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Zebra stripes in the Atacama Desert: Fossil evidence of overland flow

Justine J. Owen [a,*], William E. Dietrich [b], Kuni Nishiizumi [c], Guillermo Chong [d], Ronald Amundson [a]

[a] Department of Environmental Science, Policy, & Management, University of California, Berkeley, CA 94720, USA
[b] Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA
[c] Space Sciences Lab, University of California, Berkeley, CA 94720, USA
[d] Departamento de Ciencias Geológicas, Universidad Católica del Norte, Antofagasta, Chile

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ABSTRACT

Some hillslopes in the hyperarid region of the Atacama Desert in northern Chile have surface clasts organized into distinct, contour-parallel bands separated by bare soil. We call the bands "zebra stripes" due to the contrast between the darkly varnished clasts and the light-colored, salt-rich soil. Gravel that comprises the zebra stripes is sorted such that the coarsest clasts are at the downslope front and fine progressively upslope. How and when the zebra stripes formed are perplexing questions, particularly in a region experiencing prolonged hyperaridity. Using GoogleEarth, satellite imagery, and field observations, we report the first quantitative and qualitative observations of zebra stripes in order to test hypotheses of the mechanisms and timing of their formation. We consider soil shrink-swell, seismic shaking, and overland flow as possible formation mechanisms, and find that overland flow is the most likely. Based on cosmogenic ^{10}Be concentrations in surface clasts, salt deposition rates from the atmosphere, and content in the soils, we propose that the salt-rich soils began accumulating ~10^6 y ago and the zebra stripes formed 10^3–10^4 y at the latest. The zebra stripe pattern has been preserved due to the self-stabilization of the clasts within the stripes and the continued absence of life (which would disturb the surface, as seen at a wetter site to the south). We conclude that the occurrence of zebra stripes is diagnostic of a set of distinct characteristics of local and/or regional precipitation, soil, hillslope form, and bedrock type.

1. Introduction

Some of the most visually striking features in the hyperarid Atacama Desert of northern Chile are distinct, contour-parallel bands of sorted gravels on soil-mantled hillslopes (Figs. 1 and 2). We refer to these as "zebra stripes" because the gravel, coated with a dark varnish, sharply contrasts with the underlying light-colored, sulfate-rich soils. This pattern is distinct from the more continuous, interlocking desert pavement found on subhorizontal alluvial fans and terraces adjoining these slopes.

Zebra stripes on hillslopes appear to be a feature unique to the Atacama Desert since nothing similar has been reported to date from other deserts on Earth, despite extensive study of surface gravel in Arizona (Abrahams et al., 1986, 1992), New Mexico (Wilcox et al., 1997), California (Castle and Youd, 1972; Clark, 1972; McFadden et al., 1987; Anderson et al., 2002; Sylvester et al., 2002; Wood et al., 2005), Egypt (Adelsberger and Smith, 2009), Oman and the United Arab Emirates (Al-Farraj and Harvey, 2000), the Namib Desert (Van der Wateren and Dunai, 2001), and the Negev Desert (Yair, 1983, 1990; Yair and Kossovsky, 2002; Kuhn et al., 2004; Matmon et al., 2009). The first mention of gravel bands on hillslopes in the Atacama Desert was in a conference abstract by Beaty (1983). He called the bands "tiger stripes" and proposed that the stripes were formed due to the shrinking and swelling of the salts in the soil, but his observations were never published.

Zebra stripes may be a special case of reorganized desert pavement on hillslopes. Desert pavement is a layer of rock clasts that forms on low-gradient landforms in arid to hyperarid regions (McFadden et al., 1998). It is characterized by a single layer of rock fragments which overlie a sometimes vesicular, always gravel-poor soil horizon whose thickness varies depending on the age of the surface, rate of atmospheric dust and salt input, climate, and topography (e.g. McFadden et al., 1987, 1998; Al-Farraj and Harvey, 2000; Anderson et al., 2002; Wood et al., 2005; Adelsberger and Smith, 2009). Though several theories of desert pavement formation have been proposed, one of the best supported is that clasts "float" on the accumulation of atmospherically-derived salt and dust such that they experience constant exposure at the surface from the time the geomorphic surface is formed or stabilized (McFadden et al., 1998). The continuous exposure of desert pavement gravels in the Mojave Desert, California, has been demonstrated by comparing their cosmogenic radionuclide (^{3}He) ages with that of nearby exposed volcanic bedrock (the same material from which the soil and its desert pavement formed; Wells et al., 1995). Likewise, Matmon et al. (2009) measured cosmogenic radionuclide ^{10}Be concentrations in surface gravels and gravels from within a soil profile in the Negev Desert,

* Corresponding author. Tel.: +1 510 642 3874; fax: +1 510 643 5438.
E-mail address: Justine_Owen@berkeley.edu (J.J. Owen).

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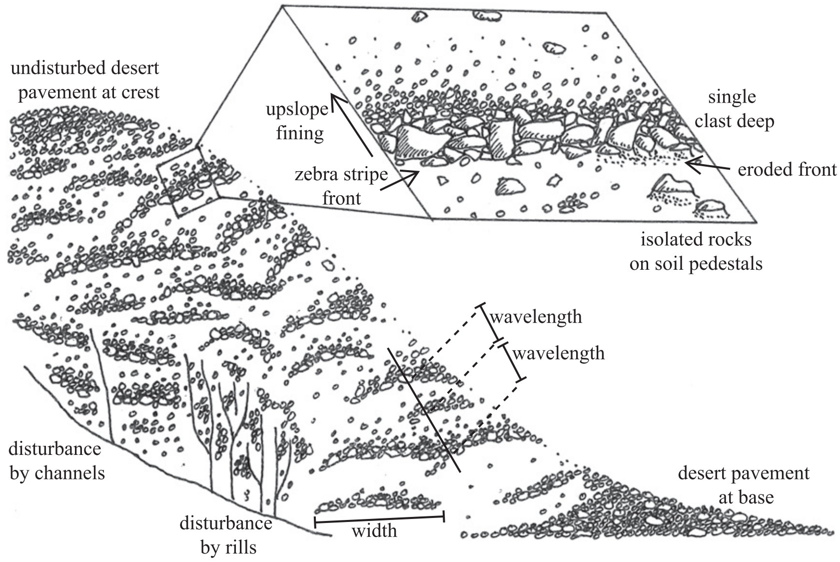

Fig. 1. A drawing highlighting the main features of zebra stripes. The size of the clasts on the hillslope is exaggerated to show sorting. Wavelength was measured along the transects as the distance between fronts, regardless of where the transect intersected the zebra stripe (middle vs. toward one end).

Israel, and used modeling to calculate that the desert pavement and the underlying gravel-free soil formed over the last 1.5–1.9 My.

On gently-sloping surfaces, patterns within desert pavement appear to at least partially preserve the topography and gravel distribution prior to the accumulation of the atmospherically-derived, fine material (Wood et al., 2005; Matmon et al., 2009). In Chile, bar and swale patterns persist in desert pavements on Miocene landforms (Ewing et al., 2006), attesting to both the importance of initial gravel distribution

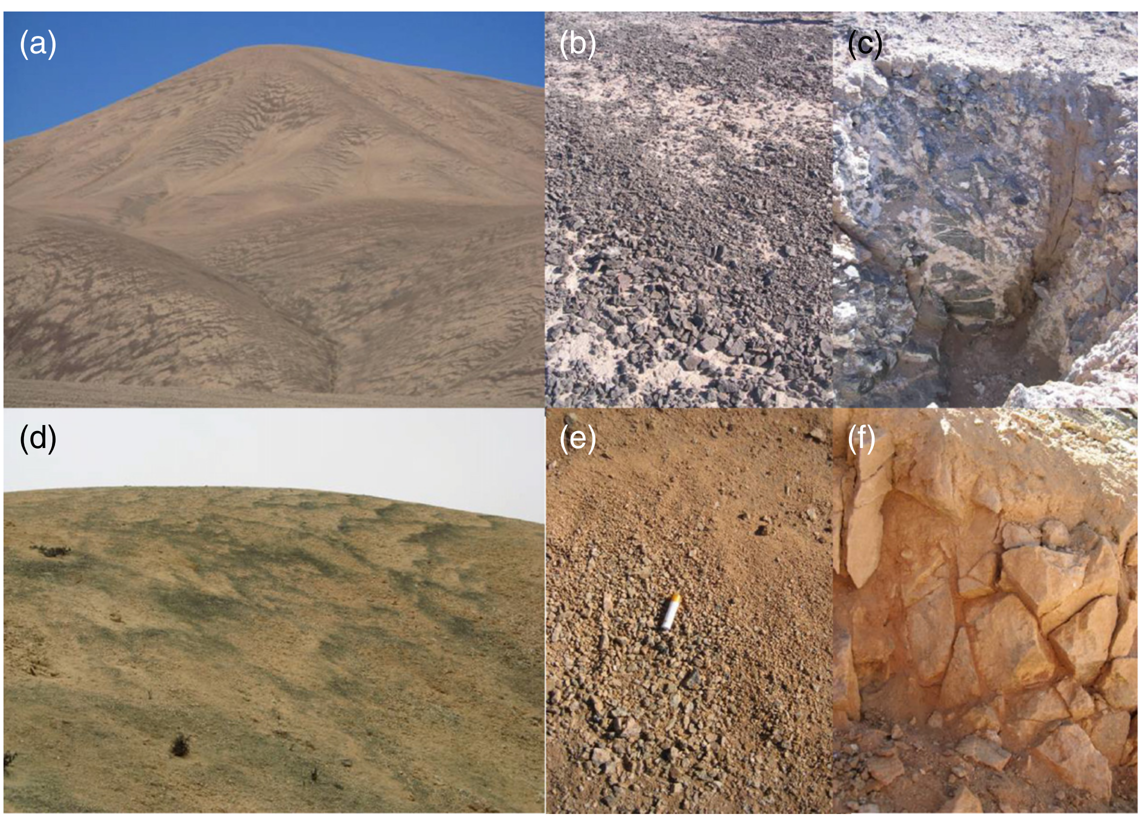

Fig. 2. Examples of zebra stripes. (a) Zebra stripes on a hillslope near Oficina Rosario (OR). (b) Close up of gravel sorting within a zebra stripe on OR, looking upslope. Gravels in the foreground were 4–10 cm in diameter and fined upslope towards a relatively gravel-free zone. The surface of the underlying soil is very smooth and light-colored due to the presence of sulfate salts. (c) Example of a soil profile on OR showing gray, angular rock fragments in a matrix of white gypsum-cemented fines. Brown vertical feature on the right side is a sand-filled crack. Excavation is 1-m-deep. (d) Example of the smaller zebra stripes at CH. In some cases, the fine gravels (the coarsest material) were colonized by lichens, producing the darker gray banding on the hillslope. (e) A close up of a zebra stripe, looking upslope, with an ~8-cm-long lip balm tube for scale. As at OR, particles coarsened downslope, but they were much smaller and the stripe was shorter along-contour. (f) A soil profile on CH showing the thinness of the gravelly soil mantle (~1 cm here) and the fracturing of the underlying bedrock. Fine red dust filled the fractures.