Earth Surf. Dynam. Discuss., 2, 1005–1022, 2014
www.earth-surf-dynam-discuss.net/2/1005/2014/
doi:10.5194/esurfd-2-1005-2014

Earth Surface Dynamics
Discussions
Open Access

Trail formation by ice-shoved "sailing stones" observed at Racetrack Playa, Death Valley National Park

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Received: 17 August 2014 – Accepted: 27 August 2014 – Published: 28 August 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Trails in the usually-hard mud of Racetrack Playa in Death Valley National Park attest to the seemingly-improbable movement of massive rocks on an exceptionally flat surface. The movement of these rocks, previously described as "sliding stones", "playa scrapers", "sailing stones" etc., has been the subject of speculation for almost a century but is an exceptionally rare phenomenon and until now has not been directly observed. Here we report documentation of multiple rock movement and trail formation events in the winter of 2013–2014 by in situ observation, video, timelapse cameras, a dedicated meteorological station and GPS tracking of instrumented rocks. Movement involved dozens of rocks, forming fresh trails typically of 10s of meters length at speeds of $\sim 5\,\mathrm{cm\,s^{-1}}$ and were caused by wind stress on a transient thin layer of floating ice. Fracture and local thinning of the ice decouples some rocks from the ice movement, such that only a subset of rocks move in a given event.

1 Introduction

Racetrack Playa in Death Valley National Park, California is a nearly flat $4.5 \times 2\,\mathrm{km}$ lakebed. The Racetrack is in many ways typical in morphology for playa lakes (indeed, almost identical in planform with a lake on Saturn's moon Titan, e.g., Lorenz et al., 2010a) but is distinguished by its relatively high elevation at 1300 m, and by the remarkable (e.g., Sharp and Carey, 1976) presence of hundreds of rocks (usually cobbles or small boulders, but some up to $\sim 300\,\mathrm{kg}$) that litter its surface. These rocks (mostly a dark grey dolomite and a few granite boulders) are very distinct against the uniform tan playa clay and often appear at the end of trails or furrows in the playa surface. These trails suggest that the rocks have moved across the surface when the playa was wet and have been considered a "mystery" for over half a century, for which various scientific and nonscientific explanations have been proposed.

Much attention has been directed towards documenting the rocks and their movements (e.g., Kirk, 1952; Stanley, 1955; Schumm, 1956; Sharp and Carey, 1976; Reid et al., 1995; Messina, 1998) and to speculating upon the conditions under which they are induced to move. However, the playa's isolated location and the extreme rarity of movement events mean trail formation has until now never been observed, and the conditions under which it occurs have not been documented. It is generally accepted that the playa surface must be wet, softening the clay to allow trail formation, and that the agency for the rock movement is wind, but significant unknowns are whether the movement is fast or slow (and the extent to which ice is required to facilitate motion). For example, Sharp and Carey, 1976, interpreted blobs of mud at the end of rock trails as indicating movement of $> 1\,\mathrm{m\,s^{-1}}$, which favored a purely wind-driven sliding movement, whereas Creutz (1962) speculated that slow movement by gentle tilts caused by clay swelling might be responsible. These various ideas are reviewed in detail by Messina (1998). Reid et al. (1995) called attention to the congruence of many trails, suggesting a mechanical connection between rocks, supporting an ice-driven model, which had been favored by Stanley (1955). Movement events are clearly highly episodic, ranging from multiple years with repeated movement reported by Sharp and Carey (1976) to more than a decade with little or no documented movement (e.g., Messina and Stoffer, 2000; Lorenz et al., 2011b). It has recently been suggested that the rate of occurrence of rock movements has been in systematic decline since the 1970s, as a possible result of climate change (Lorenz and Jackson, 2014).

2 Observations

In an effort to resolve how trails form, we initiated in 2007 observation efforts with National Park Service permission, with automatic instrumentation at the playa (Lorenz et al., 2011a). While these studies have shown the remarkably dynamic variation in hydrological condition of the playa in some winters, these observations and multiple

visits per year found at best only sporadic evidence of trail formation in the 2007–2013 period, one possible shallow trail being noted in 2009 (Lorenz et al., 2011b).

Rock movement was finally observed in situ by us (J. M. Norris, R. D. Norris) in December 2013 (see Norris et al., 2014). Movement was associated with a shallow pond on the southern 1/3rd of the Racetrack that was covered by a 3–5 mm thick layer of floating ice. Buildup of winds during the mid morning hours under sunny skies culminated in abrupt ice breakup around noon on 20 and 21 December, accompanied by popping noises of shattering ice across the floating ice sheet. rock movement occurred when partial melting of the ice near mid day allowed winds of $\sim 5\,\mathrm{m\,s^{-1}}$ to drive the ice downwind, bulldozing the rocks. Three instrumented rocks (8–17 kg), equipped with GPS receivers triggered by movement from their deployment sites recorded movement: two moved ~ 70 m over a 16 min period on 4 December 2013, and one stone moved ~ 40 m in 12 min on 20 December 2013: velocities of of ~ 2–$6\,\mathrm{cm\,s^{-1}}$ were recorded (Norris et al., 2014).

In a regular tourist visit, unrelated to any research program, one of us (J. W. Chadbourne) visited the playa on 5 January 2014 and observed movement: ice being shoved towards the southern shore of the playa drove an embedded pebble-sized rock. This movement was recorded with a handheld cellphone camera (see Supplement: videos and other material is also available at www.racetrackplaya.org) and is summarized in Fig. 1: the small rock is seen to move by a couple of cm relative to two larger rocks. The audio on the cellphone video indicates wind noise, as well as ice splintering on the shore.

In a follow-up visit on 9 January 2014, stimulated in part by J. W. Chadbourne's report relayed via a park ranger we (J. M. Norris R. D. Lorenz) observed further movements, and obtained documentation on new trails. On this occasion, a thin (5 ~ 8 mm) ice cover was again present on the playa lake at ~ 09:00 LT, which showed progressively-growing patches of melt through late morning. When freshening winds were noticed at ~ 11:45 LT (recorded with a handheld anemometer to be $\sim 4\,\mathrm{m\,s^{-1}}$ on the dolomite hill at the south edge of the playa, and $\sim 3.5\,\mathrm{m\,s^{-1}}$ by the meteorology station on the alluvial fan ~ 0.5 km to the east of the playa, Norris et al., 2014), cracks were heard and seen to form in the ice, and slow movement of several rocks was observed by eye. The motion was generally too slow to be meaningfully recorded on handheld video ; the motion was too slow to be seen on a wide-angle view, and zoomed views lacked fiducial markers against which to perceive movement (in this respect, the video by J. W. Chadbourne on 5 January is unusual because it recorded rocks within 2 m of the observer) – a moving rock moved with the ice around it so relative motion was not appearent, and the ice obscured the playa surface underneath.

Splintering of the ice at the southern edge of the playa indicated that ~ 20 cm of southward beaching of the ice sheet occurred, with a larger eastward motion. Rotation of the ice sheet (clockwise as seen from above), together with fracture of parts of the ice near the southern edge, allowed greater motion away from the edge. A pair of new tracks (documented not to be present three hours previously – Fig. 2) were formed by two rocks moving north in a congruent zig-zag pattern, consistent with their being locked in the same sheet of ice (e.g., Reid et al., 1995) – indeed several other tracks were later found with the same pattern. Another set of trails, also documented with before-and-after field photos (Fig. 3) similarly moved northwards. It is striking in this example that some rocks were moved, where other rocks just tens of cm away were not: evidently there is a strongly stochastic element to the mud friction and application of ice forces. Elements of this randomness include the rock profile (low-sitting rocks may either be submerged entirely beneath the ice sheet, or protrude only slightly such that the sheet rides over them), fractures or leads in the ice, including leads formed by other rocks, and the depth to which the rock is embedded in the mud.

Because park regulations prohibit walking on the wet mud (which would form footprints which might persist for years) it was impossible to study the tracks more closely in situ on their formation date. However, the new tracks could fortuitously also be observed briefly by aerial photography acquired around 13:00 LT by a kiteborne camera (Lorenz, 2014) which the fresher breeze now allowed to fly (Fig. 4). There was only a narrow window for such observation – windy enough to fly the kite, but before the liquid

became too disturbed – turbidity is evident in Figs. 1 and 2. Another set of tracks were seen to have formed nearby, and a number of rocks further from shore were seen in motion by the observers. Figure 5 shows a wider view of the cliff source region, and in particular sets of curved and right-angle trails that clearly show the effect of rotation of the ice sheet.

Importantly, several rocks that moved were observed not to be gripped by the ice, but were shoved from one side with the ice panel sometimes splintering against it and leaving a clear lead behind, or in some cases riding up over the rock. This shows that in these cases at least, the ice applied no buoyant uplift to the rocks. Although buoyancy has been speculated to be an important mechanism (Lorenz et al., 2011b) for some movements (by analogy with arctic coastal boulder transport, e.g., Dionne, 1993), evidently it was not required in this instance.

Timelapse imaging data, part of an ongoing program (Lorenz et al., 2010b) since 2007, showed independently (Fig. 6 – see also the Supplement) that at least ~ 4 rocks within ~ 50 m of the source cliff – likely including those we observed on-site – had moved between late morning that day and noon the following day (imaging at only 2 frames h^{-1} was permitted by Park authorities for privacy considerations, and wind-ripples on the lake surface rendered rocks invisible on the afternoon of 12/20). About ~ 12 rocks within 20 m of the south edge were observed not to move.

3 Analysis

Inspection of the timelapse imaging (see Supplement) shows that the series of movement events in winter 2013–2014 was enabled by remarkable ~ 20 cm snowfall on 23 November which led to the playa being flooded for several weeks (some rainfall was also seen 21–23 November in the timelapse sequence: a nearby weather station recorded this as 3.6 cm of rain, Norris et al., 2014). A thin, transient ice sheet formed most mornings (the coldest temperature recorded by a datalogger on the ground on the alluvial fan at the eastern edge of the playa was about −3 °C; see also Kleteschka et al., 2013).

Two of us (RDN and JMN) observed remnants of ice about 7–8 cm thick thick in the shadows of bushes along the southern shore of the Playa on 18–21 December. The timelapse video also shows that a persistent lens of grounded ice occupied the shoreline at the "source hill" for most of the December-January period: this lens appears to be sustained in part by shadowing by the cliffs (e.g., Lorenz et al., 2011).

It was observed that the ice tended to buckle and fracture against large, well-embedded rocks and the playa edge: this fracturing yielded plates with a typical width of ~ 20 cm. Experiments (Sohdi et al., 1983) on floating ice sheets (a situation of concern to arctic infrastructure – see also Weber, 1958; Dionne, 1993; Drake and McCann, 1982) and theory show that for the case here, where ice sheets are large ($L/B > 100$, where L is the ice sheet dimension and B the width of the obstacle), the buckling load P is roughly $\rho g B L^2$, where ρ is the density of water and g is acceleration due to gravity. Thus for a typical rock of $B = 0.15$ m, $P \sim 1500 L^2$. It may be noted that these experiments were conducted with ice sheets somewhat thicker (~ 2.8 cm) than those we observe at the playa, but at similar rates of movement (~ 5 cm s^{-1}). If we adopt a characteristic dimension of the fracturing plates of $L \sim 0.20$ m, we find a force of ~ 50 N. This is the appropriate force magnitude to move a ~ 15 cm (10 kg) rock: multiplying the weight of 100 N by the friction coefficient of ~ 0.5 measured in similar playa mud (Lorenz et al., 2011b), although this does not exclude lower values of friction.

Assuming a typical smooth surface drag coefficient of 0.003, the wind stress due to a 4 m s^{-1} wind is ~ 0.024 N m^{-2}. Thus a 50 N stress requires a drag area (see e.g., Reid et al., 1995) of ~ 2000 m^2 or a patch of ice of ~ 100 × 20 m, which is fully consistent with areas of exposed ice we observed on 9 January. A possibility that deserves further study is that water movements (e.g., Wehmeier, 1986), perhaps driven by wind stress on unfrozen parts of the lake, may also impart forces to the ice, allowing much smaller plates of ice to drive rocks. An additional complication is how force may be distributed among several rocks – depending on exactly how the ice is anchored to rocks and

how it fractures around them, several rocks might be moved sequentially even if their summed friction would be expected to resist ice motion. This stochastic coupling may account for the adjacent moving and nonmoving rocks we document, as well as the "corral" experiment in Sharp and Carey (1976). Figure 7 shows rocks with melt pools around them, as well as evidence that the ice sheet locally migrated away from shore (perhaps as a result of overall rotation), dragging rocks onto the playa.

A recurring weather pattern has been documented, with ice cover persisting for the morning, and wind picking up by midday. On several occasions when wind has freshened early enough, and ice persisted long enough, the ice has moved and pushed some rocks with it, forming new trails. This pattern requires night-time freezing, which in recent years has occurred on some tens of nights per year, in addition to the playa flooding. It has been suggested (Lorenz and Jackson, 2014) that the probability of rock movements may have declined since 1970 when rocks moved 3 out of 5 years that the playa was observed by Sharp and Carey (1976): the present observation of movements, the first since ~ 2005, does not substantially change this conclusion, and long-term records at nearby weather stations show a decline in windspeeds and freezing nights. On all five occasions we know rocks moved (4, 20, 21 December and 5, 9 January), ice, water and wind were present. The relatively modest winds needed to cause movement here suggest that the wind condition is fairly frequently met, and that water and especially floating ice are the rate-limiting factors (Norris et al., 2014; Lorenz and Jackson, 2014). Winter timelapse observations since 2007 have showed generally dry conditions 2007–2011 (Lorenz et al., 2011a) with the only exceptions being for a few days in early 2009, and prolonged period of flooding in February 2010. Continued observations have shown minimal liquid on the playa in the winters of 2010/2011, 2011/2012 and 2012/2013: the winter of 2013/2014 can be considered unusual.

4 Conclusions

It is possible that small rocks can be moved by wind without ice, and it is known that ice rafting is a facilitating mechanism in some movement events, not least in moving gravels out from shore. However, the trail formation and rock movements we report here support an “ice sailing” model, where wind stress applied to a wide floating ice sheet bulldozes rocks. Rock movements appear to have occurred for only a few minutes out of close to a decade (i.e., ~ one millionth of the time), and the documentation of the movements, and importantly of the conditions during long periods of non-movement, has required the application of data acquisition technology able to sustain persistent observation and thus to finally resolve the mystery of the moving rocks. We consider ourselves privileged to have witnessed this remarkable process in action.

The Supplement related to this article is available online at doi:10.5194/esurfd-2-1005-2014-supplement.

Acknowledgements. The timelapse observations were conducted with National Parks Service permission under study DEVA-00169 and DEVA-00341 and GPS loggers and weather station observations were with NPS permission under DEVA-65173. R. D. Lorenz acknowledges the support of NASA grants NNX12AI04G and NNX13AH14G. J. M. Norris and J. Ray had technical and monetary support from Interwoof. Paula Messina and NPS ranger Isabelle Woodward are thanked for drawing attention of the other authors to the observations of J. W. Chadbourne.

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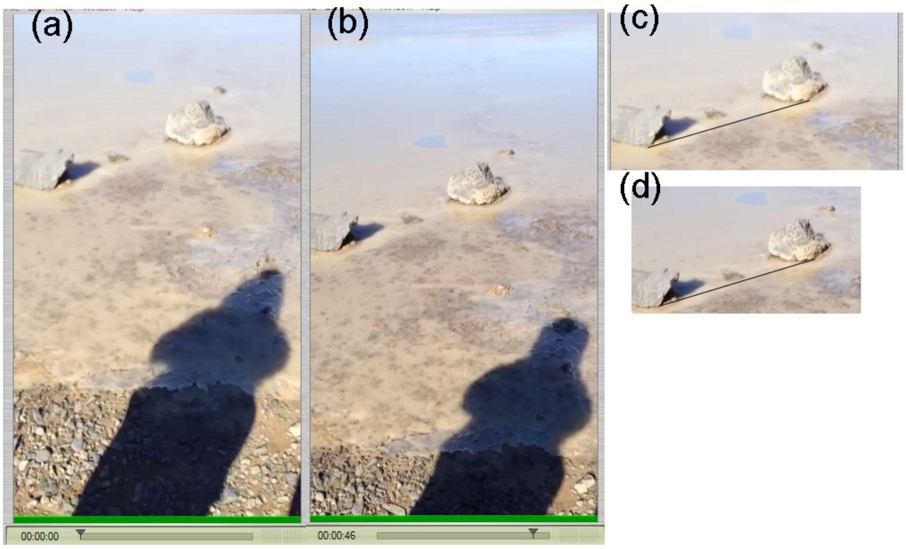

Figure 1. (a) and **(b)** are frames 46 s apart excerpted from a video acquired with a cellphone camera at 13:30 LT on 5 January 2014 by J. W. Chadbourne. Zoomed views are shown in **(c)** and **(d)**, respectively, with a fiducial line as a guide – the small central rock is seen to have moved ~ 2 cm relative to the other two larger rocks. These same rocks are seen four days later in Fig. 3, where the small rock has moved further towards the playa edge and formed a trail, and the small rock at upper right is also displaced.

Figure 2. Three parallel trails(about 40 cm apart) observed to form around noon on 9 January 2014. The photo at left was acquired at around 09:00 LT, when ∼ 8 mm of ice was present – the glazed appearance of the lake is evident. The kinked trails of the rocks in the foreground were likely formed in the previous couple of weeks in the same transient lake. In the photo at right, acquired three hours later, the two foreground rocks have moved ∼ 10 m to the north, leaving trails visible in the shallow water. The trails have dark edges where wet displaced mud is observable through the shallow semitransparent water, whereas the deeper trail center is bright due to scattering in the longer column of suspended mud. The third rock (at roughly a 10 o'clock position relative to the other two) has moved similarly, although its trail is less obvious owing to the reflection of the mountains in the water surface. The ice cover is now thin and patchy.

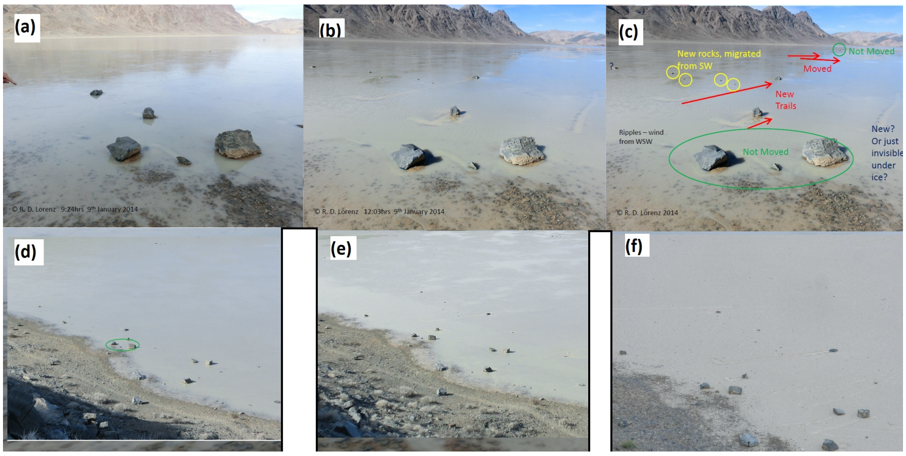

Figure 3. (a)–**(e)** acquired at the south edge of the playa on 9 January 2014, initial image **(a)** at 09:16 LT. Six rocks have moved, forming fresh trails shortly before the second image **(b)** was acquired at 12:08 LT. Trails and rocks (three rocks in the foreground have not moved) are labeled in **(c)**. Note the two larger rocks in the foreground (circled in green) with an intermediate smaller rock: the smaller rock is that observed to move in the video acquired by J. W. Chadbourne – see Fig. 1 – an is seen here to have moved further than observed on 5 January and to have formed a short trail. A view of the same set of rocks seen from the dolomite cliffs above the playa **(d)** at 11:04 LT before the movement event and **(e)** at 12:19 LT, afterwards, further constraining the time of movement. Note in the second image that pools of reflective meltwater on the surface of the ice are more extensive and that the ice has withdrawn northwards away from shore at left, consistent with it dragging rocks. **(f)** View, slightly zoomed-in, of the same site on 6 May 2014 after the lake had dried up, showing exposed trails.

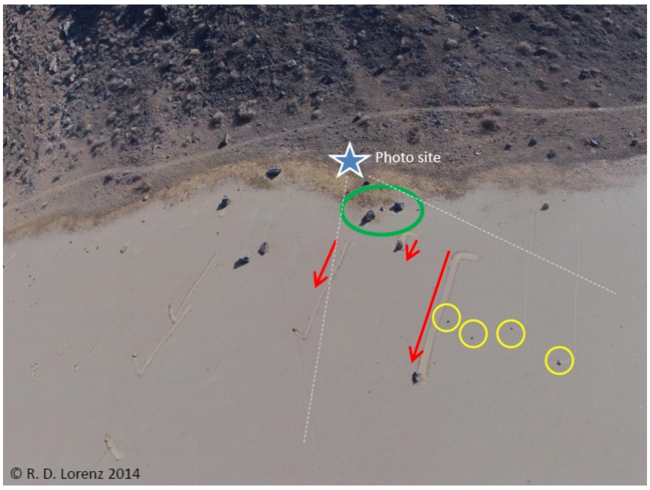

Figure 4. The fresh tracks, observed about 13:00 LT, 9 January 2014 from a kiteborne camera looking near-vertically downwards. The melting of the ice allows the mud trails to be seen through a few cm of water. The location from which Fig. 2a–c were obtained is indicated with a star. The four yellow circles are the rocks indicated by same in Fig. 2c – their trails can be faintly seen.

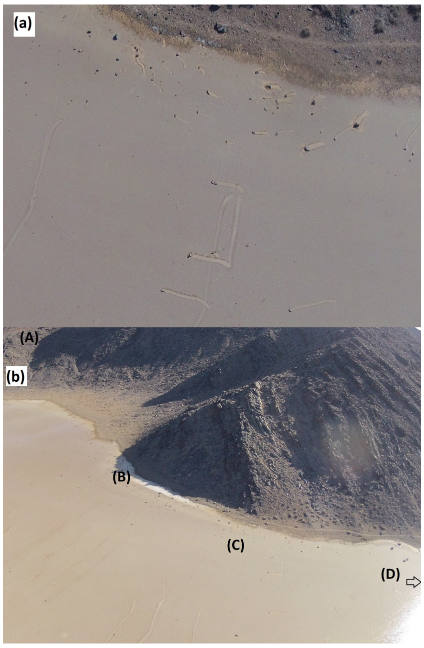

Figure 5. (a) Kiteborne view through several cm of water showing two general classes of fresh trails. A nearshore set show a curved path consistent with rotation of the ice sheet. More distal tracks show straighter paths away from the shore (i.e., northwards) and separate eastwards segments. **(b)** More distant kiteborne overview looking south from over the flooded playa, showing the source dolomite cliff and several features. (A) is the approximate location of the time-lapse camera (see Fig. 6 and Supplement), (B) is the shadowed lake edge, with thick ice lens, (C) is the location of the curved tracks shown in Fig. 4a, and (D) denotes the position (just out of frame) of the trails in Figs. 1–4.

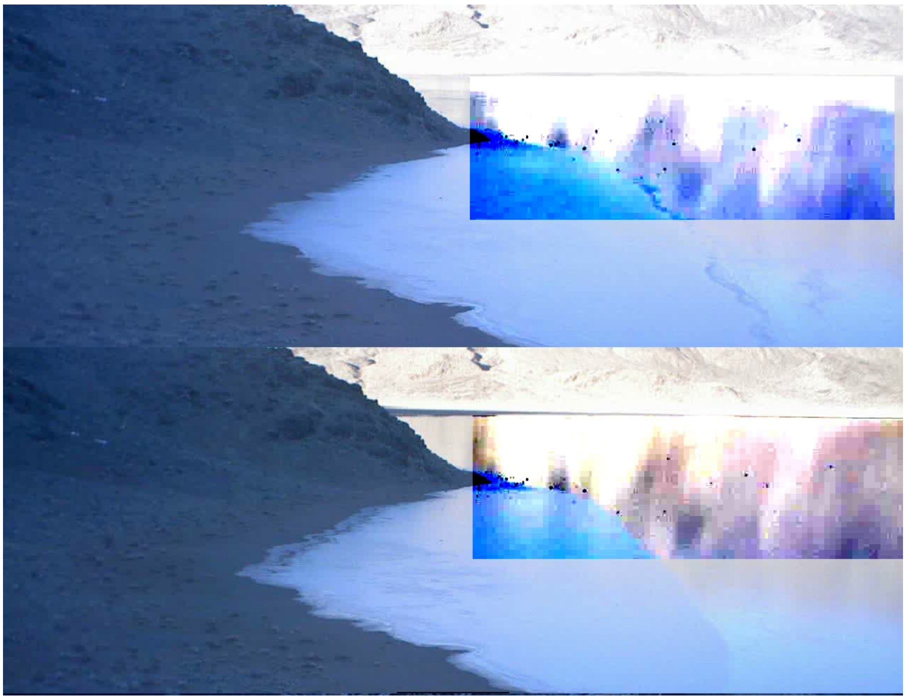

Figure 6. Montage of 2 timelapse frames (upper, 08:08 LT, 20 December; lower, 07:48 LT, 21 December). The principal difference is that the ice lens in the foreground, which accumulates in part due to its prolonged shadowing by the cliffs to the south, is slightly smaller on 21 December. The collection of rocks near the rock spit is unchanged, but 4 rocks have changed position, as seen in the contrast-stretched portion of the images at center right. The raw images, as a video file, are available as Supplement to this paper, and at www.racetrackplaya.org.

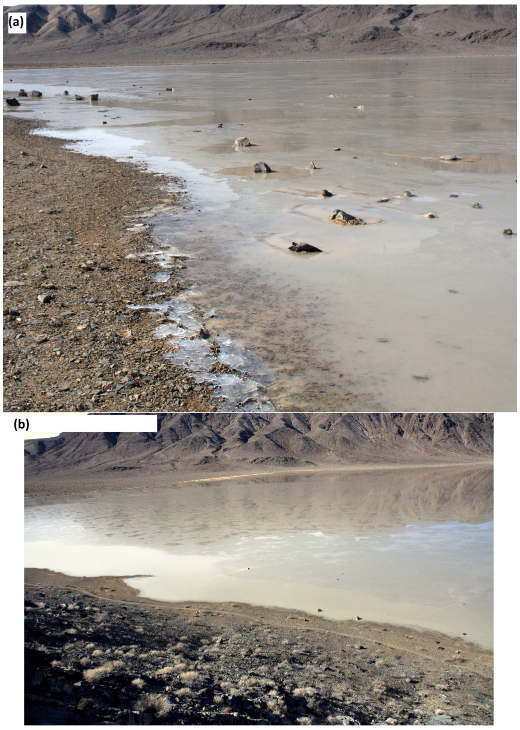

Figure 7. Images (by J. M. Norris) acquired on 9 January 2014. Upper image at 11:57 LT shows ice being pulled away from shore at top but with onshore movement at bottom. Lower image shows wider view at 12:14 LT looking somewhat to the west, showing the ice sheet having been pulled away from shore, rotating clockwise from above.