Chapter 2

Previous Investigations

While casual and scientific studies of the sliding rocks of Racetrack Playa span the twentieth century, it is not known when the features were first discovered. There is ample evidence of early habitation in the area by paleo cultures, such as the presence of chert tools and other artifacts (Hunt, 1975). An ancient trail parallels the boundary of the Racetrack, perhaps indicating periods in the past when the basin was more frequently filled with water. However, there is no record of the sliding rock phenomenon from prehistoric times.

The earliest account was documented by Stanley (1955), who described a 1915 visit to the Racetrack by Joseph Crook, a prospector from Fallon, Nevada. Crook brought his wife to the site, and showed her the stone tracks; she could not believe that the larger rocks could move naturally. She marked the position of one of the boulders, which eventually moved away.

The disbelief felt by Mrs. Crook is fairly universal among visitors to the playa, yet few researchers have attempted to follow through on their interest.

2.1 McAllister and Agnew, 1948

The first published account of Racetrack Playa's unusual surface processes was an abstract in the *Geological Society of America's Bulletin* (McAllister and Agnew, 1948).

McAllister had encountered the sliding rocks while mapping the geology of the Ubehebe Peak quadrangle for the U.S. Geological Survey (McAllister, 1956). The report contained only general descriptions as no precise measurements of the furrows had been taken. The authors speculated that "scrapers were propelled over the muddy surface of the playa, initially from the rim, by strong gusts of wind blowing consecutively from different directions, such as erratic whirlwinds that commonly produce dust-devils" (McAllister and Agnew, 1948).

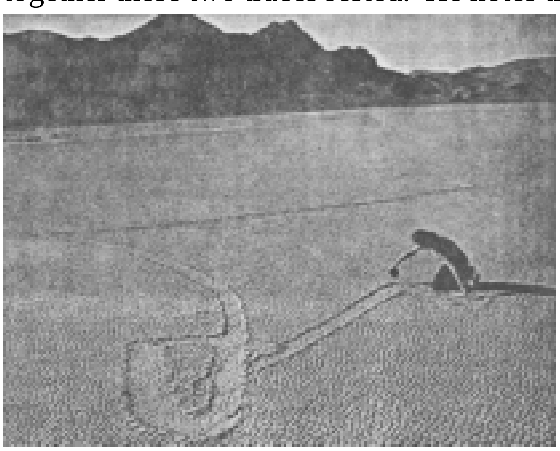
2.2 Kirk, 1952

The next report was compiled by Louis T. Kirk, whose two years of unofficial studies (i.e., non-sanctioned National Park Service field work) were comprehensively recorded in the *Journal of Sedimentary Petrology* (Kirk, 1952). As a Death Valley ranger, Kirk was motivated by his personal interest in the phenomenon, and he sought to collect accurate measurements and representative photographs to capture and preserve the rare features. Concerned with increased visitation to the park, he noted that some human-caused disturbances had already occurred. Kirk made casual observations for years, but concentrated the bulk of his measurements during twenty hours of intense field work conducted over a period of just three days.

Activities included photographing typical trails; weighing a sampling of twelve rocks with spring scales; measuring trail lengths with a surveyor's chain; determining trail depth and width with steel tape; and sighting trail headings using a Brunton compass. The dimensions, general shape and orientation of the twelve rocks studied were meticulously detailed in the report. Kirk also noted three sediment-mound features which, although irregularly shaped, were measured with steel tape and described according to orientation.

Although the physical characteristics of sliding rocks, trails and fine-grained sediment deposits were clearly described, their locations with respect to each other and to the playa outline were not. Kirk used his vehicle's odometer to find the minimum distance of each of his documented rocks to the playa perimeter, but his measurements lacked reference and direction (note that driving was fairly commonplace on the Racetrack until 1969). Locations were loosely described only in terms of quadrants (northeast, southeast, southwest, northwest), based upon imaginary and unreferenced north-south, east-west divisions.

Kirk found that the trails ranged from 34 to 786 feet (10 to 240 meters), and that the majority were straight or slightly curved with a general orientation running within 45 degrees of north from inception to terminus. He noted and photographed two trails that traced complete loops (see Figures 2.1 and 2.2). The images show a high degree of parallelism between convolutions in the trails, although it is not know exactly how close together these two traces rested. He notes that these two trails were both found in what he



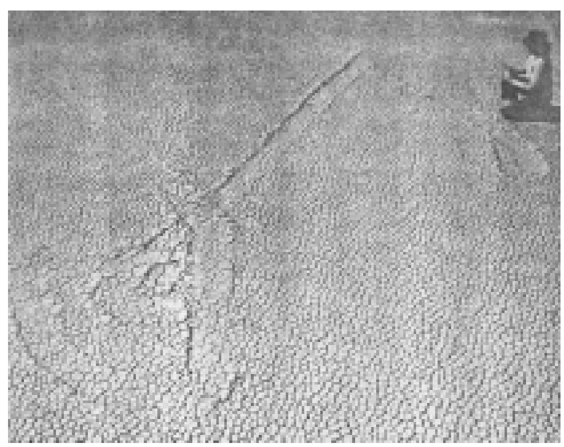


Figure 2.1 (left) and **Figure 2.2** (right): show two trails as photographed by Louis Kirk (1952). The trails' locations were not noted, although it was recorded that the granite cobble that produced the trail in Figure 2.1 (Kirk's rock #9) was about 0.03 miles (45 meters) from the playa's perimeter, while the granite cobble causing the trace in Figure 2.2 (Kirk's rock #10) was 0.1 mile (160 meters) from the boundary.

deemed the “northeast quadrant” (boundaries were not specified). Both rocks were granitic; Kirk noted that their bottom surfaces were smooth, and he suggested that this erratic behavior could be explained by the physical character of the rocks themselves. Despite the high degree of congruence in the looped sections near the termini of the trails, the trail lengths varied considerably: Rock #9 (Figure 2.1) produced a trail that was 196 feet (60 meters) long; Rock #10’s (Figure 2.2) trail, at 786 feet (240 meters), was the longest one measured.

Of the twelve rocks described, Kirk included seven limestones, four granites and one quartz, ranging in weight from 1 to 603 pounds (mass equivalent: 0.5 to 274 kilograms). The largest rock was a rectangular carbonate boulder (Rock #6) with a 60 foot (18 meter) trail, heading towards the northwest (315^{o}). Kirk noted that the largest rock neither produced the shortest trail (34 feet/10 meters, caused by one of the smaller rocks surveyed), nor did it move in the general heading of the majority of the sliders. Inferring that there was no clear relationship between rock volume and trail character, he paid close attention to rock shapes and orientations with respect to the trails they created. A summary of his collected data appears in Appendix B.

Kirk’s detailed field notes are commendable. His comment, “in general the rocks were oriented with the corner of their most streamlined appearing sides facing the trails” (Kirk, 1952) implies a rotation, possibly by wind, into this configuration. However, most of the rocks he sampled were described as “irregular” or “rectangular” hence the term “streamlined” seems somewhat contradictory. Having neither photographed each rock, nor referenced them to the trails they produced makes it difficult to decipher Kirk’s conclusion linking rock shape and trail orientation. Since only twelve rocks were described (the reasons for selecting this subset were not offered), generalizations based on such a small sample are useful but not necessarily indicative of large-scale patterns.

While his paper focuses on field observations, Kirk speculated on possible causes for the phenomenon. He cites that a large number of hypotheses had been suggested by the time of his study (i.e., anthropogenic activity, including the use of the playa as a landing strip for a miner's airplane; magnetic anomalies; seismicity), but that the most logical causative agent was wind. Kirk described an experience during a four-hour period when the wind blew across the playa alternately from the east, west and south, at approximately 30 to 40 miles per hour (14 to 18 meters per second), which he regarded as a conservative estimate. Kirk noted that while it had been widely accepted that wind was responsible for the deflation of mud curls and movement of small stones, it seemed more plausible that the same mechanism was responsible for the movement of larger rocks than to suggest that another agent caused the more dramatic boulder-slides. As a patrolling ranger, he pointed out that summer cloudbursts or winter storms may provide sufficient precipitation to adequately flood the playa surface, although the only official weather data collected in Death Valley, nearly 4000 feet (1200 meters) lower in altitude, perhaps erroneously suggest that such events may not occur. Hence he concluded that natural processes that take place when a very special set of conditions are met can explain the incidence of sliding rocks on the Racetrack. His closing remark, "it is hoped that further investigation by other observers will provide a definitive answer" was heeded, resulting in the next published report only one year later (see section 2.4, page 24).

2.3 Clements, 1952

In the same issue of the *Journal of Sedimentary Petrology* as Kirk's landmark study was a published account of similar features on a nearby playa by Thomas Clements. Somewhat skeptical about the evidence and hypothesis suggested by McAllister and Agnew (1948), Clements visited the Racetrack in the spring of 1950 to view the sliding rocks for himself. After casual observation of the furrows, Clements agreed with the earlier paper's speculation that wind was responsible for the occurrence of sliding rock trails. While other methods had been suggested by then (Clements relates the possibilities of ice; tilting of the playa; water currents; and vibrations as possible moving agents), the occurrence of high winds after a saturation event seemed to be the most logical explanation. Yet Clements noted that if this were the case, then physical conditions similar to those on the Racetrack must occur elsewhere, and sliding rock phenomena should have been observable on other dry lakes. A literature review revealed no published reports of any such analogs, so Clements conducted a field survey of nearby playas in connection with a desert research project sponsored by the U.S. Army.

Just outside the northern extent of what was then Death Valley National Monument is Little Bonnie Claire, a dry lake of similar geographic setting, altitude and physical character to the Racetrack (see Figure 2.3). Clements visited the playa in January 1952 after a rainstorm. He reported that as the sun set, the low illumination angle highlighted the barely perceptible relief of three shallow trails. Measuring 20, 14 and 2 feet in length (6, 4 and 0.6 meters, respectively), Clements noted that the intermediate furrow was caused by the movement a small basalt cobble that still remained at its terminus.

He returned in March 1952 during a wind and rain storm, camping out at the playa's north end. Clements described this twenty-four hour event as one in which winds frequently gusted to 40 miles per hour (18 meters per second) from variable directions, although most winds were northerly. On the day after the storm the playa was covered with 1 centimeter of water: "The clay surface was soft and extremely slippery, but beneath the topmost inch the material was quite firm so that a person walking on the playa sank down no more than an inch or two." Although difficult to "keep one's feet," Clements traversed the south and southeasterly portions of the playa where he noted numerous new trails. His descriptions are mostly qualitative, i.e., "some trails were straight, some were gently curved, a few had right-angle bends and a few were serpentinous." A few of the trails were measured, although the results of his measurements are only summarized in his

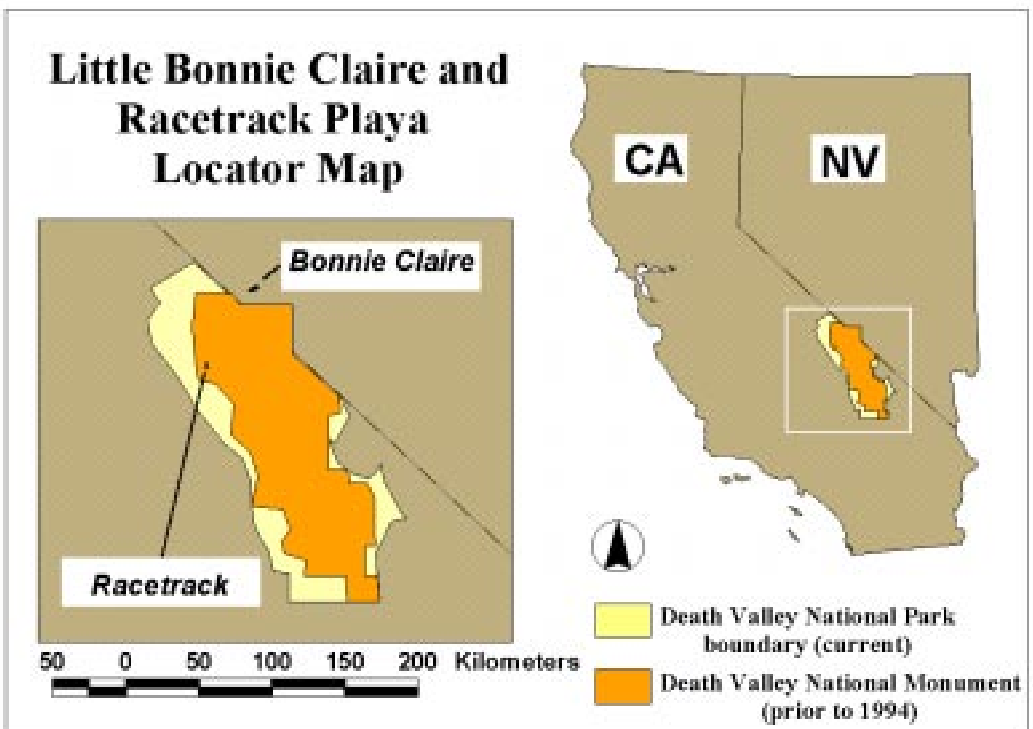


Figure 2.3: Locator map of Little Bonnie Claire and Racetrack playas.

paper; the longest trail witnessed was 138 feet (42 meters), while the shortest was only a few centimeters in length. All trails ended in cobble-sized basalt or scoria fragments, and headed generally from north to south.

Clements' observations led him to the conclusion that a combination of factors, including saturation of the uppermost clays and continual wind gusts, were all that was necessary to cause the rocks to slide. Snow covered the surrounding mountains during Clements' day at Bonnie Claire; the snow line was only slightly above the playa. Yet he doubted that accumulated water on the surface had frozen during the night. Although the ice floe theory had been suggested as a causative agent, Clements noted that the trails he observed showed little uniformity in direction and length. Furthermore, only some of the rocks moved; many had not. The lack of trail parallelism was attributed to "different [rock] sizes and local surface irregularities [compounded by] gusts from varying directions and varying competencies." As further evidence supporting the work of wind and water alone, Clements described several large boulders near the center of the playa; he contended that ice sheets would move all rocks in unison, regardless of size. Since ice-drag did not play a role in the transport of the cobble-sized rocks at the south end of the playa, it probably wasn't necessary to move the large boulders either, yet *something* propelled these large igneous blocks far from their source areas.

2.4 Shelton, 1953

John Shelton visited Racetrack Playa three times during April and May, 1952 to test whether wind could move stones as had been suggested by McAllister and Agnew (1948). He traveled to the remote location by light aircraft, landing directly on the playa surface, and then used the plane as a source of artificial wind. He transported a supply of water, an anemometer, spring balances and laboratory-cut cubes (of unspecified material) ranging in base length from 1 - 8 centimeters. Flooding the surface with water, Shelton noted that "even 3 - 4 hours of soaking is not enough to produce a smooth slippery film of mud on the playa" (Shelton, 1953), and he estimated that it might take days or weeks to achieve a sufficiently low coefficient of friction to induce rock movement. Conceding that his technique did not mimic natural processes, he confined water to an area just over one square meter, allowed it to saturate the surface, and then used a trowel to produce a uniform veneer. The airplane's propellers generated wind speeds of no more than 42.2 m.p.h. (19 meters per second), but forces were great enough to push a triangular prism of limestone weighing 19 ounces (532 grams). The largest prepared cubes didn't move, but smaller ones tumbled. Shelton attributed this to a combination of the inherently greater pressure per unit area of the cubes' bottom surfaces, and to their low vertical profiles (friction retards wind speeds at close proximity to the playa floor). Further investigations took place "at a shallow, man-made water hole near the south end of the playa" (Shelton, 1953); introduced water was naturally contained, producing a thoroughly saturated material on which the 19 ounce prism and one other natural stone moved several times under the force of propeller wash. The researcher noted that movement was slow and hesitating, and that the mud surface was actively rippled by the air blast. Shelton surmised that natural conditions are probably more conducive to rock motion for two reasons. First, the artificially wetted surface was not as slippery because the uppermost playa crusts naturally contain the finest clays, and these had been stripped away at this depression. Second, the aircraft's propellers were capable of producing only unidirectional, steady winds of limited speed. He noted the topographic configuration of the valley, and proposed that the terrain nurtures gusts of increased velocities, particularly from the southeast.

2.5 Stanley, 1955

Three years after Louis Kirk's invitation for further study of the Racetrack, George M. Stanley published a lengthy report in the *Geological Society of America Bulletin*. Stanley's first visit to the playa in December 1951 was no more than a cursory scan of the sliding rocks, but it prompted him to return for more intensive field analysis the following spring. A two and a half day visit in April 1952 resulted in the examination of several highly parallel tracks, which prompted an even more extensive mapping project a few months later. For eight days in August and September of 1952 Stanley conducted the first detailed mapping project of the Racetrack Playa's surface phenomena. With two more short excursions in November 1953 and April 1954 Stanley generated the first reasonably accurate plots of the playa's sliding rock trails.

Stanley established a series of base lines aligned by alidade on the playa surface and drove numbered tags into the dry mud alongside selected trails. Measurements from each tabbed point on a trail to two or more base line reference points were taken with steel surveyor's tape to the nearest 0.005 foot (0.175 millimeter). Base lines were interrelated by eight field measurements and later trigonometric computation to a resolution of about 0.05 feet (15 centimeters). Base lines and trail point locations were recreated on a plane table to a scale of 1 inch = 10 feet (1:120). Line features were sketched once the skeletal points were plotted, and Stanley admitted that there were some inaccuracies in his drawings due to the oblique vantage point of the field surveyor.

Concentrating field activities to the south end of the playa, Stanley mapped several highly parallel trails which varied in length between 200 and 300 feet (60 to 90 meters); when overlaid with each other the lines showed a high degree of congruence. Citing the similarities of these inscriptions, Stanley concluded that a cohesive ice sheet, measuring approximately 200 to 275 feet wide (60 to 85 meters) was responsible for rock movement. Deviations in trail length were explained as the result of an ice floe break-up. He studied trail orientation changes extensively, and described shifts in heading as the result of ice floe rotation. According to Stanley, large rocks at a distance from shore acted as obstacles; when a moving ice sheet of limited strength encountered one of these voluminous encumbrances the ice would crumple and pivot, causing changes in direction of over 10 degrees. Smaller trail “wiggles” were interpreted as the consequences of the ice sheet scraping against ice ramparts along a changing shore configuration.

A group of isolated trails more distant from the southern shore was mapped revealing analogously parallel pathways (see Figure 2.4). Unlike the majority of rocks, this group traveled from north to south. Figure 2.4 shows only one schematic of four presented by Stanley; it is representative of the survey’s level of detail, however only vague inset maps were included to help locate the general locations of the selected trails.

Upon analysis of these tracks, Stanley concluded that they were produced by a southward unit movement with counterclockwise rotation, and final divergence due to ice floe break-up. Further evidence, such as the lack of uniformity of rock size or shape in this isolated group, bolstered the ice-raft hypothesis, however Stanley did not include data on the physical nature of the rocks in his study.

Among his descriptions, Stanley observed that the longest trail was 872 feet (266 meters) although its location on the playa was not reported. He was perplexed that this extensive path was gouged by a 27-pound (12 kilogram) rounded dolomite whose long axis was transverse to the track for its entire length. The author questioned how wind could have accomplished this without causing the rock to tumble, and suggested that only ice could allow for the smooth sliding motion implied by the trail. Another example, also without geographic reference, was that of a rectangular dolomite block of 30 pounds (14 kilograms) with a trail that, for a substantial fraction of its total extent, crossed an area littered with small stones. An unnamed geologist cited in the paper presumed that this cobble could have slid on clay up to this debris puddle, then tumbled through it, resuming its tractive motion when encountering clay again on the other side. Stanley disagreed:

> "It would be contrary to the laws of transport for wind to roll away this

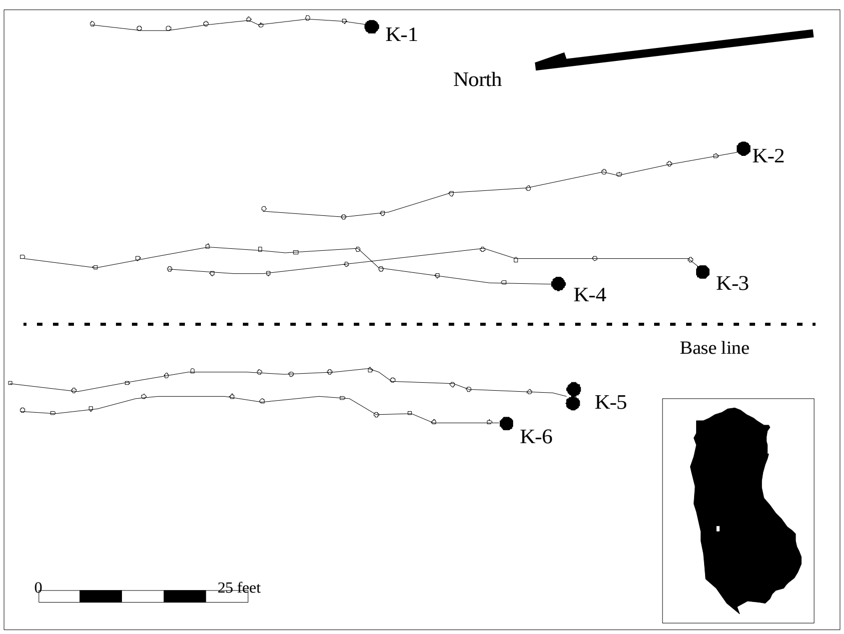


Figure 2.4: Six trails in the west-central part of the Racetrack Playa as mapped in 1952, showing the base line used for reference. Rocks moved generally from north to south and show similar motion (note that trail K-5 is headed by *two* rocks which may have moved in unison). Stanley concluded that all six rocks were embedded in an ice sheet that broke up, separating the rocks into two subsets: one including K-1, K-2 and K-3, and the other including K-4, K-5 and K-6. The second subset may have fractured further. Inset (lower right) shows the location of the enlarged map with respect to the Racetrack Playa's outline. (After Stanley, 1955.)

> large rock and leave the hundreds of tiny stones that constitute the point traversed, even though most of the paved stones protect one another from wind. Also, to slide a rock over stones, unlubricated by wet clay and slightly upgrade, would require more force than wind could apply to it without ice as an intermediary."

This statement and others neglect the cohesive nature of the playa muds when they become saturated. Stanley argued that light-weight materials, including twigs and burro droppings, could not be propelled by wind across the playa without tumbling, hence such objects would not leave characteristic scars. The fact that they did, he argued, offered further support for the ice-floe theory; Stanley envisioned protrusions in the ice sheet inscribing down into the soft muds as the entire frozen mass glided over the playa. However, the playa surface becomes both slick and sticky when saturated. Light objects, like the dolomite block, may resist tumbling and rolling because a single surface may be "glued" to the tacky surface, yet entire objects glide despite this fact; the forces may be substantial enough for propulsion, but not powerful enough to overcome surface adhesion to the gummy deposits below.

Stanley cited the work of Kirk (1952), but interpreted the observed mud mounds described by the earlier paper as the work of ice, possibly scraping the softened clays as a migrating ice tongue. Kirk measured an 84 foot (26 meter) swath that widened from 2.5 inches (6.3 centimeters) to 12 feet (3.7 meters); a feature with this morphology was originally interpreted to have been caused by spreading turbid water. Stanley explained this divergent pattern as the result of an ice floe that "pressed more widely on the mud as it overreached the bounds of a shallow supporting pool" (Stanley, 1955). Scalloped shorelines and ridges of large stones parallel to the encroaching alluvial fans at the playa boundary were interpreted as ice shove features. Stanley contended that rocks of "this size" (no quantitative data were included) could not have been transported by waves in such a shallow lake. He specified several rocks, protruding about one foot (0.3 meter) above the playa floor evenly spaced along the western margin. The rocks were tilting to the south, implying that the prevailing winds that may have produced the ice rampart feature were emanating from the north. This conclusion is consistent with the southerly headings of trails mapped on the west side of the playa (see Figure 2.4.)

Bolstering the ice hypothesis, Stanley's paper included a narrative report of an incident that occurred on December 3, 1952 east of Reno, Nevada. The central transcontinental telephone line was suddenly and mysteriously disconnected, leaving many telephone customers without service. A repair team traced the source of the problem to a small lake in Carson Sink. Phone lines crossed Toulon Lake, a 775-hectare depression which was flooded that winter; at an elevation of 1188 meters above sea level, the water in the shallow lake had frozen. Repair personnel discovered that 20 telephone poles supporting over 1000 meters of cable had been knocked over into the lake. Some of the poles had been erected within corrugated metal reinforcements, but they too were uprooted. A sheet of ice 10 centimeters thick with a major axis length of 5 kilometers had formed on a half meter of water. Winds estimated at 15 meters per second caused the ice sheet to move, reportedly shearing off or uprooting the telephone poles, and transporting them and their mangled caissons about 100 meters from their original upright locations. Stanley contended that similar conditions may exist on the Racetrack, and analogous mechanisms may be responsible for the presence of sliding boulders.

When reviewing the work of previous researchers, Stanley responded to Clements who questioned why this phenomenon isn't more widespread. "A logical answer might be that most other playas (of Mohave-Colorado Desert) are lower, and temperatures to develop sufficient ice would depend considerably on elevation" (Stanley, 1955).

A follow-up visit to the Racetrack in mid-April 1954 yielded many new, unmapped tracks. Among the fresh discoveries, Stanley noted a series of six irregular zig-zagging trails about one kilometer east of the Grandstand, a few tracks near the south end with a northeasterly trend, and most curiously, about 100 fresh southward tracks along the west side of the playa (Stanley, 1955). He noted that most of the trails, from a few centimeters to 6 meters long, were gouged by rocks but some were produced by twigs of sagebrush. A few more indications of recent activity were found southeast of the Grandstand, where rocks and burro dung produced southerly traces up to 23 meters long. Hence, it was presumed that conditions favorable to rock traction (whether by ice floe or wind alone) must have existed during the winter of 1953-1954.

2.6 Schumm, 1956

Noting the controversy between the two schools of thought, Stanley Schumm published a paper in the *Journal of Sedimentary Petrology* summarizing the relative merits of the ice floe and "wind only" theories. He cited the observations of Guilcher and Cailleux (1950) who described the presence of incongruously large pebbles (ranging in maximum dimension from 1 to 4 centimeters) forming discontinuous lenses 10 to 20 centimeters below the surface of the Veluwe Hills in the Netherlands. These sands constitute mounds up to 3 meters in height, and are believed to have been deposited during the Würm glacial epoch during the Pleistocene.

The deposition of the pebbles, as the result of aeolian transport, is difficult to reconcile since the smaller particles constituting the Veluwe matrix material (sand, silt and clay) would have been deflated by forces capable of carrying pebbles. Guilcher and Cailleux (1950) suspected that the sand deposits may have been glazed by ice as wind carried pebbles away from adjacent stream channels. Pebbles may have skidded up these ice ramps until ultimately coming to rest in their current layers.

Schumm also reviewed the work of Grove and Sparks (1952) who conducted experiments to test the hypothesis of Guilcher and Cailleux. A pivotable slab of ice was placed in a wind tunnel capable of sustaining airflow at 75 kilometers per hour (21 meters per second). Beach pebbles ranging in mass from 4 to 56 grams (from 3 to 52 cubic centimeters in volume) were placed on the ice sheet positioned horizontally, and at increasing slopes. The researchers noted that the uppermost surface of ice melted during the course of the tests, thus further reducing friction. Their results showed that the largest sampled pebble (52 cubic centimeters) slid up a 5 degree slope when maximum wind speeds (75 kilometers per hour) were attained. Once in motion, the pebble continued moving up a slope 5 degrees steeper with wind speeds remaining constant. Results of their study, summarized in Table 2.1, show that pebbles of similar size to those found in the Netherlands could indeed be set into motion by wind, *uphill* on an icy surface, and could remain in motion on even steeper slopes by sustained wind speeds, or on constant grades by diminishing wind speeds.

Table 2.1: Wind velocity required to initiate movement of pebbles on various grades. (After Schumm, 1956.)

Pebble	Mass (grams)	Volume (cubic cm)	Wind Speed in Kilometers per Hour		
			60	70	75
a	56	52	---	1^{o}	5^{o}
b	33	22	0.5^{o}	5^{o}	7.5^{o}
c	24	14	1^{o}	6^{o}	9^{o}
d	12	8	3^{o}	16^{o}	19^{o}
e	4	3	5^{o}	20^{o}	20^{o}

Grove and Sparks (1952) noticed that the lightest pebbles rolled and tumbled while more massive ones slid. A graph of pebble weights versus experimental wind velocities required to initiate and maintain motion is shown in Figure 2.5. Extending these plots to include much larger rocks (as are present on the Racetrack) shows that wind speeds over 300 kilometers per hour are needed to overcome the inertia of a 1-kilogram cobble on a flat, icy surface (see Figure 2.6).

In response to the lower threshold speeds measured by Shelton, the author supposed that “the downward blast of propeller wash (may have been) a more effective propelling force than winds moving essentially parallel to the surface” (Schumm, 1956) as was the case in the wind tunnel. The graph shown in Figure 2.6 suggests that 0.5 kilogram rocks can be moved only by winds exceeding 140 kilometers per hour. Yet winds of this nature, according to Schumm, are uncommon, and rocks much more massive are typical on the Racetrack. It is for these reasons that he concluded that while wind alone may explain the uphill motion of the Netherlands’ pebbles, “some other agents must be introduced to move the heavier rocks."

This model assumes that the relationship between pebble weight and threshold wind speed is linear, and that the small sample size (n=5) and fairly limited size range used in this study are representative of much larger objects. The wind tunnel used directed air horizontally, which may not mimic natural conditions, particularly when considering the terrain surrounding the Racetrack playa. And yet another factor, pore pressure within a body of mud, was neglected in favor of substituting a uniform sheet of ice as the surface medium. The theoretical consideration of subsurface pressure was the topic of another paper by Sharp, published in 1960.

2.7 W.E. Sharp, 1960

Sharp's paper derived the equations that may explain motion on a muddy surface taking into account internal fluid pressure. He defined the quantity λ which represents the

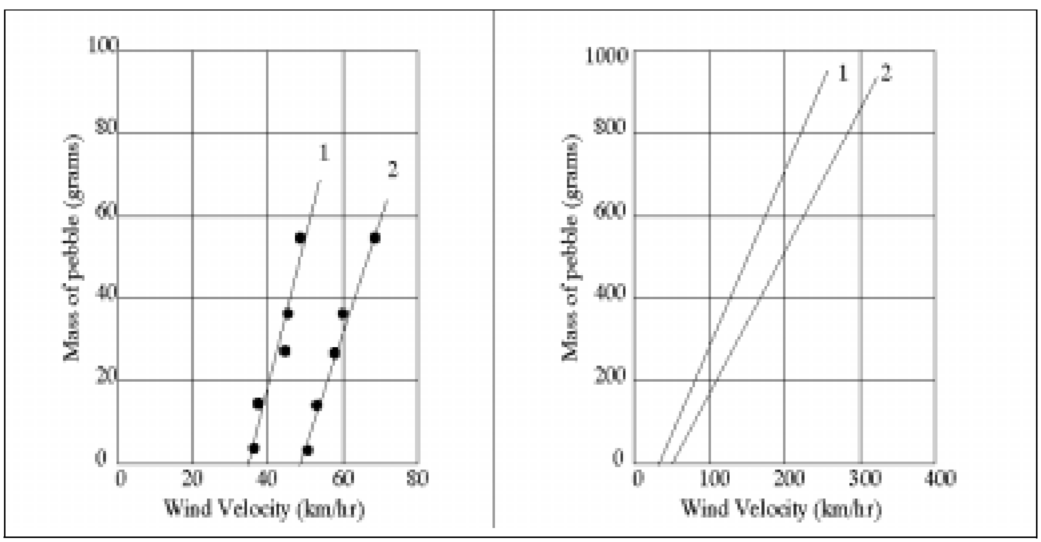


Figure 2.5 (left) shows the relationship between pebble mass and wind velocity needed to initiate movement on an icy surface (line 2), and that needed to maintain motion on an icy surface (line 1). **Figure 2.6** (right) shows an extension of the regression lines of Figure 2.5 to high wind velocities and larger sediments. Regression 1 shows wind speeds needed to maintain motion; regression 2 shows wind speeds required to initiate motion. (After Schumm, 1956.)

ratio of pore pressure to overburden pressure (i.e., the weight of the rock). This value can theoretically be equal to a maximum of 1.0, as in the case of suddenly placing any massive object on any water-saturated material (this is the principle behind the operation of an ordinary hydraulic jack). This pressure ratio decreases as water leaks from the pores under the object, hence values of 1.0 cannot be realistically maintained over time. However, the muds comprising the Racetrack surface are quite impermeable so pore-trapped fluids hardly migrate at all, maintaining a fairly high λ value.

Sharp conducted experiments at Harper Dry Lake in San Bernardino County, CA to determine realistic values for λ under natural conditions. He towed a conglomerate boulder (dimensions: 15 x 20 x 26 centimeters) in a mud-filled channel, and measured forces required to slide it with a spring balance. He noted that the surficial mud had to be no deeper than 3 centimeters since the rock tended to sink into thicker deposits, requiring forces two- or three- times greater to overcome resistance. His results yielded an experimental λ value of 0.64 for this rock sample.

The conclusions of Sharp's experiment were based on physical measurements and theoretical physics. A brief summary of the logic behind Sharp's progression follows. The frictional resistance of the rock to motion may be expressed by a variation of Coulomb's Law (Hubbert and Rubey, 1959):

$$\tau = \tau_o + (S - P)\tan\phi \qquad \textbf{Eq. 2.1}$$

where τ = shearing stress necessary for movement; τ_o = cohesion to mud; S = normal stress caused by the weight of the rock; P = pore pressure in the mud; and ϕ = angle of internal friction.

Since:

$$\lambda = \frac{P}{S} \quad \textbf{Eq. 2.2}$$

then Coulomb's Law may be expressed as:

$$\tau = \tau_o + S(1-\lambda)\tan\phi \quad \textbf{Eq. 2.3}$$

If τ_o approaches zero, then the equation reduces to:

$$\tau = S(1-\lambda)\tan\phi \quad \textbf{Eq. 2.4}$$

Both sides are multiplied by the bottom (contact) area of the rock, resulting in:

$$F_1 = mg(1-\lambda)\tan\phi \quad \textbf{Eq. 2.5}$$

where F_1 = force exerted by friction; m = mass of the rock; g = acceleration due to gravity.

The force exerted on the rock by wind is:

$$F_2 = \frac{1}{2}\rho_a V^2 C_D A_f \quad \textbf{Eq. 2.6}$$

where ρ_α = density of air; V = wind velocity; C_D = drag coefficient; A_f = frontal area of the object.

If the force of the wind equals or exceeds the force exerted by friction ($F_2 \geq F_1$), the conditions necessary for rock movement are met. Substituting into equations 2.5 and 2.6, this translates to:

$$\rho_a V^2 C_D A_f \geq 2mg(1-\lambda)\tan\phi \quad \textbf{Eq. 2.7}$$

Solving for λ:

$$\lambda \geq 1 - \left(\frac{(\rho_a C_D)}{2g(1-\lambda)\tan\phi}\right)\frac{V^2 A_f}{m} \qquad \textbf{Eq. 2.8}$$

At standard temperature and pressure, $\rho_\alpha = 0.001226$, $C_D = 1.05$ for a cube with a flat planar surface, tan $\phi = 0.404$ for dry mud, and $g = 980$ cm/sec^2. Substituting into Eq. 2.8:

$$\lambda \geq -1.63x10^{-4}\left(\frac{A_f}{m}\right)V^2 \qquad \textbf{Eq. 2.9}$$

Sharp plotted (A_f/ m) values against λ for different wind velocities, and concluded that all relationships necessary to calculate requisite rock movement on the playa were derived. Masses and dimensions of the twelve rocks sampled by Kirk (see Appendix B) were converted to *cgs* units and substituted into Sharp's derived equations. Sharp concluded that wind speeds greater than or equal to 37 meters per second would be required to move the conglomerate specimen used in his experiment on a saturated playa.

Noting that the act of placing the sample boulder into the wet channel resulted in higher measured pore pressures than those assumed common in nature, Sharp specified that measured λs for rocks decreased when they were placed on a dry surface subsequently saturated (i.e., values far less than 1.0 [λ = 0.34] resulted when the playa deposits were artificially flooded). He deduced that "even in the special case where the rock is placed on wet mud, reduction of the effective coefficient of friction of sufficient magnitude to explain the movement of the majority of skidding rocks could not be obtained."

Using actual playa deposits and calculated values of λ, the coefficient of sliding friction was estimated as ranging from 0.145 to 0.26. Theoretical wind speeds from 33 to

45 meters per second (75 to 100 miles per hour) were calculated as traction thresholds for a rock placed on an already-wet channel, and for a rock on an artificially flooded initially-dry playa, respectively. Still, Sharp concluded that “wind velocities required to move playa scrapers over surfaces of wet mud are higher than those commonly met in nature.”

2.8 Creutz, 1962

Another hypothesis totally discounted wind as a driving force. In 1962, E. Creutz argued that since “each of the rocks had its own well-determined direction of motion, and these directions are all different” wind could not be responsible for the phenomenon. He similarly dismissed the suggestion that seismic activity in the area contributed to the rocks’ movement, but proposed yet another possibility. Creutz stated that the rocks move downhill, and that the boulders respond merely to the force of gravity.

Having visited the playa, Creutz noted that many trails indicated movement away from the shore and towards the center of the dry lake. Yet some trails that he observed had acute changes in direction; in one case a rock appeared to have moved in opposite directions with a near-180° turn midway. Although this single observation may appear to contradict Creutz’s belief, he explains that “downhill” is a rather temporary and changeable direction, dependent on the water content in the playa muds. He contended that a significant component of the playa sediments is bentonite or similar swelling clay, and that after a rain storm the surface slowly rises.

Assuming that the Racetrack surface is perfectly level (contradicting the observations of Stanley [1955] and others) Creutz suggested that differential saturation of the playa muds would cause some sections to swell more than others, resulting in a distinct gradient. This thixotropic behavior is a function of the amount of wetting, and on the depth of the clay layer. According to Creutz, nearshore clays absorb more water due to the proximity of an impermeable barrier underneath, and therefore tend to rise. The resulting bowl-shaped playa surface would promote rock movement away from the encroaching alluvial fans. The dilemma of the rock that reversed direction was justified by the author as follows: “with continued rainfall the swelling of the thicker mud near the center of the lake will be greater than that of the thinner layer near the shore.” Creutz believed that with continued flooding, the central deposits rise farther, and send the rocks back towards the now-lower shore.

Creutz described “two sink holes near the southern shore of the lake, about 200 feet from its edge.” No maps were included in his report, so the exact location of these features is vague. Creutz believes that these depressions indicate outlets for water, and that they are positioned at the lowest part of the playa. He reported that many of the rocks appeared to be moving in a direction leading to those craters, and that some tracks end in them. While this supports his “gravity only” theory, it does not explain the 180° bends in some trails.

Creutz tested the effects of saturation on different depths of swelling clays in the laboratory. Using dry bentonite (although the bentonite fraction of the Racetrack is not known), he added water to varying quantities of the material packed into graduated cylinders. He found that thin layers of bentonite expand and reach maximum volume more rapidly than thick layers of the clay. This occurs because water initially fills pore spaces, and only later penetrates the crystalline layers of the mineral (which is what causes the volumetric increases). Thin layers of clay have few pore spaces that are filled rapidly; surplus water is free to assimilate into the sheet silicate in a short period of time. Longer infiltration periods are required to clog the pores of thicker clay deposits, so expansion is delayed. Another experiment showed a direct relationship between the amount of water added to bentonite and the resulting degree of swelling. Creutz concluded that “this experiment and analysis thus seem to verify the hypothesis that the swelling of mud as it absorbs moisture accounts for the rocks’ moving about the Racetrack” (Creutz, 1962).

2.9 Bradley, 1963

Harold Bradley’s first visit to the Racetrack was in April 1956 when, after several days in Death Valley, he was surprised to observe it as a lake-filled basin. Although Death Valley hadn’t received any precipitation during his stay, he remarked that the incidence of rain must be highly localized for there to have been a substantial accumulation on the playa. He explored the southern water-filled end of the Racetrack on foot, where there was as much as 4 inches (10 centimeters) of standing water; coating the sub-aqueous surface was “exceedingly slippery shallow mud on a firm base” (Bradley, 1963). The water did not seem to infiltrate the playa deposits too deeply, and Bradley was surprised when he dug a three-foot (one meter) deep hole near the water’s boundary to see that the clay was absolutely desiccated.

The ponding water was propelled by a strong southerly wind, and it formed tongues that moved uphill towards the north. The fan-like feature described by Kirk (1952) and interpreted by Stanley (1955) as the work of ice may in fact have been produced by a wind-driven migrating distributary as witnessed by Bradley. The researcher drove on the playa and found that his vehicle skidded across the progressing “fingers,” regaining traction and coming to a halt only after reaching the dry hard-baked clay beyond. His experience led him to remark that "when wet for a half inch or less (the clay) forms an effective lubricant over which small bottomed stones might slide easily if pushed in some way."

During his 1956 visit, Bradley observed several trails with no rocks present at either end. He surmised that blocks of ice, as proposed by Stanley (1955) may in fact have produced such features. However, the reports of Ranger Louis Kirk (1952) intimated that such scars were produced by rocks that had later been vandalized. In fact, Bradley described one trail with a decidedly rough appearance, as though the rock that produced it was dragged on the playa when it was dry. Another suspect trail had footprints alongside, suggesting that a rock had been dragged by people. Yet the vast majority of the trails appeared to be of natural origin; Bradley reviewed the most popular hypotheses in his paper.

He suggested that Creutz's proposal that rocks are influenced by gravity alone needed further study, citing the possible role of differential swelling of clays as valid. Yet Bradley pointed out that Creutz limited his discussion to trails heading in towards or out from the center of the playa. Stanley's (1955) detailed inventory documented many rock paths roughly parallel to the western shore; the thixotropic nature of clays could not be used to explain the existence of trails where slopes were not expected.

Bradley found merit with both the ice floe hypothesis suggested by Stanley (1955), and by the aeolian transport mechanism supported by McAllister and Agnew (1948). He pointed out that while unit motion of groups of stones was suggested by some of Stanley's plots, the presence of large numbers of independent trails implied that ice was not required for rocks to slide. In either case, the author believed that wind was ultimately “the motive power when surface conditions and wind happen to be precisely right” (Bradley, 1963).

2.10 Sharp and Carey, 1976

An extensive survey of the Racetrack’s sliding rock activity was conducted over a span of seven years by Robert P. Sharp and Dwight L. Carey. Visiting the playa on sixteen occasions from May 1968 until May 1975, the duo monitored the progress of thirty labeled rocks by fixing their positions with respect to steel stakes driven into the clay surface. When rocks moved from their original referenced positions, new stakes were buried alongside. Of the thirty rocks sampled, twenty eight moved on at least one occasion during this lengthy investigation.

This was the first such long-term approach used by a research team, and the information gleaned over time far surpassed that of any single previous study in quality and quantity. Although Sharp and Carey never actually witnessed any rocks in motion, having a baseline for comparison to previously-made measurements allowed them to infer periods of greatest activity. They found that events were episodic; greatest activity occurred during the winters of 1968-1969, 1972-1973, and 1973-1974 (Sharp and Carey, 1976). Still, some rocks moved in none of these events, while others moved in one, two or all three.

Rocks sampled were spatially distributed over the southern end of the playa (see Figure 2.7), and they represented the variation in lithology, shape and volume of specimens common to the Racetrack (see Appendix C). Rocks were marked, assigned letters and names, after one syenite specimen produced a “beautiful trail” between visits early in the study. Sharp and Carey named the rock that had produced this 64-meter track “Mary Ann” after the wife of a friend. The tradition continued, and each rock in their survey was ultimately designated by a woman’s name.

The two men produced trail maps using Brunton compass headings and by pacing the rocks’ routes. The authors cited Donald W. Carney, a ranger at the time, who correlated rock movement episodes with contemporaneous meteorological events. For example, while visiting the playa on February 28, 1969, Carney noted several new trails; a significant winter storm took place on January 14 of that year, so he concluded that activity must have followed that rain. More precipitation fell on March 8 and, Carney noted during his next visit on March 17, the same rocks had moved again.

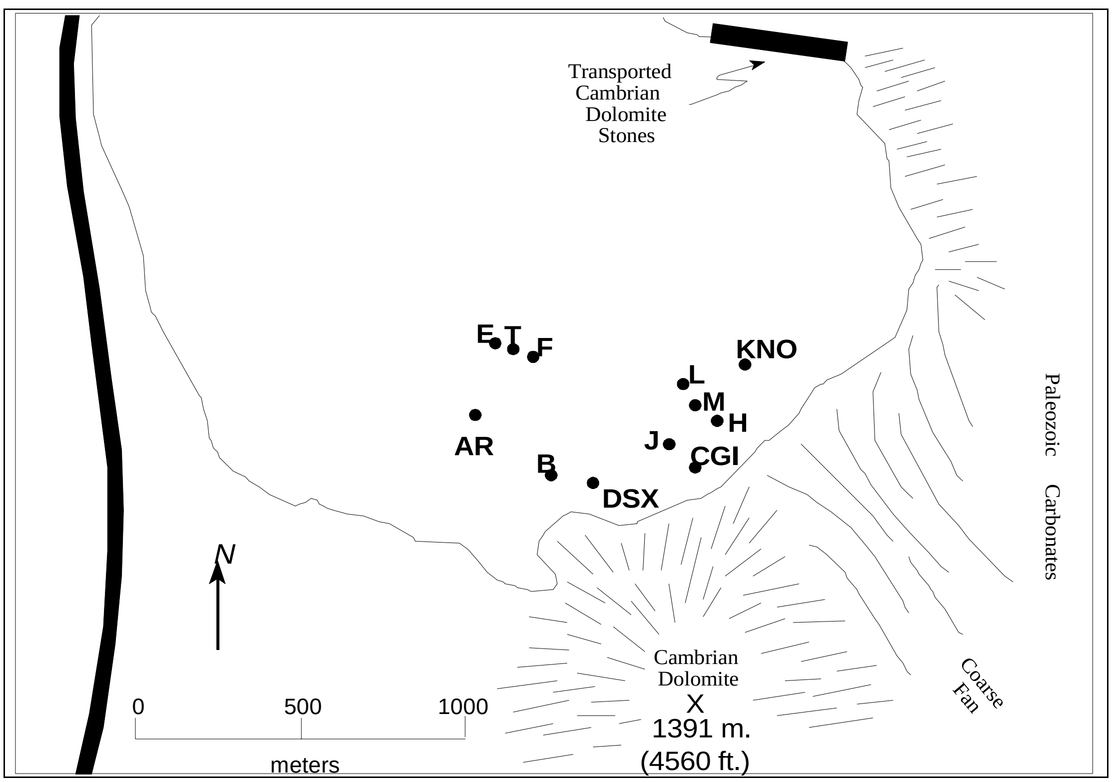


Figure 2.7: Approximate locations of labeled stones in Sharp & Carey’s study. Letters refer to individual stones, or the rock clusters described by Table C1, Appendix C (page 248). (After Sharp and Carey, 1976.)

Rock movement was not limited to major events since a few stones (E, “Peggy” and R, “Hortense”) made trails when no other rocks did during the winter of 1970-1971. The frequency and timing of his visits that fall helped Carney conclude that these isolated rock movements took place on or about December 2, 1971, three days after a heavy rain on November 29.

The longest single-event trail carved during the seven-year period was 201 meters, and the greatest cumulative movement was 262.3 meters; both distinctions are held by a small irregular cobble (H, “Nancy”). Appendix C details the extent of trails produced during the survey period.

The direction of movement was predominantly from southwest to northeast during this period, with each trail displaying its own share of deflection from net heading (see Figure 2.8). An aberration of as much as 63^{o} was noted for one segment within an other-wise ordinary northeast-heading trail (R, “Hortense”). Sharp and Carey linked the relative straightness of furrows to the basal configuration of the rocks causing them. They con-tended that angular rocks produced the most regular paths, while smooth or rounded rocks tended to wander erratically.

Clusters of rocks in the groups labeled D, G and C showed significant departures from the general northeasterly trend, and members of the K, L, M, N and O groups experi-enced 90^{o} clockwise deviation from the norm in 1972-1973, resulting in southeast-head-ings. Figure 2.7 shows the locations of these rocks closest to the playa boundary. Unusual deflections in these localities “possibly reflect a perturbation of the wind pattern by the south shore bedrock ridge” (Sharp and Carey, 1976).

Single stones were reported to have displayed contrary motion to that of nearby

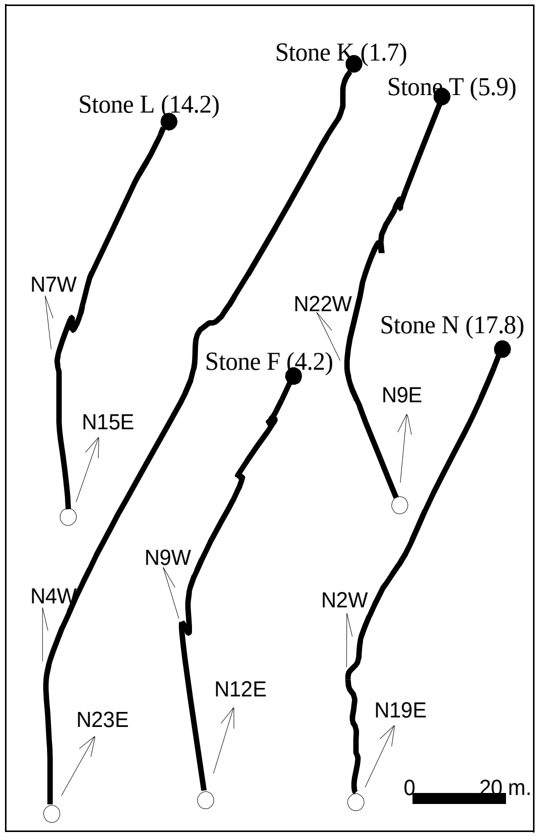


Figure 2.8: Plan of trails produced by rocks between January 14 and March 17, 1969. Masses of some rocks (in kilograms) appear in parentheses. Single barb arrow shows initial movement direction; double barb arrow shows net heading. Maximum separation between tracks is about 600 meters. Note the general northeasterly heading and individual variations within this trend. (After Sharp and Carey, 1976.)

rocks during the same movement episode. For example, Sharp and Carey cited stone I ("Kristy") which moved north for 50 meters, and then back towards the south-southwest an additional 55 meters, coming to rest only 20 meters from its original starting point. The event in which this erratic behavior took place was in 1973-1974 when 23 of the 30 monitored rocks moved in a northeasterly direction (see Appendix C).

The highly independent behavior of the thirty monitored rocks is inconsistent with the ice floe theory discussed by Stanley (1955), yet Sharp and Carey described evidence of freezing conditions on the playa. Striated swath marks across the mud cracks were interpreted as the results of ice sheets scraping against the playa surface, and the researchers also noted that ice molds were preserved in the fine-grained sediments. Sharp and Carey designed an experiment to test the hypothesis that ice sheets play a role in rock movement.

Steel stakes were arranged in a 168 centimeter circle known as "the corral" (see Figure 2.9). Several rocks were placed into the space defined by the stakes, and their positions were monitored. On two occasions, a rock slid out of the corral, leaving the others behind, and creating a trail beyond the boundary defined by the stakes. Sharp and Carey noted that when stone XX moved in 1973-1974, another rock of similar character remained undisturbed. If ice sheets propelled rocks as a unit mass, this observation could not be explained. In fact, the stakes themselves would cause ice to fracture, implying that none of the rocks in the corral should have moved if ice provides the only vehicle for activity. Besides this set-up, natural concentrations of stones on the open playa floor exhibited nonuniform behavior, which suggested that ice is not a significant factor.

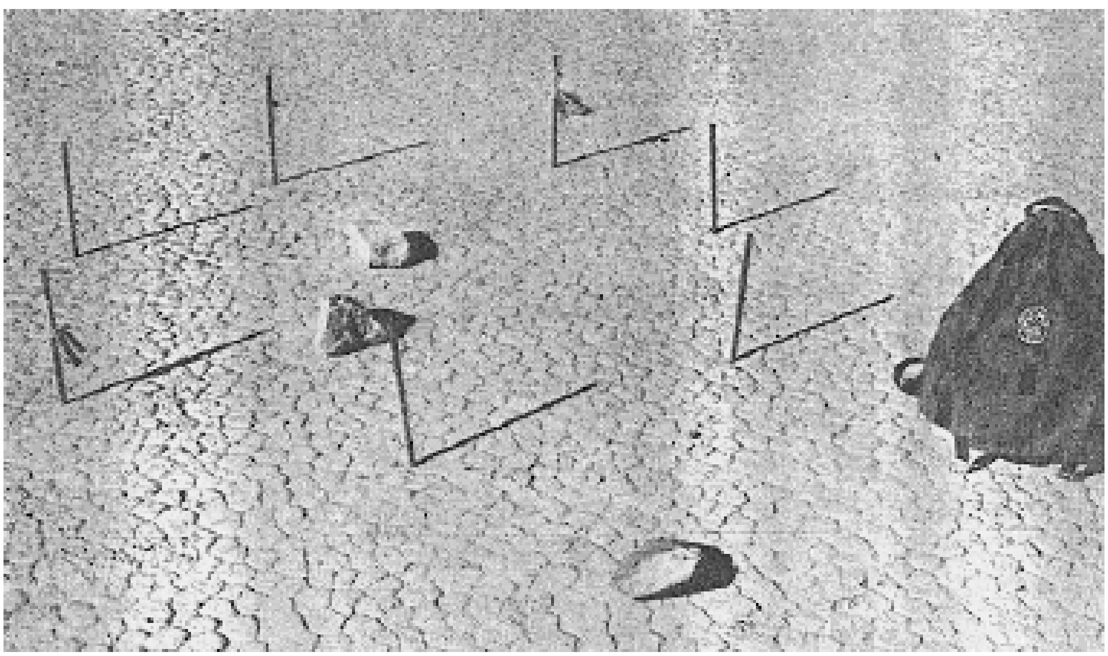


Figure 2.9: The "corral," constructed by Sharp and Carey contained several rocks, only some of which slid out. (From Sharp and Carey, 1976.)

Based on the results of this monitoring arrangement, Sharp and Carey concluded that “stones are individually skidded and rolled along a wetted surface of Racetrack Playa by wind, in spite of calculations (by W.E. Sharp, 1960) and comparisons (of Schumm, 1956) suggesting that this is unlikely because of the unreasonably high wind velocities seemingly required” (Sharp and Carey, 1976). The incidence of diverging, converging and crossing trail configurations (see Figure 2.10) inscribed during inferred solitary events implies that rocks are forced by wind alone when the physical nature of the playa surface meets a set of prescribed conditions. While Stanley suggested that non-parallel trails may result from ice floe break-up, Sharp and Carey recommended an alternative explanation.

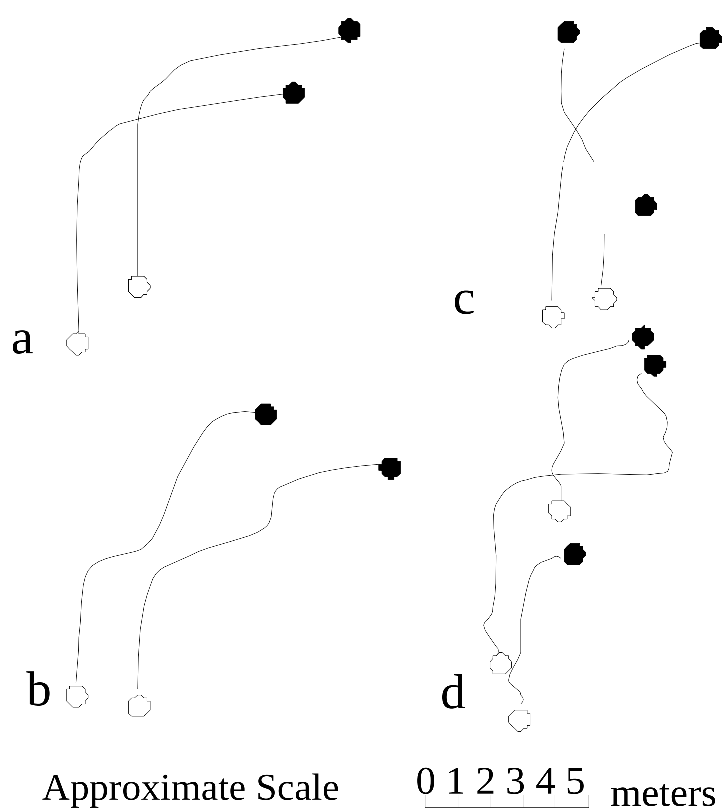


Figure 2.10: Diagrammatic sketches of field relationships of small stone contemporaneous tracks. Closed circles indicate the terminal positions of the rocks; open circles mark origins. (After Sharp and Carey, 1976.)

Were the playa saturated so that a thin slimy film formed on the surface collecting between desiccation polygons, this fine clay veneer may provide an almost frictionless surface on which rocks can move under natural wind conditions. They added that rock movement takes place some time following flooding events, after the settling of the finest clays out of suspension. Sharp and Carey argued that earlier experiments conducted by Shelton (1953) did not allow for the formation of this fine clay film; since experimental conditions did not adequately imitate natural processes, Shelton's results may have over-estimated the force of wind necessary to move rocks. Furthermore, based on observations of trail morphology, Sharp and Carey estimated that rocks may slide at a speed approaching 1 meter per second during major rock moving episodes. This contrasts Shelton's observations of the "hesitating and slow" movement of his experimental cobble (Shelton, 1953), not to mention the almost imperceptibly sluggish progress predicted by Creutz (1962). Despite the convincing arguments offered by the valuable contributions of Sharp and Carey, the possibility that wind alone may cause this phenomenon continues to be debated.

2.11 Reid et al., 1995

A team of researchers headed by John B. Reid published the results of observations made during seven visits from 1987 to 1994. To test the previously proposed hypotheses, the group mapped widely spaced tracks into a precise coordinate system with an electronic theodolite. They also conducted direct measurements of forces required to slide a representative boulder on an artificially wetted surface. Their results provided strong evidence in favor of the formation of ice rafts as a precondition for rock movement.

Reid and a group his of students plotted "a large number of widely spaced tracks" following episodes of motion in the 1980s and early 1990s. Distances between the trails surveyed was as great as 500 meters. Translating the trails to the same start point (0,0) they found a striking congruence between them despite wide distances separating them (see Figures 2.11 and 2.12).

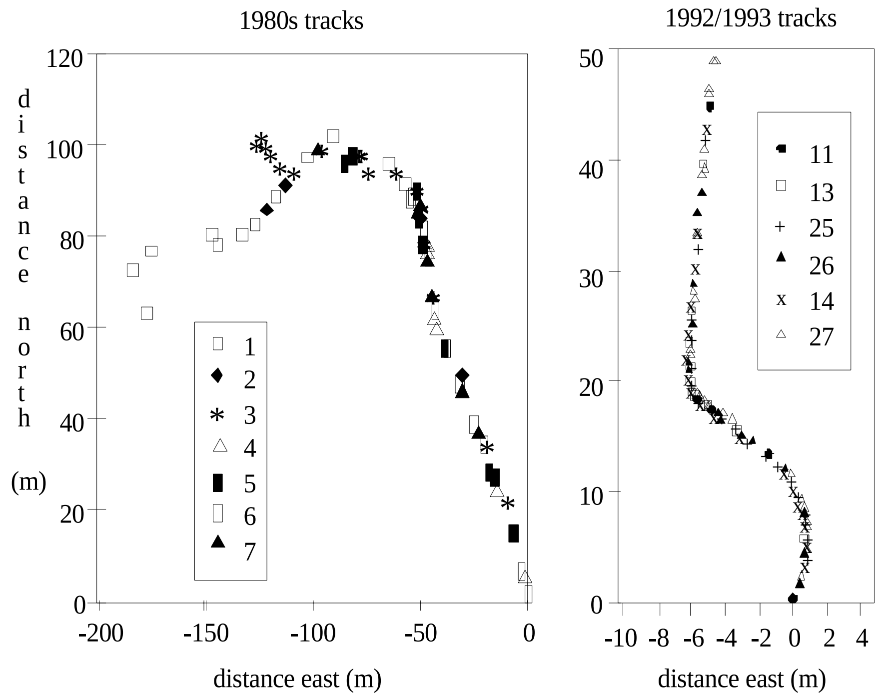
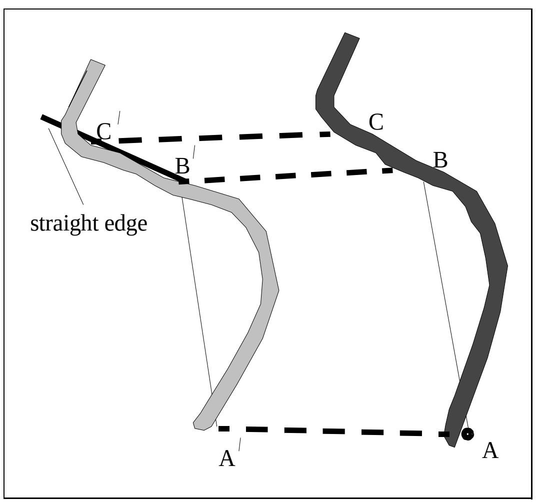


Figure 2.11 (left): Seven tracks mapped in the 1980s normalized to 0,0 show remarkable congruence initially, with later divergence. **Figure 2.12 (right):** shows six trails plotted after a 1992-1993 episode. Numbers and symbols in the insets of each graph represent rock identifiers. (After Reid, et al., 1995).

Initial parallelism was sometimes followed by ultimate divergence (Figure 2.11), and was explained by the researchers as the result of ice floe disintegration. The 1993 survey resulted in dramatic intertrack correlations between 23 mapped trails (Figures 2.13 and 2.14).

Reid et al. used the outstanding results of their surveys to bolster the idea that ice is an essential component of the rare playa processes. They addressed the results of Sharp and Carey's (1976) corral experiment which appeared to categorically oppose the ice sheet hypothesis. "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" (Reid, et al., 1995).

Further substantiation was added when the results of a friction measurement yielded a surprisingly high value. The group surrounded a 12-kilogram angular dolomite fragment by wooden slabs, flooding the area with water. Two hours afterwards, the muds were saturated to a depth of 3 centimeters. Dislodging the rock required a force about equal to the rock's weight (*w*), but motion was sustained by forces as low as 0.6 *w*. Based on these spring balance measurements, it was estimated that the coefficient of kinetic friction (μ) for this rock on this artificially wet surface was 0.8. This value seems inordinately high, but was defended as a direct result of the irregular rock fabric of the specimen. To contrast, the coefficient of friction for bare feet on the flooded playa surface is estimated at 0.1 (Reid et al., 1995), which is about the same as that for ice on ice (Bacon, Cahill and Tombrello, 1996). These estimates suggest that the small percentage of smoother, more-



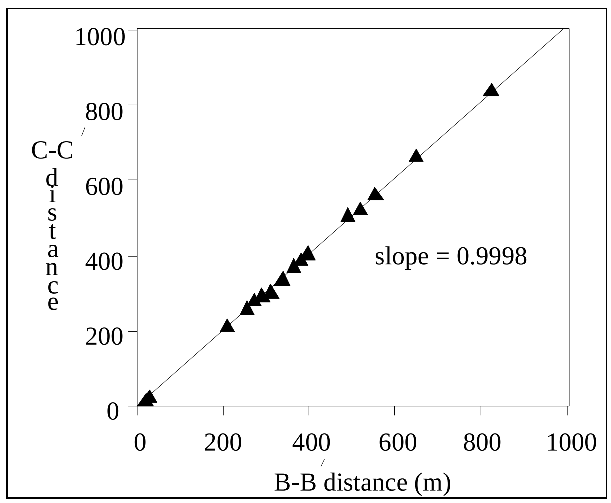


Figure 2.13 (left)**:** A schematic representation of actual intertrack and intratrack distances. A six-meter straight edge was used to locate common tangent points, B and C, of gently curving tracks. **Figure 2.14** (right)**:** Comparison of intratrack distances for 23 trails in 1992-93 computed as shown in Figure 2.13. Trails were separated by up to 300 meters, and yet the absolute measured difference between B-B' and C-C' values is 6.4 ± 5.6 cm. Regression line shows a very high degree of correlation. (Reid, et al., 1995.)

rounded rocks move more frequently, yet none of the surveys found this to be true. Reid et al., used this revelation to promote the ice floe hypothesis as well.

It should be noted that this method of artificial saturation was questioned by Sharp and Carey twenty years before when reviewing the work of Shelton (1953). As with the earlier experiment, Reid et al. did not account for the formation of a thin film of the smallest clay fraction, which would expectedly settle out of standing water over time. The expediency of measurements made by Shelton (1953) and Reid et al. (1995) may be to blame for the unusually resistant surface conditions reported.

2.12 Bacon, Cahill and Tombrello, 1996

Cahill et al. (1994), conducted field measurements of winds at Owens Lake, 80 kilometers southwest of the Racetrack. On the basis of these surveys, it was found that gusts of up to 40 meters per second were common occurrences at this locality. Furthermore, the extreme flatness of the terrain and smoothness of the dry lake surface results in a vertical compression of the atmospheric boundary layer (see Figure 2.15).

While maximum wind speeds over land surfaces are typically encountered approximately 1 meter above ground, the velocity gradient for flat playas is quite steep and vertically shallow. Bacon, Cahill and Tombrello reported that wind velocity 4 centimeters from the ground at Owens Lake was still 90% of wind speed measured 1 meter above the surface. They related these observations to the wind tunnel experiments reported by Schumm (1956), and noted that the pebbles tested were so small (i.e., they did not protrude up into the airflow substantially) that they could not be used as analogs to much larger rocks. Cobbles and boulders would be subjected to far greater forces, since they

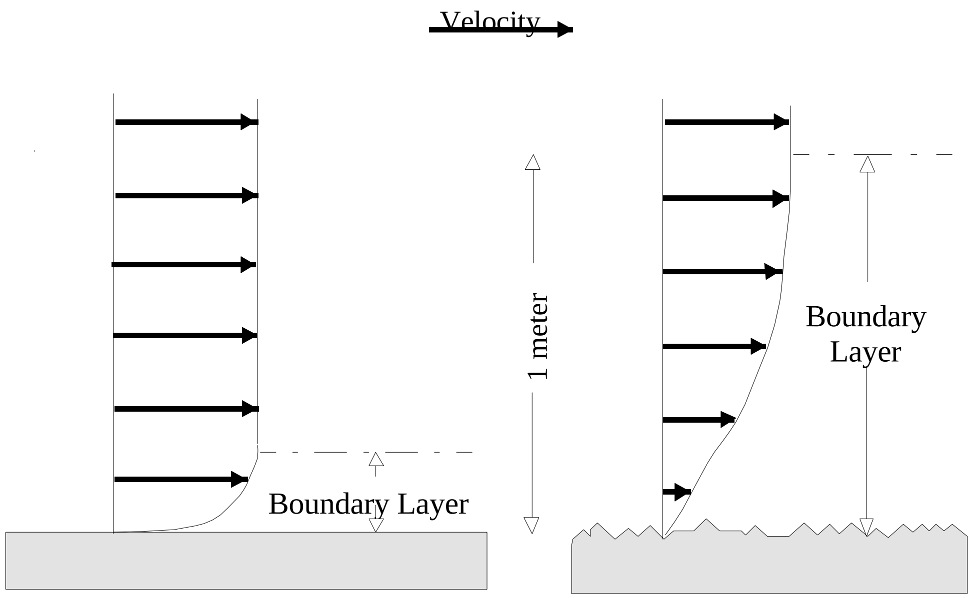


Figure 2.15: The velocity profile of wind above the ground is influenced by surface roughness of the terrain. As wind flows over flat, smooth surfaces such as Owens Lake and Racetrack Playa, maximum wind speeds are encountered only a few centimeters above the ground (left). Rough terrain promotes friction, increasing the height of the atmospheric boundary layer (right). (After Bacon, Cahill and Tombrello, 1996.)

extend higher into the vertical zone of maximum wind speeds.

Bacon, Cahill and Tombrello derived mathematical proofs to find the expression of force required to move an idealized rectangular rock:

$$F_D = \frac{1}{2} C p V^2 A_f \qquad \textbf{Eq. 2.10}$$

where C is the drag coefficient, A is the area of a cross-section of a rock, and p is the density of air (≈ 1.29 kg/m^3). Note the equivalent formula as cited by W.E. Sharp (1960) (Eq. 2.6, page 36).

Bacon, Cahill and Tombrello (1996) explained that the drag coefficient C is a function of the shape of the rock; the value can be as low as 0.5 for highly rounded and smooth stones, to slightly greater than 1.0 for blocky, rectangular rocks. The frictional force may be calculated by:

$$F_f = smg \qquad \textbf{Eq. 2.11}$$

where s is the coefficient of static friction, m is the mass of the rock and g is the acceleration due to gravity. The frictional force must be less than the drag force for a rock to move. When the forces are equal ($F_D = F_f$), the coefficient of static friction may be computed by combining Equations 2.10 and 2.11.

$$S_T = \frac{1}{2}\frac{(CpV^2A_f)}{mg} \qquad \textbf{Eq. 2.12}$$

Instead of solving for wind velocity (as was done by Shelton [1953], and Schumm [1956]) Bacon, Cahill and Tombrello, who had already established an estimate for probable wind speeds on the Racetrack substituted those values encountered on Owens Lake for (V = 40 meters per second) in Equation 2.12. They solved, instead, for the coefficient of static friction for selected rocks. The data they used were taken directly from Sharp and Carey (1976) (Appendix C).

The value for the cross-sectional area of Sharp and Carey's rocks was taken to be the mean, since rock orientation and wind direction would alter this quantity. This was computed as follows:

$$A_f = h\sqrt{lw} \qquad \textbf{Eq. 2.13}$$

Substituting 0.8 for C (this is a mean value considering the variation in rock shapes) in

Equation 2.12, the team computed the threshold coefficient of friction (μ)for all rocks monitored by Sharp and Carey assuming wind forces of 80% of V (for rocks with low vertical profiles), and 100% V assuming extension up beyond the atmospheric boundary layer. The results of their calculations appear in Appendix D. When only 80% of the upper air velocity is considered, the mean coefficient of static friction for Sharp and Carey's rocks is 0.27; assuming the full force of wind, the average coefficient of static friction for this same subset is 0.42 (Bacon, Cahill and Tombrello, 1996). W.E. Sharp (1960) concluded that sliding friction values for rocks on a wet playa surface were from 0.145 to 0.26 (see page 37); since threshold coefficients are typically double the dynamic values of μ, the work of Bacon, Cahill and Tombrello is consistent with that of the earlier work, although their conclusions are not the same.

It is the opinion of Bacon, Cahill and Tombrello that a combination of high observed wind shear, compressed boundary layer and the likelihood of a slimy lubricant forming on the playa several hours to several days after a wetting event is enough to explain the sliding rock phenomena on the Racetrack.

2.13 Sharp and Carey versus Reid, Polissar and Williams, 1996

The wind vs. ice theories continue to be debated. A comment and reply were published in *Geology* with summary conclusions of each research team's (Sharp and Carey [1976], Reid et al., [1995]) investigations.

Much of what was written in these short papers reiterates earlier conclusions, yet they considered the more recent work by Cahill (1994) and Bacon, Cahill and Tombrello (1996). While Robert Sharp's comment that ice *may* transport rocks on occasion, but is not a requisite condition for stones to move, John Reid's reply is less flexible. Taking the work of Bacon, Cahill and Tombrello (1996) into account, Reid et al. measured the wind profile on nearby North Panamint Playa and found no such collapse of the boundary layer. Wind speeds at a height of 5 centimeters were 50% of those at 1.5 meters. Reid et al. therefore maintained their earlier position in support of ice sheets.

Hence the conflicts continue. Even now, nearly a half century from the first detailed study, no one has been present to witness an event. Since no definitive spatial data existed for the playa (until this research), no complete baseline map of trails and rock positions had yet been published. The remote location or the Racetrack and the inhospitable conditions that must exist there during storms have been successful in keeping the motive mechanism a mystery.