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A unifying model for planform straightness of ripples and dunes in air and water

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ABSTRACT

Geologists, physicists, and mathematicians have studied ripples and dunes for more than a century, but despite considerable effort, no general model has been proposed to explain perhaps the most fundamental property of their morphology: why are some bedforms straight, continuous, parallel, and uniform in planform geometry (i.e. two-dimensional) whereas others are irregular (three-dimensional)? Here we argue that physical coupling along the crest of a bedform is required to produce straight crests and that along-crest flow and sand transport provide effective physical mechanisms for that coupling. Ripples and dunes with the straightest and most continuous crests include longitudinal and oblique dunes in unidirectional flows, wave ripples, dunes in reversing flows, wind ripples, and ripples migrating along a slope. At first glance, these bedforms appear quite different (ripples and dunes; air and water; transverse, oblique, and longitudinal orientations relative to the net sand-transport direction), but they all have one property in common: a process that increases the amount of along-crest sand transport (that lengthens and straightens their crests) relative to the across-crest transport (that makes them migrate and take the more typical and more three-dimensional planform geometry). In unidirectional flows that produce straight bedforms, along-crest transport of sand is caused by along-crest flow (non-transverse bedform orientation), gravitational transport along an inclined crest, or ballistic splash in air. Bedforms in reversing flows tend to be straighter than their unidirectional counterparts, because reverse transport across the bedform crest reduces the net across-crest transport (that causes the more typical irregular geometry) relative to the along-crest transport (that smoothes and straightens planform geometry).

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1. Introduction

1.1. Purpose

Most ripples and dunes are irregular in planform geometry (Fig. 1a–c), but a seemingly disparate assortment of bedforms are unusually regular (Figs. 1d–f, 4–6, and Table 1). These exceptionally two-dimensional bedforms include: (1) wind ripples, (2) bedforms that are oriented parallel or oblique to flow rather than transverse; (2) bedforms migrating along a slope, and (4) bedforms in reversing flows (waves, tides, and seasonally reversing winds). The goals of this review are to consider what these diverse bedforms have in common and thereby learn what processes control bedform straightness.

1.2. Definitions

A variety of measures have been proposed to quantify bedform two-dimensionality or the degree to which bedforms have long straight crests and troughs, constant elevation of crests and troughs, uniform spacing or wavelength, and lack of defects (Tanner, 1967; Allen, 1968a; Venditti et al., 2005a). The two-dimensional bedforms considered here (Figs. 1d–f; 4–6) are exceptionally two-dimensional —more so than most bedforms in unidirectional flows than are typically described as "two-dimensional" (Harms, 1969; Allen, 1977).

Three-dimensional structure of bedforms can be defined by a variety of geomorphic attributes including sinuous crestlines or troughs, crests or troughs with varying elevation (such as scour pits in the troughs), terminations or junctions of troughs and crests, intersecting

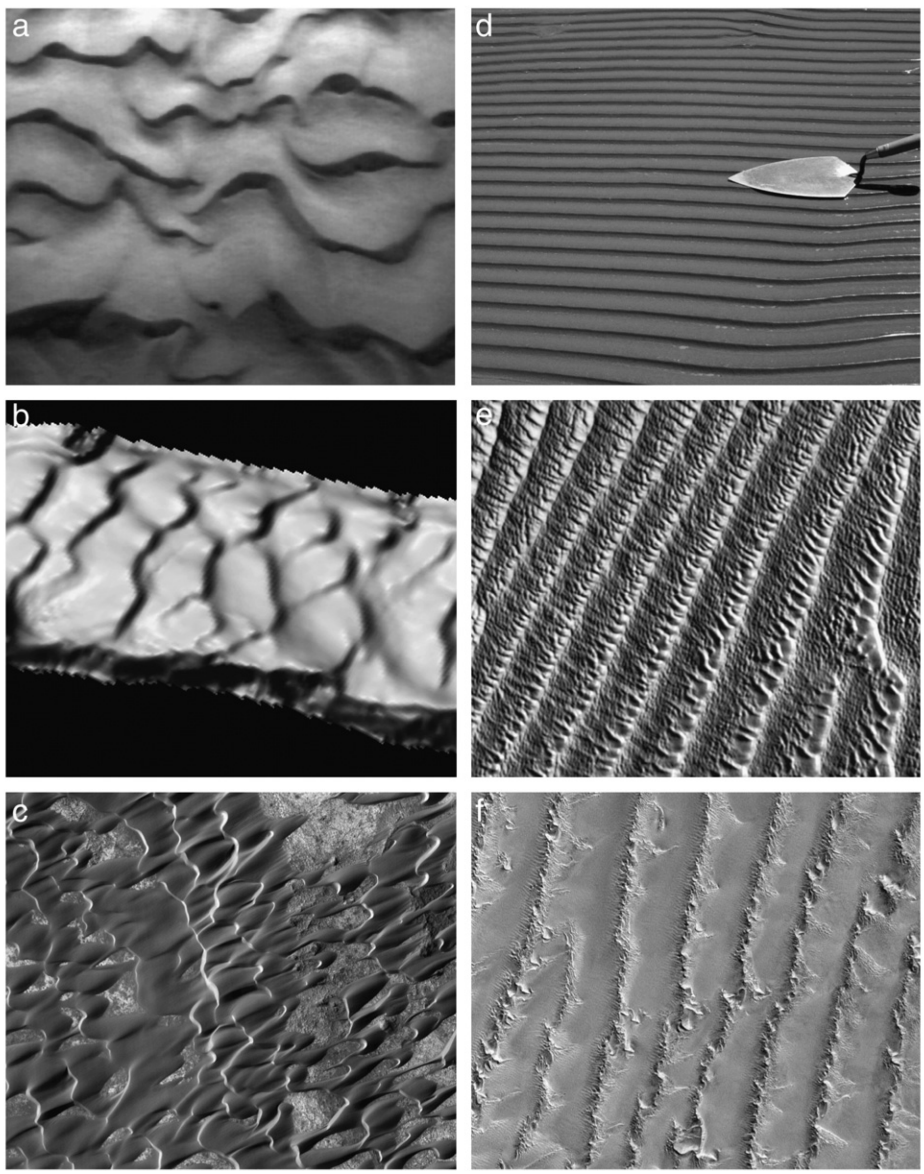

Fig. 1. Three-dimensional ripples and dunes in unidirectional flows (left column a–c) and two-dimensional ripples and dunes in reversing flows (right column d–f). (a) Ripples formed by unidirectional flow in a lab flume; flow is from top to bottom; field of view is 40 cm from right to left. (b) Dunes in unidirectional flow in the Colorado River in Grand Canyon viewed by multibeam sonar (Kaplinski et al., 2009); channel width is approximately 70 m. (c) Crescentic eolian dunes on Mars (winds roughly from right to left; field of view ~6 km × 6 km); (Image: NASA/JPL/University of Arizona; Nili Patera Ripples ESP_017762_1890). Right column shows straight-crested bedforms created by reversing flows. (d) Ripples formed by reversing wave-generated flow on a sand bar in Colorado River in Grand Canyon. (e) Dunes formed by reversing tidal currents, San Francisco Bay, California (Barnard et al., 2011); wavelength is 60 m. Superimposed dunes demonstrate along-crest sand transport (from bottom to top in image). (f) Eolian dunes formed by seasonally reversing winds, Namib Desert; dune wavelength is 2 km. Superimposed dunes demonstrate along-crest sand transport (from bottom to top in image). Landsat Earth as Art series; USGS and NASA.