Feature

Wind erosion of the wind-deposited Navajo Sandstone, USA

Outcrops of the Early Jurassic Navajo Sandstone in southern Utah and northern Arizona, south-western USA are being actively eroded by sand-laden, south-westerly winds. Small-scale stepped topography with risers facing into the wind develops even on steep canyon walls when wind-swept grains strike the rock at a low angle. Photosynthetic, endolithic microbes directly underlie most outcrop surfaces; the crusts formed by these organisms are essential to formation of the small-scale steps. Wind erosion of highlands also forms troughs and pits that are tens of metres across. The pits have deeply scalloped, overhanging walls, and contain central domes surrounded by 'moats' filled with dune sand. Wind erosion of aeolian sandstone is favoured by a positive feedback mechanism in which grains that are liberated from outcrops by impacting particles become a fresh supply of pre-sorted abrasive particles for further attack.

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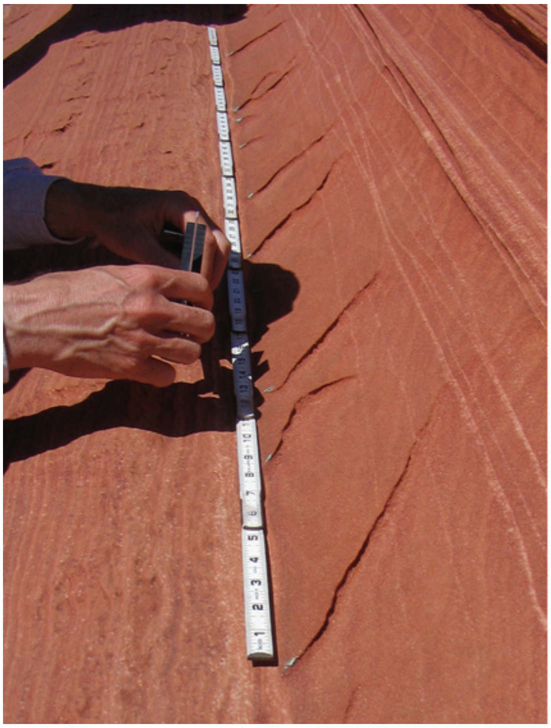
The cliffs and canyons of the Colorado Plateau of southwestern USA make the region a geologist's paradise, and each year the breath-taking red rocks also attract more than 12 million visitors who seek photographs and aesthetic experiences in the Plateau's 27 national parks and monuments. Many of the cliff-forming sandstones that provide the scenery were deposited over a span of 100 million years by wind-blown dunes migrating across the Supercontinent Pangaea. The major features of the landscape were sculpted by the power and persistence of flowing water, and it is clear that rockfalls generate arches. Wind usually plays a minor role in erosion of these landscapes. However, while carrying out sedimentological fieldwork on the bedrock of the region, researchers have become aware that modern winds are playing an important geomorphic role at some localities. Outcrops of Lower Jurassic Navajo Sandstone are especially intensely scoured by sand-laden, southwesterly winds. The products of this process range in scale from rhythmically spaced, millimetre-high escarpments on rock surfaces to scour pits in bedrock that reach tens of metres in depth and diameter.

The Navajo Sandstone

In southern Utah and northern Arizona, the Navajo Sandstone is a large-scale cross-bedded aeolian sandstone (Fig. 1) that reaches 600 m in thickness. The Navajo sand sea was arguably the largest recorded

Fig. 1. Large-scale cross-strata within the Navajo Sandstone in northern Arizona. Dune migration was left to right; wind-ripple strata weather in positive relief relative to coarser, more friable grainflows (avalanches).



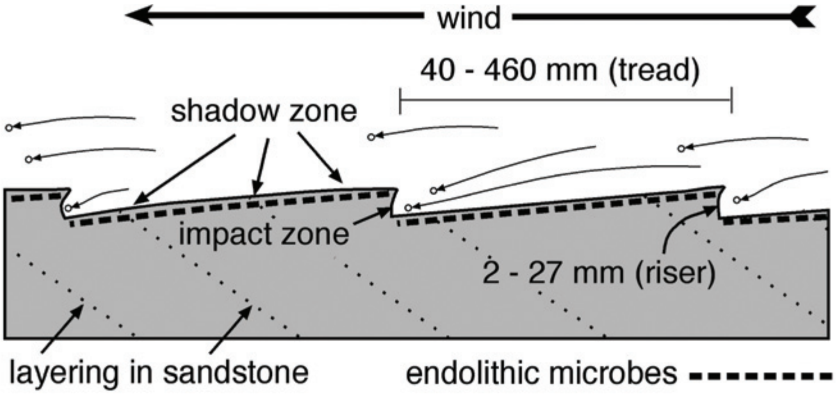


Fig. 2. **A.** Little stair steps cut by sand-laden winds blowing parallel to the ruler; steps are cut into grainflows; adjacent wind ripple strata (left) commonly lack the steps (Photo: Shirley Yik). **B.** The risers of the steps face into the wind, and are cut by low-angle impacts. Risers only form where endolithic microbes form a resistant crust.

Fig. 3. The endolithic, photosynthetic microbes that live just below the outcropping surfaces of sandstones turn green when wetted.

in Earth history. In large modern deserts, signs of life are typically sparse, but Navajo outcrops commonly contain abundant trace fossils made by insects, and some cross-strata are replete with the tracks of small dinosaurs. In many outcrops it is easy to differentiate thick, steeply dipping, relatively coarse grainflow strata (sand avalanched down the dune slipface), from thinner, finer grained, inverse-graded wind-ripple deposits that accumulated on slopes below the angle of repose. Grain-size ranges from about 100 to 1000 μm. Some grainflow deposits have porosities greater than 30 per cent, and are nearly devoid of cement, making them quite friable. Millions of years ago, every sand grain saltated to the site of deposition. Therefore, each is hard enough to withstand considerable transport, each is large enough not to cohere to its neighbouring grains after release from the bedrock, and each is the appropriate size to saltate again. Thus aeolian sandstones are a perfect source of the grain impactors necessary for aeolian erosion

Today, across much of the Colorado Plateau, the Navajo Sandstone is exposed in broad expanses of ‘slickrock’, ranging in elevation from 1000 to 3000 m. Vegetation is typically sparse, and is dominated by small trees and shrubs that grow along joints and in accumulations of dune sand. Winds are dominantly from the south-west; the strongest winds accompany the eastward passage of frontal systems.

Baby steps

Many of the sandstone outcrops in our study areas that are exposed to strong, sand-bearing winds have developed a system of small-scale, transverse treads and risers (Fig. 2); risers are a few millimetres to several centimetres high and the intervening treads range from 4 cm to half-a-metre across. The dominant winds in this part of the world come from the south-west, and with only a few exceptions where steep topography generates strong eddies, the risers face south-westward. The little steps are formed by high-velocity, low-angle impacts of wind-borne grains. Risers, which are often undercut, face upwind and shield downwind risers from abrasion in the same way that (under depositional conditions) the crests of wind ripples protect downwind troughs. In contrast to wind ripple deposits, these erosional forms can develop on slopes exceeding 60 degrees, and are present high on some cliff faces (sand grains saltating over a loose sand surface rarely reach heights of more than a metre because they lose much of their kinetic energy when they ‘splash’ into the substrate, but when grains are transported over hard bedrock surfaces, they can reach much greater heights). When grains saltate over the surface of a sand dune, their characteristic low angle of impact with the substrate (typically 10–15 degrees) is determined by the ratio of their downwind and fall velocities. The steps formed on steep rock surfaces are typically aligned perpendicular to contours and were also formed by low-angle impacts, but were cut by winds that were constrained

Fig. 4. Flute-like scours cut into sandstone by wind blowing right to left.

Fig. 5. Iron-rich concretion surrounded on three sides by a crescent-shaped scour. Wind was lower left to upper right. Note risers in lower portion of photo.

by canyon walls; when winds were forced to turn, the paths of sand-sized grains were not deflected, and the sand was hurled at high velocity against those walls at a low angle.

Sastrugi—erosional forms cut into snow by the wind—can be very similar in shape and scale to the steps and risers we have seen on sandstone outcrops, but all the steps we have observed in snow develop only where pre-existing strata of differing resistance to abrasion are being eroded. The sandstone steps typically develop at high angles to the layering within the rock (Fig. 2B). The sandstone steps only form on porous rock surfaces that harbour photosynthetic, endolithic microbes (Fig. 3). These microbes provide the differential resistance needed for the stair steps to develop.

On some outcrops, risers are strongly curved into a flute-like form (Fig. 4). Because the steep (and often undercut) apex of these structures faces into (rather than away from) the general flow direction, their form is quite different from that of the flutes cut into mud and seen, for example, on the bases of turbidite sandstones. Wind ripples are commonly called ballistic ripples in order to distinguish them from subaqueous ripples; perhaps these erosional structures should

Fig. 6. Compaction bands weathering in relief along the East Kaibab Monocline in southern Utah. Bands are present only in grainflows; they are absent from adjacent wind-ripple strata (upper left).

Fig. 7. Large, wind-eroded troughs at 'The Wave'. Strong winds drive sand through the central trough from the lower right (Photo: Shirley Yik).

be called ballistic flutes.

Where concretions are present within the sandstone, they provide another indicator of the importance of wind abrasion on sandstone surfaces. These preferentially cemented, highly resistant masses weather out in strong relief, and are commonly surrounded by crescentic scours that open downwind (Fig. 5). Compaction bands are another feature brought into relief by wind erosion. These structures formed in great abundance within grainflow-dominated outcrops of the Navajo Sandstone along portions of the East Kaibab Monocline. The bands formed perpendicular to the direction of maximum compressive stress, and, within them, quartz grains are crushed and annealed. Wind erosion has removed the sandstone between the bands, leaving them in stark relief (Fig. 6).

Large troughs and scour pits

In addition to the small features described above, sand-laden winds have also eroded large troughs and pits into the Navajo Sandstone. 'The Wave' (Fig. 7)—one such erosional feature near the Utah–Arizona border—is a magnet for photographers; images of this feature are highly likely to be found in the southwest wherever calendars and coffee-table books are displayed. Steps and risers cut by flying sand adorn the smoothly curved sides of The Wave (Fig. 8), and a large pile of dune sand lies just downwind. Although water may have played some role in loosening the grains from the walls, making a case for a water-carved origin for The Wave is quite difficult because the drainage catchment for the feature is less than 0.05 km^2.

Steep-walled scour pits on or near the tops of buttes or mesas have also formed from aeolian action (Fig. 9). Again, their topographically high posi-

Fig. 8. Wind-eroded treads and risers high on the sides of The Wave (the left wall shown in Fig. 7).

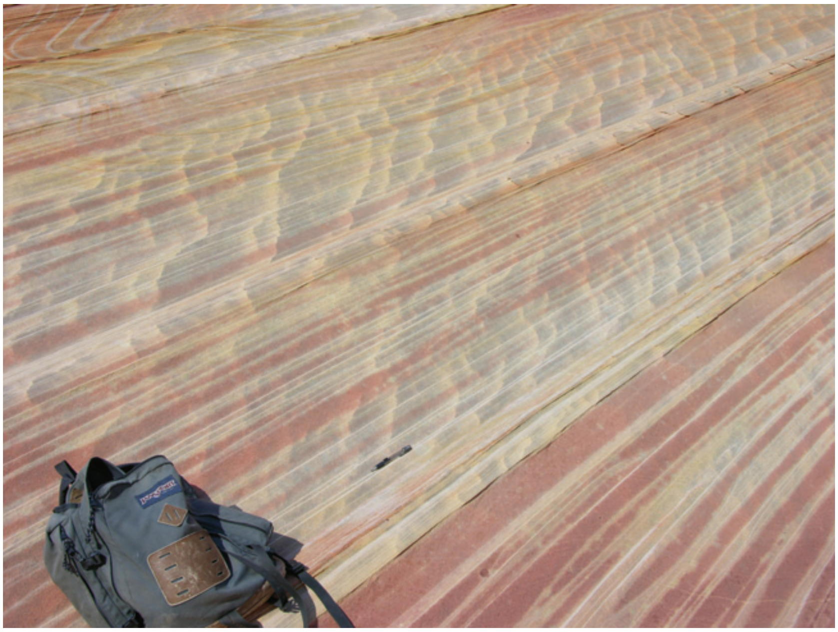


Fig. 9. Large, wind-eroded scour pit just below the top of a sandstone ridge. Note central knob and surrounding, sand-filled 'moat'. Person (arrow) provides scale (Photo: Jim Elder).

tions preclude a fluvial origin. Acceleration of surface winds over the highlands increases the kinetic energy available for aeolian abrasion. These pits have diameters and depths measuring tens of metres and, like The Wave, are decorated by small-scale erosion features. Most have scalloped, overhanging walls; along north-facing, overhung walls, smooth, abraded surfaces lack steps and risers. This may be because the endolithic microbes that are required for formation of the little steps cannot thrive in such low-light environments. In several of these pits, a central bedrock high is surrounded by a sand-filled 'moat' (Fig. 9). In one pit, thinning of the overhanging wall has proceeded to the point that rock falls have generated window-like arches (Fig. 10). The walls are a major source of abrasive particles that become trapped within the depression only to be cast again and again against the walls, every time the swirling winds reach threshold velocity. Where wind-ripple strata (resistant) and grainflows (friable) are interbedded in the walls, the rock is differentially eroded, producing a scalloped effect (Fig. 11).

Slickrock ecology

Rocks can be abraded in areas where wind energy is high, vegetation is meagre, and sand grains are available to serve as impactors. The Navajo Sandstone is composed of weakly cemented grains, all of which can be transported by the wind. If some of these grains are released, they can initiate a feedback loop resembling a self-sustaining chain reaction: a small number of initial impactors, through collisions with sandstone outcrops, free more impactors. Endolithic microbes, however, bind the near-surface quartz grains in sandstone outcrops, forming resistant crusts. Although the crusts can be locally undermined by wind-blown sand to form the small erosional features described here, about 95 per cent of the crust surface area within these fields remains intact. Microbial binding reduces the amount of sand available for aeolian abrasion, and blocks the positive feedback mechanism. Clogging of pore space by microbial filaments may also reduce infiltration, thereby enhancing runoff and hastening the removal of loose sand accumulations from the outcrop—another self-

Fig. 10. Erosion pit in which walls have been sufficiently thinned to allow arches to form via rockfall. People sit on the pit's central knob (Photo: Jim Elder).

Fig. 11. Scalloped walls of large erosion pit. Portions of cross-strata dominated by grainflows are preferentially eroded.

enhancing feedback mechanism—that, in this case, increases the area of slickrock.

As they grow, many plants alter their environments in ways that lead to invasions by species better adapted to the new conditions. Other plants, however, are able to engineer their surroundings in ways that assure their continuing control of the habitat. For example, certain grasses and conifers are able to exploit wildland fire to their own advantage, and allelopathic plants generate toxins that other plants cannot tolerate. In unlithified, desert and semi-desert soils, cyanobacteria and nonvascular plants exude mucilaginous organic compounds that glue organic matter and soil particles to form a sturdy cryptobiotic crust. By influencing the infiltration, percolation, retention and evaporation of water, these organisms have a major impact on other animals and plants. Accordingly, these microbes have been termed ecological engineers. The endolithic microbes described here similarly act as ecological engineers—preserving their slickrock habitat by limiting wind-blown sand accumulation and restricting rooted plants to small sand patches and bedrock joints.

Conclusions

The grains within the Jurassic Navajo Sandstone make perfect impactors for wind erosion, and friable grainflow strata are especially vulnerable to attack. This erosion, driven by strong south-westerly winds, leaves distinctive landforms on both a small and a large scale that are not described in modern geomorphology textbooks. Endolithic microbes form a resistant, relatively impermeable 'skin' on the rocks that, when broken, is cut into a distinctive pattern of centimetre-scale treads and millimetre-scale risers. Larger landforms include smooth-walled troughs and scour pits that are testimony to the long-term persistence of the 'slickrock' environment on the Colorado Plateau.

Suggestions for further reading

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