depressions suggesting that mud at least 1 cm deep (with or without a veneer of fine clay) covered the playa when they formed. Levee formation may involve pushing material aside as a bow wave by a smooth rock or bulldozing by a more angular rock. The latter case should produce the high μ values we measured, and as a result, no realistic wind will likely move bulldozing rocks without help from ice sheets. Smoother rocks, however, may hydroplane rather than bulldoze and make levees under lower μ conditions.

On some occasions, tracks have no levees suggesting that thin mud on a firm substrate allowed rocks (especially the smooth syenites?) to skim with a much lower μ. These tracks seem incompatible with the ice sheet theory because of the considerable time (more than several hours) needed for a lake to form and freeze. Our wetting experiments showed that within an hour or so, the surface softened to a depth of 1–2 cm, making levee formation unavoidable. Rocks that leave no levees must move early (or late?) in a wetting event, or during initial thawing of a frozen wetted surface (J. Shelton, 1995, personal commun.). Important for Sharp and Carey's model, they do not involve ice sheets. Eriksson et al. (1996) have recently described rock trails in South Africa with no levees; they conclude that frozen dew in polygonal desiccation cracks may have provided very low friction, but ice sheets can apparently be ruled out.

Dolomites resting on surfaces with "tear-pants" texture are very unlikely to skim. Their sharp corners should bulldoze even thin mud layers, and their "teeth" will penetrate thin mud and bite into the more rigid substrate. Some dolomite surfaces, though, do not have pitted weathering suggesting a range of μ values even for a single rock.

Wind Profile. The wind profile near the ground is of central importance. Cahill et al. (1994; 1995, personal commun.) measured the profile at Owens Dry Lake playa whose surface consists of fine alkali dust beneath a thin salt crust. When strong winds disrupt the salt crust and the dust is entrained, the profile collapses toward the surface and winds at 5 cm elevation climb to ~80% of their strengths at 10 m. Using Cahill's profile and assuming velocity at 5 cm is 32 m/s, Bacon et al. (1996) have calculated the average critical sliding μ for 31 Racetrack rocks to be 0.3 ± 0.2. Although the smooth syenites on thin mud may have such μ values, we question whether Cahill's profile is applicable to the Racetrack. No crust or underlying dust exists at the Racetrack, and collapse of the wind profile should not occur. Indeed, on June 5, 1995, at Panamint playa (whose surface resembles the Racetrack) with wind speeds at 1.5 m of about 25 m/s (55 mph), we found the wind at 5 cm to be half that at 1.5 m elevation or ~40% of that expected at 10 m. Because the wind speed is squared in the force equation, the available force is reduced fourfold if our measured profile applies. We also tried kicking small rounded basalt scoria cobbles (diameters of ~10 cm) along the surface at right angles to the wind to measure their downwind deflection. Despite their relatively low densities and rolling motion, no rock was deflected more than about 20 cm in travels of 3–4 m, suggesting relatively weak forces at the ground despite gale force winds at 1.5 m elevation.

All said, we agree with Sharp and Carey's assertion that two separate mechanisms must exist for Racetrack sliding. Are there others?

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