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Q16 Supporting on-line material Table 1: GPS coordinates of rocks and trail ends: R = rock, IN = in the artificial trench, n = no trail recorded, T = recorded trail, C = complex, E = edge of playa, H = mud pile present, M = multiple, I = ice related.Supporting on-line material Table 2: GPS coordinates of possible spring systems identified on Racetrack playa. There are three groups: Spinal, Edge, and Gindarja.Supporting on-line material Table 3: GPS coordinates of artificial trench breaches (see Fig. 1). IN = breach from playa side. OUT = breach from the road side.

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Sliding stones of Racetrack Playa, Death Valley, USA: The roles of rock thermal conductivity and fluctuating water levels

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ABSTRACT

On occasion, Racetrack playa in Death Valley National Park becomes flooded and temperatures then drop appreciably below freezing. The thermal conductivity of rock is greater than that of water, so heat is conducted from a partially-submerged rock faster than from water. Consequently, a collar of thicker ice forms at the water surface, a layer of ice forms on more deeply-submerged parts of the rock, and playa sediment beneath the rock may even become frozen to it. While this occurs, only a surface layer of ice forms on water away from the rock. Once the ice becomes thick enough, perhaps only 5–10 mm, either the buoyancy of the ice or additions of water to the playa by rain, snow-melt, or groundwater seepage then reduce the normal force between the rock and the playa to the point where wind shear can move the ice sheet with its entrained rocks, making trails (Stanley, 1955; Reid et al., 1995). After the ice melts, rocks are left at the ends of the trails, sometimes atop a pedestal of silt. A renewed increase in water level on the playa before the ice melts may lift a rock completely free of the playa surface and whisk it away, leaving a rockless trail. Changes, during a movement event, in rock orientation or water depth may result in along-track changes in width. Rock speeds are likely tens to hundreds of millimeters per second. Q5

1. Introduction

Racetrack playa, a 6.6 km^2 endorheic lake at an elevation of 1132 m, is located in Death Valley National Park in southern California (Fig. 1). A 196 km^2 catchment area drains to it. The playa surface is nearly level; measurements by Sharp and Carey (1976) under windless conditions when the playa was completely flooded show that the north end is ~50 mm higher than the south end. The playa sediment consists of fine sand (24%), silt (41%), and clay (35%) (Sharp and Carey, 1976). When dry, the playa surface is covered with polygonal cracks, and littered with cobbles and boulders up to 0.5 m in mean dimension. The rocks are commonly at the ends of shallow trails, perhaps first described by McAllister and Agnew (Sharp and Carey, 1976). Similar trails have been observed on other playas in southwestern USA (Clemens, 1952; Sharp and Carey, 1976; Wehmeier, 1986) as well as in South Africa (Eriksson et al., 1996).

Theories that attempt to explain the trails on Racetrack playa appeal to wind (Mcallister and Agnew, 1948), wind coupled with ice (Stanley, 1955; Reid et al., 1995; Lorenz et al., 2010), hydration-induced swelling (Creutz, 1962), seismic vibrations, and slimy algal under-coatings (Messina, 1988; Messina and Stoffer, 2000). The universal requirement of all hypotheses is the presence of water on the playa (Lorenz et al., 2010). Theoretical analyses and experiments have shown that gusts of wind across a wet, slippery playa surface both could (Bacon et al., 1996) and could not [rocks would rather tumble (Sharp, 1960)] slide rocks like those on the playa.

On some occasions, several rocks have left nearly parallel trails, or trails that turn together around an axis. This has been interpreted as indicating that multiple rocks were moved at the same time while locked in ice (Stanley, 1955). Temperatures fall below freezing during the winter, allowing water on Racetrack playa to freeze (Sharp, 1960; Sharp and Carey, 1976; Lorenz et al., 2010). Such ice has been observed by Stanley (1955) and by Lorenz et al. (2010), the latter through time lapse photography. The event that Lorenz et al. observed occurred when a rare winter snowfall melted and supplied water, which then ran off to the playa and refroze.

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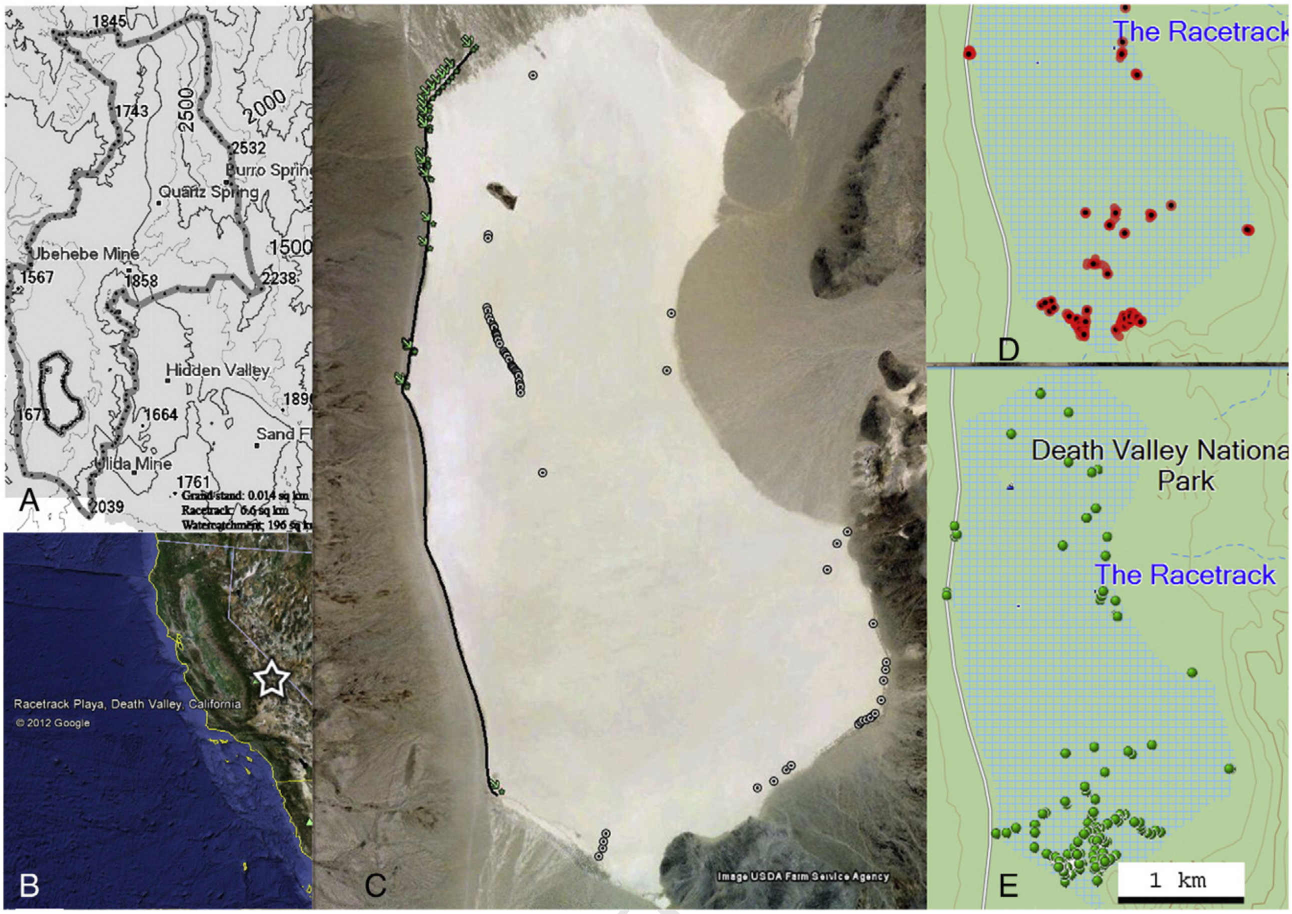

Q2 **Fig. 1.** Racetrack playa: satellite images downloaded from Google Earth (© 2012 Google) on November 17, 2009. Topographic maps are from Garmin Inc. A. Area draining to Racetrack playa. B. Location of Racetrack playa in southwestern United States. C. Google image of the playa, showing also drainage pathways on alluvial fans bordering the playa. = conical depression. Black line is artificial trench with breaches indicated with green symbols. D. Locations of trails that we studied. E. Other rocks and trail ends on the playa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Herein we adopt the ice model and make three contributions to it: (*i*) through numerical modeling, using the finite element method, we show that the temperature distribution in a partially-submerged rock, surrounded by ice, and cooled by conduction from the air–rock interface leads to a collar of thicker stronger ice around the rock, thus facilitating lifting, (*ii*) playa sediment beneath the rock may become frozen to it although the surrounding playa surface remains thawed, and (*iii*) after an initial ice layer has formed, additional water draining into the playa as surface or groundwater can lift the ice and rocks, facilitating movement and explaining both piles of playa sediment at the ends of trails and trails without rocks at their ends (Kletetschka and Kawasumiova, 2011).

2. Field work

Our field work focused on mapping trails, rocks, and other features of the playa surface. We paid particular attention to morphological details of the tracks and of the deposits (including the rocks) at their ends. We outlined several trails with colored pushpins, photographed the trails, and measured their widths every 120 mm. To capture the general rock distribution throughout the playa, we mapped the locations of 148 rocks (see Supporting on-line material Table 1) with the use of a Garmin GPS receiver (GPSMAP®). We also mapped wet conical holes in the playa surface and breaches in an artificial levee along one side of the playa (Fig. 1D).

To measure temperature and humidity in the playa silt, we inserted hygrochron sensors in a small hole in the central southern section of the playa on March 13, 2010. Sensors were placed at depths of 2, 10, 20, and 30 cm beneath a dolomitic rock that had left a clear trail (see Supporting on-line material Table 1). Data loggers were programmed to record temperature and relative humidity once every hour (Fig. 2). The loggers and sensors were retrieved on April 6, 2011.

3. Laboratory and numerical experiments

In the laboratory, ice was formed on the surface of a “lake” in which a small granite clast was submerged. Water was then added to observe its effect on the ice–clast–water–sediment system. Numerical experiments consisted of using finite element modeling software (FEMM 4.2) to calculate the extent of ice formation near rocks on the playa and the potential for freezing playa sediment to the base of the rock.

4. Field observations

Trails commonly ended in “an inconspicuous low broad pile” of playa sediment (McAllister and Agnew, 1948). We observed piles that were 0.1 to 0.6 m in diameter and 10 to 40 mm high. The texture of the piles differed from that of the normal playa surface (Fig. 3), perhaps due to different drying conditions. Desiccation fractures penetrated the piles; in some cases the resulting tiles differed from the surrounding playa mosaic in size and shape. Several piles contained rock or plant fragments or insect parts, up to 30 mm across. Several also contained thin clay curls, 1–3 mm across. Some of this foreign material is likely windblown. In some instances, rocks were

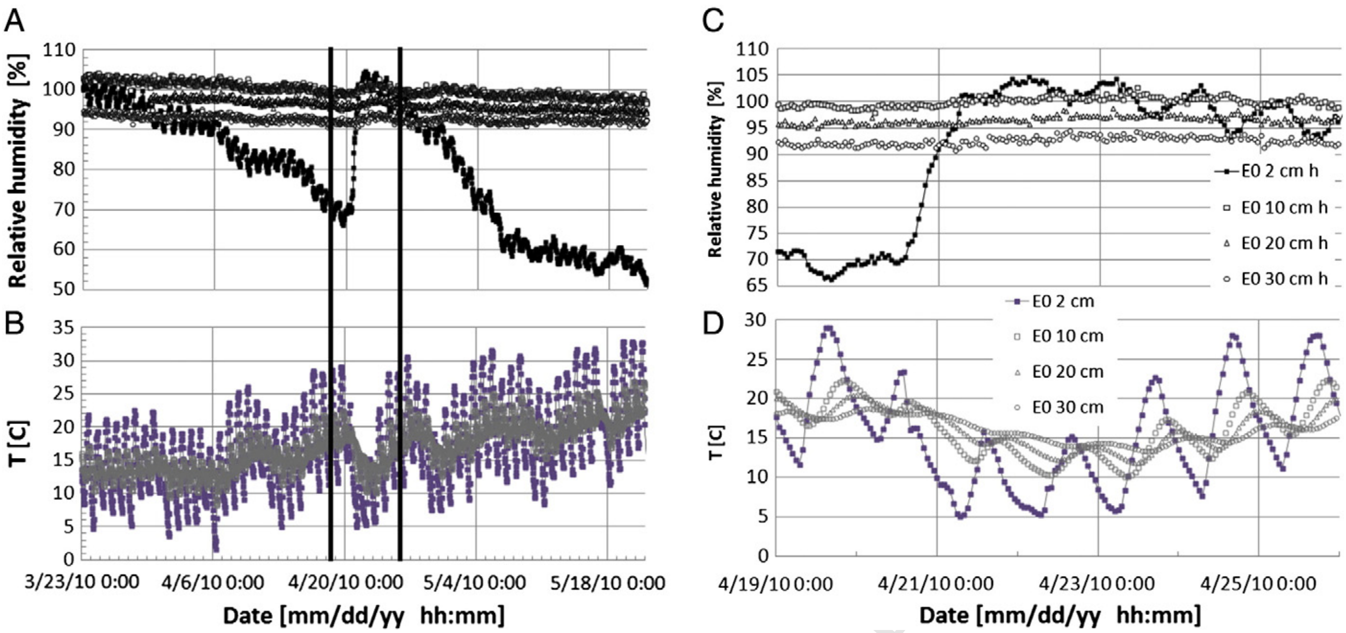

Fig. 2. A two month segment of the data logger record showing relative humidities and temperatures is shown on the left. The segment of the record between two black lines is enlarged on the right. Sensor depths are shown. Sensors were beneath a 7 kg dolomite rock.

perched on top of the pile, while in others no rocks were present, although an impression of a rock might be (Lorenz et al., 2011). Trails commonly extended 150 to 300 mm beyond the rocks at their ends (Figs. 3E and 7E).

Some trails in the central and the south-central part of the playa widen in the direction of rock movement (Fig. 3). Widening occurred on trails which ended at a rock and on trails that didn't (Fig. 3E). There were cases in which the width of the trail was significantly larger than the rock itself. Sharp and Carey (1976, pp. 1708) noted that track widths may vary by as much as 40% and attributed this to rotation of the stone while in transit, thus placing "different basal dimensions orthogonal to the direction of movement." They do not, however, report either systematic widening or widths that exceed the maximum dimension of the stone tool.

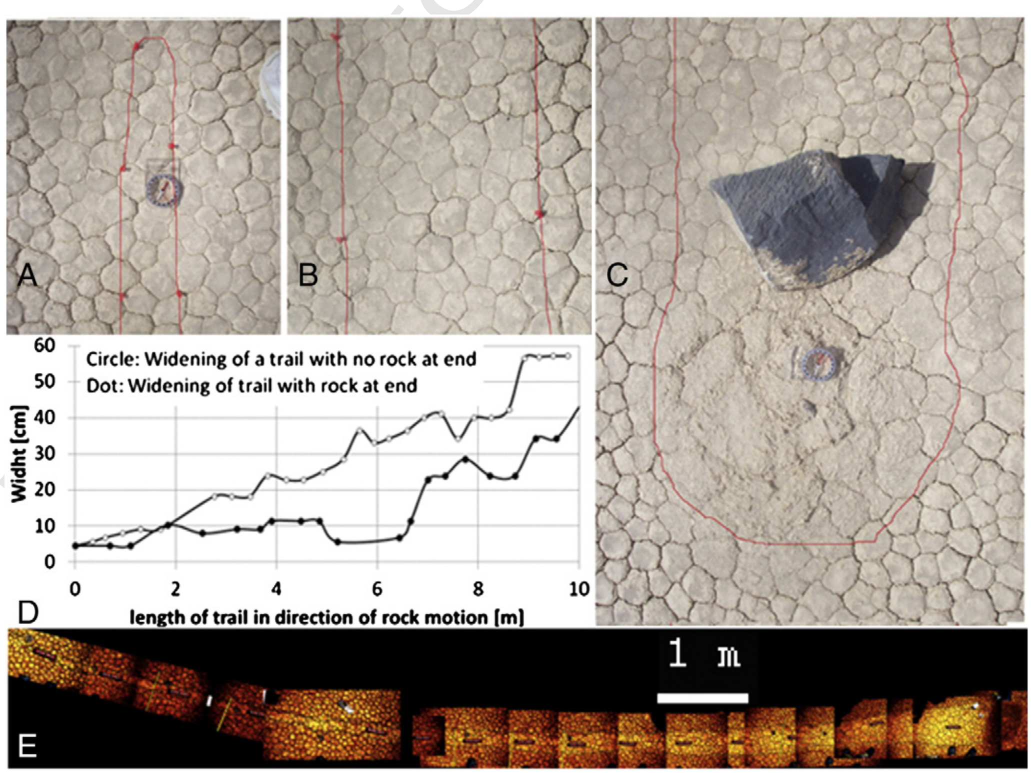

Fig. 3. Widening of trails in the direction of rock motion. A, B, and C are a sequence along a trail that has a rock at its end. The trail is narrower than the rock in A, about the same width as the rock in B, and wider than the rock in C. D: Measurements of the widths of the trails in A–C and E versus distance along the trail. E: Successive images of a trail which does not have a rock at its end. Inferred direction of motion is from left to right, the direction in which the trail widens.

A number of roughly conical depressions in the playa surface, some as deep as 0.3 m (Fig. 4), were mapped. The depressions occur in three alignments (Fig. 1 and Supporting on-line material Table 3). The first, herein named Spinal Springs, is in the central part of the playa. It is 550 m long and starts, at its northern end, with conical depressions only a few centimeters deep. Traced southward the depressions increase to ~5 m in width with scattered creosote shrubs. They then narrow and become shallower again, and finally disappear. Further north and south along this linear formation, there were several other depressions that may be a continuation of the Spinal Springs alignment. The second aligned sequence, Edge Springs, is along the southeastern edge of the playa. The alignment parallels the toes of alluvial fans along the base of the steep mountain range. The third sequence, Gindarja Springs, consists of three large indentations aligned in a northwesterly direction. Two are completely within the playa and the third is on the edge. All three are associated with significant vegetation (Fig. 4).

The main park road crossed the playa surface until 1969, when a new road was established west of the playa (Pronovost, 2011). Included in this construction was a 4.0 km long, steep-sided trench along the playa margin, designed to prevent off-road travel. Management of this trench ceased in 2000. Breaches have formed in several locations where water entered the trench from one side or the other (Supporting on-line material Table 3 and Fig. 1). These breaches increase in frequency northwards, where the playa is shallower and where gullies have formed, extending several tens of meters out onto the playa surface.

5. Data from temperature sensors

Temperature and humidity records from the hygrochron sensors are shown in Fig. 2. The temperature recorded by the sensor at 20 mm depth appears to have followed the atmospheric temperature (not measured) as expected. For every 100 mm increase in depth below 20 mm, the amplitude decreases ~50% and the lag increases ~4 h.

We used these data to estimate the thermal diffusivity, κ, of the playa sediment for subsequent use in our numerical modeling experiments (Table 1). The variation of temperature with depth in an infinite half space, the surface of which is subjected to a temperature that varies sinusoidally with time is given by (Carslaw and Jaeger, 1959): Q6

$$\theta(z,t) = \overline{\theta} + \frac{\theta_r}{2} e^{-z\sqrt{\frac{\omega}{2\kappa}}} \sin\left(\omega t - z\sqrt{\frac{\omega}{2\kappa}}\right) \quad (1)$$

where θ is temperature, z is depth, t is time, $\overline{\theta}$ is the mean temperature, θ_r is the temperature range, and ω is the period of the oscillation (2π radians per day or 0.0000727 rad/s in our case). We know θ as a function of time at different depths, z. Focusing on the measured temperature maxima and minima, we take the derivative with respect to time:

$$\frac{\partial\theta}{\partial t} = \omega \frac{\theta_r}{2} e^{-z\sqrt{\frac{\omega}{2\kappa}}} \cos\left(\omega t - z\sqrt{\frac{\omega}{2\kappa}}\right) \quad (2)$$

which has maxima and minima at $\left(\omega t - z\sqrt{\frac{\omega}{2\kappa}}\right) = \pm\frac{\pi}{2}$. To express this in terms of the time lag between a temperature maximum or minimum at the surface and the corresponding maximum or minimum at depth Δz, we solve for t and take the derivative with respect to z, thus: $\frac{dt}{dz} = \sqrt{\frac{1}{2\omega\kappa}}$, or in finite difference form: $\frac{\Delta t}{\Delta z} = \sqrt{\frac{1}{2\omega\kappa}}$. Solving for κ then yields: $\kappa = \frac{(\Delta z)^2}{2\omega(\Delta t)^2}$.

From Fig. 2, a typical time lag between the temperature peak at 20 mm depth and that at 300 mm is 10 h or 36,000 s, yielding $\kappa = 0.42$ mm^2/s. This is comparable to other measurements of thermal diffusivities of soils (e.g. Parikh et al., 1979). Q7

6. Numerical modeling experiments

The finite element model was a steady state 2-D model of a rock embedded 20 mm in sediment and partially submerged in water, the surface of which was frozen. The software we used provides a steady state solution to the heat flow problem, and thus cannot replicate

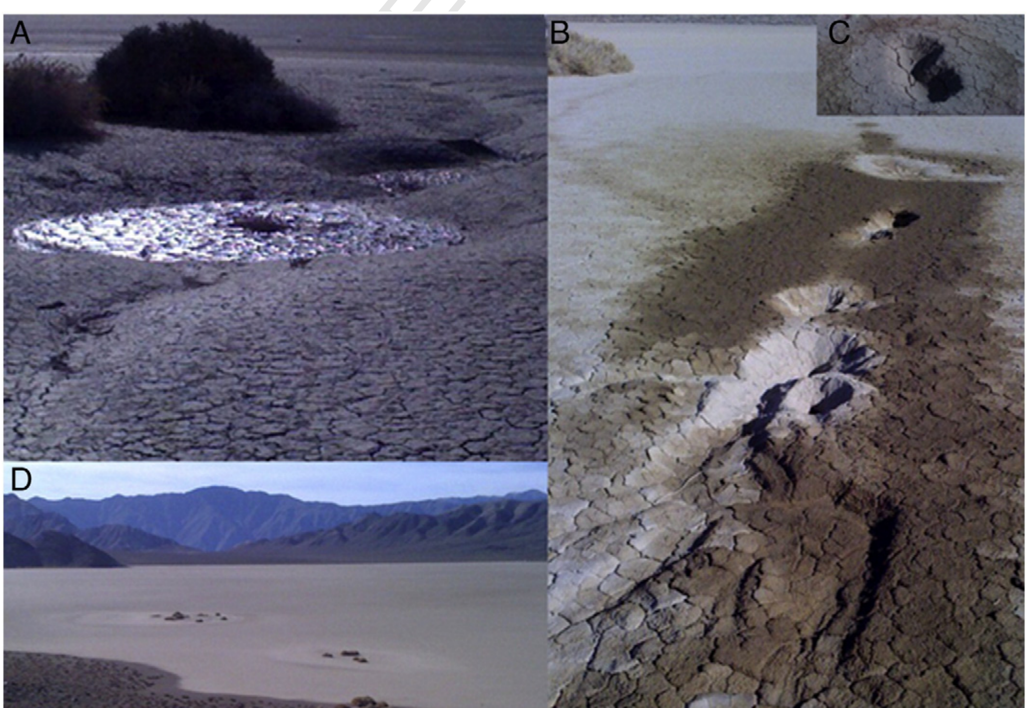

Fig. 4. Two of the conical depressions that may become artesian. A: An oval basin, 0.3 m deep, with moist sediment in its bottom. B. Several conical depressions 11 m NE of the one shown in A. The largest is 0.25 m across and 0.15 m deep. C: Two conical holes 0.15 m across and 0.1 m deep located about 15 m west of the one shown in A. D. Overview of two large depressions on the playa. The further one is that shown in A. The two depressions are 140 m apart.

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Q21 **Table 1**
Input parameters for the finite element modeling of the temperature distribution (Tipler, 1999). Thermal conductivity came out from temperature profile measurements in Fig. 2. (Meeker, 2010).

Material	Thermal conductivity [W/m K]	Heat capacity [MJ/K m^3]	Density [kg/m^3]
Water	0.560	4.170	1000.0
Ice	2.200	1.900	900.0
Dolomite	2.000	2.170	2200.0
Sediment (clay)	0.490	1.182	1477.0
Air	0.018	0.001	1.2

thickening of the ice through time. The rock was rectangular, 200 mm wide and 170 mm high. It was given the thermal properties of dolomite because carbonate rocks are frequently found at the ends of trails. The sediment was 500-mm thick. Its bottom was kept at a constant temperature of 6 °C. The water was 80 mm deep and capped by 20 mm of ice, above which was a 500 mm layer of air kept at temperatures from -15 °C to −1 °C in different experiments. The thermal properties used are listed in Table 1. For the model shown in Fig. 5, we chose an air temperature of −4 °C, as such values were recorded by our own temperature measurements. For the same time periods, temperatures were recorded at the Hunter Weather Station, located 15 km SE of the Racetrack, and 940 m higher (see: http://mesowest.utah.edu/index.html) where, roughly consistent with a moist adiabatic lapse rate, temperatures were generally 3–7 °C colder. The uniform air temperature was established with the use of a convective heat transfer boundary between the air and the ice so that the ice–air interface was close to −4 °C. The 0 °C temperature at the base of the 20-mm ice layer allowed study of the temperature distribution after an initial ice crust formed on the lake. Results from the model (Fig. 5) show that the entire rock, along with some of the surrounding water and adjacent sediment, could freeze if the boundary temperatures we specified were maintained for a sufficiently long time.

Of particular interest in Fig. 5 is the formation of an ice "bulb" around the rock and penetrating ~30 mm into the sediment. In nature this bulb would merge with ice on the water surface, as suggested by the dashed lines, thus forming an ice collar around the rock. Such collars are commonly seen around rocks in streams and lakes in nature (e.g. Lorenz et al., 2011 and our own observations) but do not appear in our steady-state numerical model because the ice

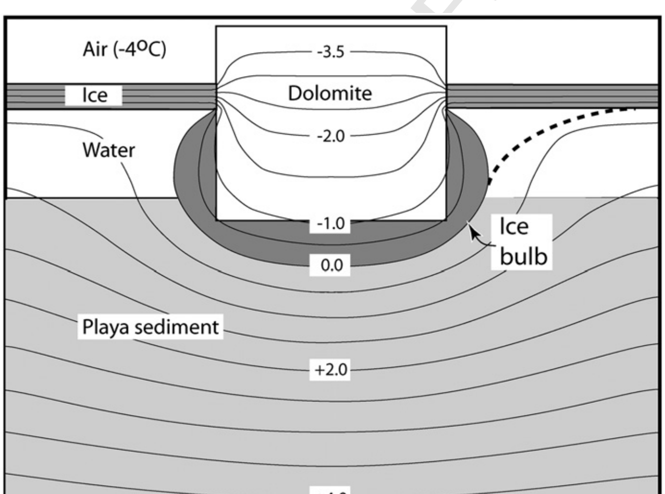

Fig. 5. Steady-state finite element model of the temperature distribution around a rock on a playa. Rock is 200 mm wide and 170 mm high and is embedded 20 mm into the playa sediment. It is partially immersed in water 100 mm deep, the top 20 mm of which is frozen. The base of the sediment, at a depth of 500 mm, is held at 6 °C, the air above the ice at −4 °C, and the water/ice interface at 0 °C. White area is volume of water between 0 °C and 0.5 °C.

thickness is specified and the ice/water interface is fixed and is kept at 0 °C.

Eq. (1) can be modified to include the gradient in temperature with depth, dθ/dz, thus:

$$\theta(z,t) = \overline{\theta} + \frac{\theta_r}{2} e^{-z\sqrt{\frac{\omega}{2\kappa}}} \sin\left(\omega t - z\sqrt{\frac{\omega}{2\kappa}}\right) + z\frac{d\theta}{dz} \qquad (3)$$

and solved for $\theta(z,t)$. For a sinusoidal temperature oscillation at the surface varying from −4 °C to +4 °C over a day, the minimum temperature at a depth of 100 mm, the distance from the water surface to the bottom of the model rock, is ~−1.6 °C and occurs 0.15 day after the minimum temperature at the surface. At this depth, temperatures below freezing persist for nearly half a day. Although the temperature distribution will be modified by the growth of ice around the rock, it seems likely that ice will also form in the playa sediment, freezing it to the bottom of the rock.

7. Laboratory experiments

In the laboratory, a transparent open-topped rectangular box, 400 mm long, 15 mm wide, and 150 mm deep was filled with playa sediment to a depth of 60 mm. A fragment of granite, 10 mm in mean dimension, was placed on top of the sediment. Granite is the second most common trail-making lithology on Racetrack playa. The rock was then submerged in 50 mm of water. A copper sheet (350 × 400 × 2 mm) was placed inside the aquarium so that one edge barely penetrated the water surface while the other edge was in contact with liquid nitrogen inside a separate Styrofoam container. The heat extracted through the copper sheet mimicked a freezing episode on the playa.

Once the ice was sufficiently bonded to the granite fragment, the copper sheet was removed, and an additional 30 mm of liquid water (0 °C) was added above the ice to simulate input of additional runoff. The water seeped between the ice and the glass wall of the tank and lifted the ice and the granite fragment. As this occurred, some of the sediment frozen to the bottom of the granite fragment was also lifted. This silt thawed and fell back to the bottom in irregular avalanches as the system was allowed to warm to room temperature. This probably reflects warming of the water beneath the ice by heat flow from the lateral boundaries, and may not occur in nature.

As the rock was rather small and the conditions quite artificial, the principal value of this experiment was to guide our thinking on the origin of tracks on playas, and perhaps suggest processes that we might not otherwise visualize. Hooke (1968) referred to this as similarity-of- Q8 process modeling.

8. Discussion

Ice as thick as 75 to 100 mm has been observed on Racetrack playa [(Stanley, 1955, pp. 134); Stanwood, unpublished, cited by (Sharp and Carey, 1976, pp. 1715)] and, as noted, ice formation was observed during February 2009 (Lorenz et al., 2011). In the latter case, a storm left what appeared to be several centimeters of snow on mountains and alluvial fans surrounding the playa. Snow melt during the day flooded the playa. Freezing temperatures and/or radiative cooling during the night then left a layer of ice on the water surface.

Several researchers have accredited the movement of stones on Racetrack playa to ice, with this mechanism perhaps explaining the movement of stones on other playas. Stanley (1955) first suggested it and Reid et al. (1995) and Lorenz et al. (2011) provided additional support. The common observation that several tracks are parallel when straight, remaining the same distance apart, or describe arcs around a common centerpoint when curved, suggests that the rocks moved simultaneously, locked together by a rigid framework (Reid et al., 1995). This is particularly convincing evidence for the ice model. Sharp and Carey (1976) expressed some doubt about the role

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of ice because a rock that they were monitoring moved out of a "corral" of stakes that they placed around it. Lorenz et al. (2011), however, showed that the stakes were too far apart to conclusively reject the ice hypothesis.

8.1. Origin of the trails

Our conceptual model for trail formation is as follows: First, as several investigators have previously suggested, the playa must become flooded and then the temperature must drop significantly below freezing. Owing to the increased thermal conductivity of rocks, the first ice to form on the flooded playa is likely to be in collars around partially submerged rocks. As the ice thickens, these collars become stronger. Ice also forms around the rock below the collar (Fig. 5). Once ice becomes thick enough to bond firmly to a rock, further thickening exerts an upward force, reducing the normal force between the rock and the playa surface and thus decreasing the horizontal force needed to move the ice with the entrained rock. A rock may be fully supported by a volume of ice ~20 times the volume of the rock (Lorenz et al., 2011). Once a rock is fully or nearly fully supported, additions of water will decrease the normal force between the rock and the playa surface still further and can actually lift the rock free of the surface. Additions of water may be through further runoff, perhaps generated by snow melt as in the case that Lorenz et al. (2011) documented, or by influx of groundwater.

Groundwater may emerge at the playa surface when water tables in the bordering alluvial fans rise above the level of the playa surface. Messina and Stoffer (2000, pp. 258), for example, observed water upwelling in one of the conical depressions in the surface of Racetrack playa. The Spinal Springs alignment of conical depressions suggests the presence of a giant desiccation crack. Such cracks may extend to depths in excess of 5 m (O'Neil, 1965), and could provide a pathway for water through the otherwise relatively impermeable playa sediment at a rate relevant to the present discussion. The Edge Springs alignment is near the playa margin. In such locations, gravel beds and playa sediments likely interfinger at depth (e.g. Jansson et al., 1993, Fig. 2a). Thus, the Edge Springs depressions could easily tap water from a gravel bed extending beneath a surface layer of playa sediment. Lifting of ice and attached rocks by addition of water through these springs could be necessary for track formation during calm weather when wind stress is too low to provide much setup, and also when surface runoff from a flooding event has ceased due to infiltration.

Once the normal force is reduced sufficiently, either wind stress or currents can move the ice with its cargo of suspended rocks across the playa, making trails. Currents strong enough to move the ice are most likely to result from waves resulting from relaxing of wind stress. Wind pushes water to one side or end of the playa, resulting in set-up. When the wind lets up, the water surges back across the playa in a form of seiche.

Eventually, water is lost through evaporation or infiltration, or the ice melts, and rock movement stops, leaving the trails to confuse curious observers.

8.2. Ice thickness required to support a rock

In the previous section, we noted that a certain ice thickness is required before the additional buoyancy provided by the ice is sufficient to reduce the normal force between the ice and the playa surface. Here we make a rough estimate of this thickness. Consider a spherical rock of radius r. The weight, W, of a rock that is half-submerged in water is:

$$W = g\frac{4}{3}\pi r^3\left(\rho_r - \frac{1}{2}\rho_w\right) \quad (4)$$

where ρ_r and ρ_w are the densities of rock and water, respectively. We want to know how thick, h, a layer of ice, surrounding a rock, would have to be to support the rock without fracturing as the ice is lifted by freezing of more water beneath it or by addition of water to the playa. The key ice properties are the elastic modulus, E (~4.5 GPa), Poisson's ratio, ν (0.3), the flexural strength, σ_f (0.6 MPa), and the stress intensity function $f(\alpha)$, where

$$\alpha = \left[\frac{12\left(1-\nu^2\right)\rho_w g}{Eh^3}\right]^{1/4} r \quad (5)$$

(Fransson, 2009, p. 17–19). Empirically,

$$f(\alpha) \cong [0.6159 - ln(\alpha)]\frac{\alpha}{2} + \frac{\pi\alpha^2}{64}. \quad (6)$$

Then:

$$h = \left[\frac{3(1+\nu)f(\alpha)}{\pi\alpha\sigma_f}W\right]^{1/2}. \quad (7)$$

As α is a function of h (by Eq. (5)), this must be solved iteratively. For a rock of radius 0.05 m and density 2750 kg/m^3, for example, W would be 12 N. An ice layer 5.3 mm thick then yields $\alpha = 0.18$, $f(\alpha) = 0.21$, and Eq. (7) is satisfied (doubling r increases h to 15 mm). In other words, ice only a couple of millimeters thick would exert a significant upward force on the rock, and by the time the ice reached a thickness of ~6 mm it could fully support the weight of the rock. At this point, however, the ice would be bowed down elastically ~2 mm (Fransson, 2009), so further lifting of the ice would be needed to detach the rock from the bed.[1]

8.3. Rates of rock movement

As noted, some trails appear to extend a couple of decimeters beyond the rocks at their ends, a characteristic also noted by Sharp and Carey (1976). Sharp and Carey (p. 1715) also called attention to "unusual accumulations of playa mud on the outsides of sharp curves." Here we explore the possibility that these features are a product of a muddy bow wave driven in front of the moving rock. The kinetic energy of sediment-laden fluid being pushed by a rock is: $\frac{1}{2}m\overline{u}^2$ where m is the mass of fluid and $\overline{u}$ is its mean speed. Once the rock stops, this energy is dissipated as the sediment cloud "surges" forward. If the force applied to the cloud is F, the cloud stops after distance s. Thus: $\frac{1}{2}m\overline{u}^2 = Fs$. F may be approximated by $A\tau$, where A is the cross-sectional area normal to the direction of movement and τ is the shear stress. In a fluid, $\tau = \mu\frac{du}{dz}$ where μ is the dynamic viscosity and z is the vertical coordinate. Thus, we have, in finite difference form:

$$\frac{1}{2}m\overline{u}^2 = A\mu\frac{\Delta u}{\Delta z}s.$$

Let's consider a column of sediment 10 mm on a side and 20 mm high, and make a very crude approximation of the velocity profile in the column as shown in Fig. 6. The velocity increases from 0 at the bed to a maximum, u_m, at a height of 10 mm and then decreases to zero at a height of 20 mm. The upward decrease above the middle of the column is due to shear with the overlying fluid. The mean speed, $\overline{u}$, is $u_m/2$. We choose the following numerical values for the parameters: $m = 2.6$ g (a density of 1.3 g/cm^3), $A = 1$ cm^2, $\mu = 1$ poise (1 g cm^{-1} s^{-1}) (Julien and Leon, ca 2000, Fig. 2), $\Delta u = u_m$, $\Delta z = 1$ cm, and s = 200 mm

[1] Fransson (e-mail comm., 3/13) notes that if the water level rises slowly while the ice is thin, the ice may become bowed downward, flooding an annulus around the rock. This would weaken the ice.

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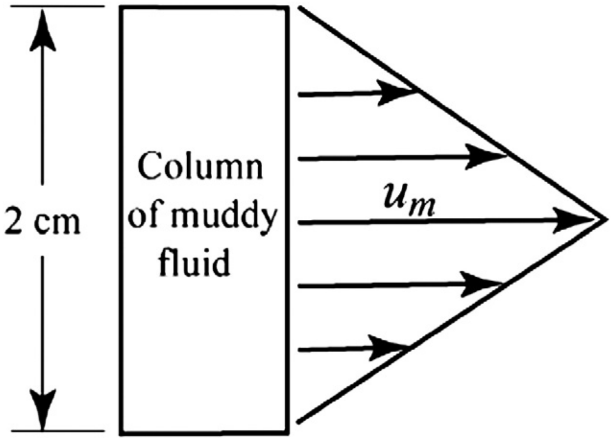

Fig. 6. Sketch of geometry used in calculation of rock speed.

(Figs. 3E and 7E). Then u is ~310 *mm/s*. This appears to be a plausible speed for a rock bound in ice which is driven by wind speeds of a few meters per second; it is consistent with Sharp and Carey's (p. 1715) 'guess' of 0.5 to 1 m/s and Reid et al.'s (1995) estimate, based on wind drag on sheets of floating ice, of a few tenths of a meter per second. Speeds likely vary substantially, depending on wind speed and duration, the normal force between the rocks and the playa surface, the size of a seiche if one is involved, and the size of the ice floe.

If rocks, entrained by ice and thus moving over a playa surface, have such bow waves, the waves would also form a narrow wake spreading laterally from the rock. Fine sediment in this wake would settle out once the rock had passed by. We think it noteworthy that many trails do not seem to be actual depressions in the playa surface, but rather look like burnished paths, as if one were to make a pathway across a dirty linoleum floor with floor waxer (Figs. 3 and 7E). Might this appearance be a consequence of settling of fines from a wake? Might this explain trails that are wider than the responsible rock?

9. Conclusions

Racetrack playa serves as the catchment for a large drainage area and is closely surrounded by steep hillsides that can capture a significant amount of precipitation. In winter, this precipitation may well be in the form of snow. Runoff from rain or melting snow periodically floods the playa. If temperatures then drop below freezing, ice collars form around rocks, and as the collars grow outward and expand, they apply a buoyancy force to the rocks (Lorenz et al., 2011). If the ice becomes thick enough, either this buoyancy alone, or that provided by further addition of water to the playa can lift the ice and any attached rocks, reducing the normal force between the rock and sediment below, and thereby reducing the drag force that the playa can exert on the rock to the point where relatively modest winds or seiches can move the floe. If the freezing front penetrates through the rock into the lake bed, a clod of playa silt may be lifted with the rock and dragged along. Q14 When finally deposited, the rock will be sitting on top of a pile of playa sediment. Rock speeds are likely in the range of hundredths to several tenths of a meter per second Multiple rocks in the same floe, all moving and turning in tandem, can scour tracks that have distinctive signatures (Stanley, 1955; Reid et al., 1995).

The following observations are clarified by our model:

- Silt piles under rocks (Figs. 3C and 7E) are likely composed of playa sediment that was frozen to the bottom of the rock and transported with it.
- Trails may be left with no trace of the responsible scoring agent if rocks that have left trails are subsequently lifted off the playa surface, most likely by further additions of water to the playa, and moved. This may leave only an impression in the mud pile.
- Changes in track width may be caused in at least three ways. Buoyancy may be lost as bits of an ice flow break off or as the ice around a rock bows downward elastically or plastically. Rocks may rotate while being dragged, thus presenting faces of different widths in the direction of movement (Sharp and Carey, 1976). Water depth may change rapidly as a seiche moves across the playa (tracks probably form too quickly for evaporation or infiltration to lower the water level significantly).
- Trails wider than the rock may be attributable to a clod of frozen playa sediment on the bottom of a rock and wider than its base. Trails may also widen if the speed increases (as the coefficient of friction decreases from its static value to a dynamic value) and the ice with its entrapped rock gains momentum, resulting in lateral displacement of "plowed" silt.
- Trails seemingly extending beyond the rock, as shown in Figs. 3C and 7E, suggest a bow wave that sloshed forward as the rock stopped, probably abruptly. This implies a rather high speed.

Our principal contributions to the long standing discussion about the origin of trails on Racetrack playa are: (i) that because rocks have a higher thermal conductivity than water, a bulb of ice, potentially including some underlying playa silt, likely forms around a partially-submerged rock when temperatures drop below freezing for some period of time, and (ii) once the playa is flooded and a sufficiently thick layer of

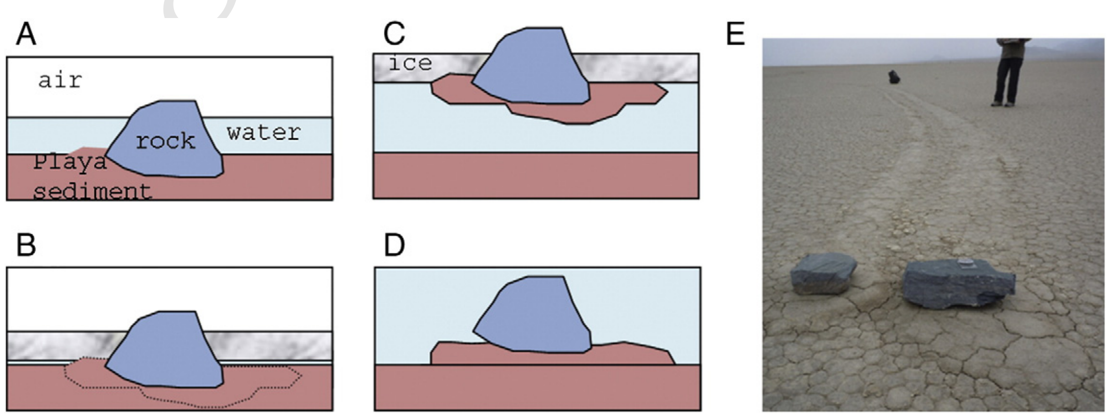

Fig. 7. Cartoon showing a rock, along with some of the underlying playa mud, being lifted, transported, and left on top of the mud pile. A. Water enters the playa and surrounds the rock. B. Water freezes, and due to larger thermal conductivity of the rock, some of the water-saturated silt and clay beneath the rock also freezes. C. Further water influx lifts the ice along with the rock and frozen sediment. D. The water drains away or evaporates and the ice melts leaving the rock on top of a mud pile. E. Photograph of two rocks that sit on top of mud piles.

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ice forms on the surface, additions of water to the playa can lift the rocks. Q15 Both are so obvious, so we wonder why we didn't think of them years ago.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2013.04.032.

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