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“Chevrons” are not mega-tsunami deposits—A sedimentologic assessment

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ABSTRACT

Since the introduction of the term “chevron” for large v- or u-shaped bed forms in Egypt and the Bahamas, others have adopted the term to describe large-scale coastal bed forms in Australia, Madagascar, and elsewhere. These authors interpret “chevron” bed forms as deposits of mega-tsunamis resulting from Holocene oceanic asteroid impacts. We reason that chevron-type bed forms are common and are present far enough from the coast to preclude tsunami genesis. Moreover, we argue that “chevrons” are not mega-tsunami deposits by modeling tsunami behavior and evaluating sediment-transport conditions under which such features formed. We model the southern Madagascar case, with an impact source in the Indian Ocean, and show that a modeled wave approach is inconsistent with “chevron” orientation. We then evaluate sediment-transport conditions under which these “chevron” bed forms could persist, i.e., bed-load transport. In our analysis, no conditions specified generate pure bed-load transport, and most result in pure suspended-load transport.

INTRODUCTION

The term “chevron” was originally used independently by Maxwell and Haynes (1989) and Hearty et al. (1998; also see Bryant et al., 1997) for large, v-shaped, sublinear to parabolic landforms in southwestern Egypt and on islands in the eastern, windward Bahamas (GSA Data Repository Fig. DR1[1]). While the Egyptian “chevrons” are indubitably active eolian features, the “chevrons” in the Bahamas are inactive and have been variously interpreted as eolian bed forms, storm-related features, and large-wave (possibly tsunami) deposits (Hearty et al., 1998; Kindler and Strasser, 2000, 2002; Hearty et al., 2002). In any case, it is clear from cross-bedding within the Bahamian bed forms that they are deposits associated with bed-load transport. In scale and geometry, they resemble modern shallow-water bed forms on the Bahamas platform (Fig. DR1) associated with spillover of currents focused between islands (cays). They also resemble parabolic dunes from around the world (Fig. 1), many of them demonstrably eolian. However, the Bahamian chevrons typically do not repeat regularly, with predictable wavelengths, as do ripples and dunes.

Since introduction of the term “chevron” several others have adopted the term (e.g., Bryant, 2001, and earlier papers; Kelletat and Scheffers, 2003; Abbott et al., 2006a, 2006b, 2007; Scheffers et al., 2008) to describe large-scale, sandy coastal bed forms. These authors interpreted many of these “chevron” bed forms as mega-tsunami deposits of Holocene age (past ~10 k.y.) and suggested that they point to oceanic asteroid impacts (e.g., Masse, 2007). This group of authors tends to reject an eolian, parabolic-dune interpretation, and they liken the forms to giant swash marks.

In a brief essay, Pinter and Ishman (2008, p. 37) challenged the interpretation of “chevrons” as mega-tsunami deposits, based essentially on the principle of Occam’s Razor, arguing that an eolian interpretation is simpler and more reasonable: quoting Carl Sagan (undated), “(precisely because of human fallibility) extraordinary claims require extraordinary evidence.”

A persistent challenge in the history of science, however, is to discriminate between scientific flimflam and outrageous but viable hypotheses. Geoscientists are well aware of some cases where what appeared at the time to be outrageous hypotheses (Davis, 1926) eventually showed scientific merit, commonly after refinement of the original idea, but also sometimes after major opponents died. At the least, outrageous hypotheses can serve heuristic purposes, driving proponents and critics to pursue evidence and arguments.

Perhaps the best-known outrageous hypothesis in the realm of surface processes was J Harlen Bretz’s megaflood hypothesis (Soennichsen, 2008). In fact, one of the main mega-tsunami proponents, Ted Bryant (2001), dedicated his book to Bretz and compared the giant ripples of the eastern Washington Scablands to Bryant’s examples of “chevrons” as a means of arguing for a megaflow. Unfortunately, his comparison is false: the Scabland giant ripples are made of boulders and spaced accordingly, whereas the real comparison in eastern Washington to “chevrons” is the Palouse parabolic dunes of sand (Fig. 2; Table 1).

Are “chevrons” parabolic eolian dunes, mega-tsunami bed forms, or something else? We argue that they are not mega-tsunami deposits by taking a physical approach of modeling tsunami behavior and evaluating sediment-transport conditions under which these features formed. While our strongest argument is that

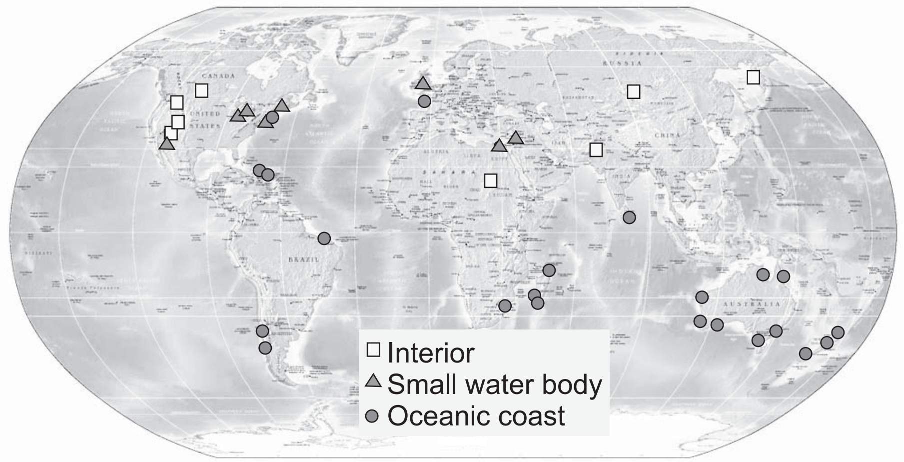

Figure 1. Selected localities around the world of large bed forms identified as parabolic dunes and/or as “chevrons.” Localities are classified by their relationship to a coastline; “interior” cases have no relationship to a coastline; “small water body” cases require improbable impact scenarios; for “oceanic coast” cases, impact hypothesis requires further evaluation. For images, see Figure DR2. Also see Scheffers et al. (2008) for their map of some coastal forms and for satellite images.

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[1] GSA Data Repository item 2009102, supplemental calculations and additional images and references, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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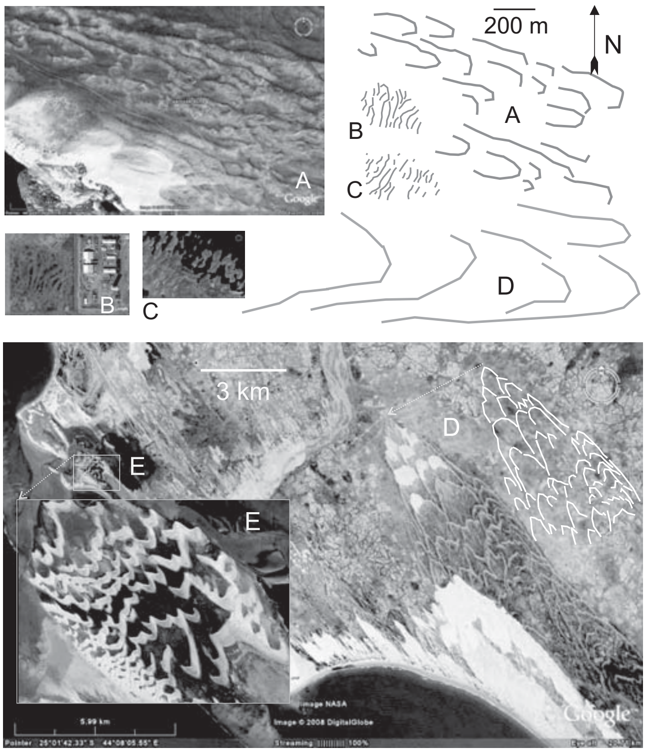

Figure 2. Large bed forms in eastern Washington State (above, left, shown at same scale) and southern Madagascar (below, with inset). Images are from Google Earth. Upper right: Sketch outlines of bed forms A–D all shown at the same scale. A—parabolic dunes in the Palouse region, eastern Washington, directly east of the Columbia River; B—giant current ripples near Spokane, eastern Washington; C—giant current ripples in the Palouse region of eastern Washington; D—coast of southern Madagascar showing "chevrons," sand streaks, and barchans (the latter enlarged in inset, E).

these "chevrons" are not mega-tsunami deposits, we also agree with Pinter and Ishman (2008, and references therein), that these features are mostly eolian parabolic dunes.

BED-FORM CHARACTERISTICS

Basics of Bed Forms

On a mobile bed such as sand, bed forms such as ripples and dunes are repeating, geometrically regular topographic features whose basic characteristics—length *L*, height *H*, and shape—are predictably scaled based primarily on grain size (more properly, settling velocity, w_s), shear stress τ, and flow depth *h*. Other factors include variation in bed erodability (e.g., from vegetation), sediment supply, flow structure, and bed roughness. Ripples, in our definition, are scaled by grain size *D*, which scales saltation length, where 1000*D* is approximately bed-form wavelength *L*. Dunes are scaled with the typical excursion length of grains, and will grow until they are limited by sediment availability or flow depth *h*, where bed-form height $H < 0.5h$. The simplest types of these bed forms have typical aspect ratios *L*/*H* of 10–30, a well-defined cornice, and angle-of-repose lee faces leading to grain-flow cross-stratification. Longer bed forms may have significantly larger aspect ratios and lower-angle lee faces. Some use the term "sand waves" for these larger structures, or for those with larger *L*/*H* ratios.

Ripples and dunes are stable on the bed when the skin-friction component of shear stress is low, so grains are saltating regularly. Because the bed forms themselves extract momentum from the flow, low skin friction is maintained as bed forms grow. As shear stress increases, however, grains lose regular contact with the bed, generating the grain-transport condition known as suspension, where grains travel with the flow rather than having regular bed contact (Yalin, 1977). When the suspension condition is reached, bed forms wash out, leaving a plane bed and generating planar lamination. This transition is not instantaneous: as shear stress increases, bed forms of increasing wavelength wash out; i.e., ripples wash out before dunes.

The transition from bed load (and bed forms) to suspended load (and plane bed) has been quantified with the dimensionless Rouse number $p = w_s/\kappa u_*$, where w_s is settling velocity of the grain size of interest, κ is von Kármán's constant (~0.4), and shear velocity $u_* = \sqrt{\tau_b/\rho}$, where τ_b is boundary shear stress and ρ is fluid density (Vanoni, 1975; Yalin, 1977). When $p >$ ~2.5 for a particular grain size in a particular fluid, bed-load conditions prevail (e.g., Julien, 1998) and bed forms will exist in that grain size. When $p <$ ~0.8, suspended-load conditions prevail (e.g., Julien, 1998), and bed forms of the particular grain size will wash out.

TABLE 1. SUMMARY OF SOME RELEVANT BED-FORM CHARACTERISTICS

		Grain diameter, D (m)	Bed-form length, L (km)	Bed-form height, H (m)	L/H (m/m)	L/D (m/m) × 10^4
a	Subaqueous sand ripples, typical	0.00015	0.00015	0.01	15	0.1
b	Subaqueous sand dunes, typical	0.00015	0.015	1	20	10
c	Washington State giant ripples	0.02–0.3	0.04–0.1	1–5	20	~0.03–0.2
d	Washington State parabolic dunes	~0.001	~0.3	~3	~100	~25
e	Oolite chevrons, Bahamas*	0.002	3–10*	8–25	~400	150–500
f	Australia "chevrons"	0.002	0.5–3	~3–30†	~100–200	25–150
g	Madagascar "chevrons"	0.002	0.5–3	~3– 30†	~100–200	25–150

*Not regularly repeating.

†Estimates based on general characteristics in literature.

Sources: a, b—Middleton and Southard (1984); c—Baker (1973); d—satellite and field; e—Hearty et al. (1998); f—Kelletat and Scheffers (2003); g—satellite, Abbott et al. (2006b).

Basic Characteristics of Parabolic Dunes

Parabolic dunes are defined by their characteristic u shape, with the open part of the u facing upcurrent (Figs. 2 and 3). The form is characteristic of cases where there is some sediment trap such as vegetation to anchor the tails; thus parabolic dunes are most common in semiarid climates, and also along marine, lake, and river shorelines. The theory of parabolic dunes has been well studied using case histories of vegetation changes (e.g., Tsoar and Blumberg, 2002; Duran et al., 2008), laboratory simulations (Duran et al., 2008), and numerical simulations (Nishimori and Tanaka, 2001; Duran et al., 2008; Nield and Baas, 2008). Both Duran et al. (2008) and Nield and Baas (2008) show that in the same fluid dynamic conditions, unvegetated surfaces yield barchan dunes, and vegetation anchoring yields parabolic dunes (see Figs. 2D and 2E). Virtually all well-documented cases of parabolic dunes are eolian, but it is possible that shallow-marine vegetation might also serve as anchors, creating the condition for parabolic dunes on carbonate platforms, such as those in the Bahamas (Fig. DR1).

Basic Characteristics of "Chevrons"

In order to assess the mega-tsunami interpretation, we summarize the basic physical characteristics of the "chevron" bed-form cases where such an interpretation has been invoked, in particular Australia and Madagascar (Table 1). Scientists who have worked in the Bahamas have not invoked impact-generated tsunamis. Bed-form parameters of interest include orientation (provides transport direction; not tabulated), bed-form height (provides minimum flow depth), component grain size (for model-

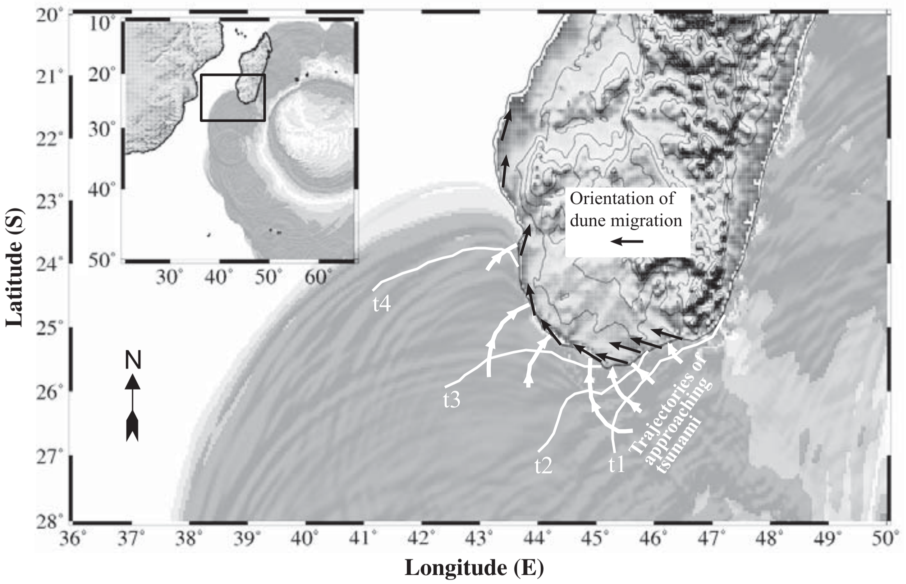

Figure 3. Modeled tsunami propagation from point source located in area specified by Masse (2007) and suggested in abstracts by others (e.g., Abbott et al., 2006a, 2007). Time lines of wave crests in white, with wave approach at right angles. Orientation of large bed forms shown in black (see also Figs. 3D, 3E).

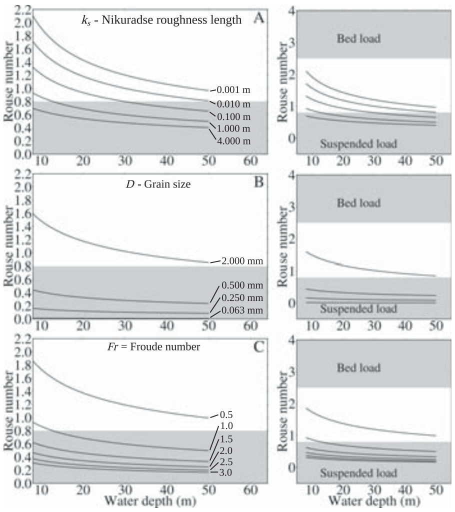

Figure 4. Plots of Rouse number versus water depth. A: Different lines represent different roughness lengths; grain size *D* = 1 mm in all cases so settling velocity is kept constant. B: Different lines represent different grain sizes; Froude number (*Fr*) and roughness length are kept constant at 1.0 (dimensionless) and 1 m, respectively. C: Different lines represent different Froude numbers; grain size is constant at 1 mm, and roughness is 1 m.

ing sediment transport), and elevation of the "chevrons" above sea level (for maximum flow depths). For elevation above sea level, we do not consider lower sea levels of the early Holocene (>5000 yr ago); lower sea level would only make the mega-tsunami argument weaker.

ASSESSMENT OF THE MEGA-TSUNAMI INTERPRETATION

Impact-Tsunami Assessment

The orientation of these bed forms (e.g., Figs. 2, DR1, and DR2) can generally be mapped via satellite images (also see Scheffers et al., 2008). By examining such images, we originally became skeptical of the tsunami interpretation because many of the "chevrons" are oriented at low angles to the coastline, and the orientations persist over distances and topographies that should steer flowing water, but not wind.

We chose the southern Madagascar case to test the tsunami hypothesis by modeling tsunami behavior. At what angle would the tsunami approach the coast? We logically assume the long axes of these bed forms to be (or to have been) parallel to the flow. We model a tsunami with a circular source located at the proposed impact site (Fig. 3). We use an initial wave shape corresponding to a small impact in deep water (as in Ward and Asphaug, 2000) and propagate the wave over regional bathymetry, using MOST code (Titov and Synolakis, 1998). In modeling, we consider only relative wave amplitudes, because in this case we are more interested in the pattern of wave approach to the coast.

Modeled wave approach is inconsistent with bed-form orientation (Fig. 3). The waves generated by the impact spread out in a circular wave pattern, and when they enter the nearshore area, the wave fronts refract, resulting in wave crests being almost parallel to the shore and wave approach perpendicular to that (Fig. 3). Thus the expected sediment-transport direction and bed-form orientation would be perpendicular to the shoreline, or nearly so, unless steered by local topography. However, in Madagascar and elsewhere, the bed forms are not oriented perpendicular to the shoreline, as for a tsunami approach, but rather at various angles (Fig. 3; also see Scheffers et al., 2008). One might argue that certain coastal chevrons, but only those at very high angles to the coast, are the result of edge waves, generated by the interaction between the incoming waves and coastal geometry and nearly normal to the crests of refracted incoming waves. However, edge waves contain less energy than the refracted incoming waves, due to frictional energy loss of inundating water masses. This loss results in progressively smaller amplitudes and shorter wavelengths, giving rise to substantially and progressively smaller inundation. Significant edge waves did not develop in our model.

Sediment-Transport Assessment

As discussed above, authors such as Abbott et al. (2007), Bryant (2001), and Kelletat and Scheffers (2003) have postulated that "chevrons" are coastal bed forms (which they sometimes call dunes and sometimes liken to swash marks) developed under mega-tsunami flow conditions. We make the case that "chevrons" are regular bed forms, as clearly illustrated in the Madagascar case (Fig. 2). As bed forms, they must have developed in flow that met physical conditions allowing bed-load transport. That is, the Rouse number p must exceed 2.5. With the help of the Rouse number, we can test the postulate that "chevrons" are tsunami deposits; i.e., do bed-load conditions exist in subaqueous flows of the scale suggested?

For the postulated flows and given grain sizes, we investigate transport regimes in a simplified manner. For example, we consider depth-averaged, steady flow and scale that flow by the Froude number $Fr = u/\sqrt{gh}$, where u is flow velocity, g is gravity, and h is water depth. Because the flow of interest is overland flow during inundation, water depth is understood as flow depth.

The Rouse number is a relationship between grain settling velocity w_s and shear velocity u_*, so to obtain Rouse numbers for the "chevron" cases of interest (Table 1; Fig. 4), we estimate those parameters. We obtain settling velocities for given grain sizes D from a method given by Ferguson and Church (2004). We estimate shear velocities with the law of the wall under hydraulically rough conditions and with flow velocity scaled by the Froude number Fr (Appendix DR1):

$$u_* = \frac{Fr\sqrt{gh}\kappa}{\log\left(30h/k_s\right)},$$

in which k_s is the Nikuradse roughness length. We examine the relationship between p and h under the influence of varying roughness k_s, grain size D, and Froude number Fr and ask, when do bed-load conditions obtain?

We let k_s vary over four orders of magnitude ($k_s = 0.001$ m to 4.000 m) to study the influence of larger roughness elements (Fig. 4A) because in our approach, we cannot account for influence of bed forms on transport regimes. Evaluating form drag realistically requires three-dimensional (numerical) modeling with given bed-form geometry and accurate knowledge of the flow. The larger the roughness length, the smaller the Rouse number (Fig. 4A) for constant flow depth, because larger roughness lengths generate larger friction velocities at constant flow conditions ($Fr = 1$).

To examine the influence of grain size D on Rouse number p, we plot p as a function of flow depth h for varying D (Fig. 4B). Larger grains settle faster and therefore have larger Rouse numbers. For example, in the cases examined, the Rouse numbers for $D = 0.5$ mm (the transition from medium to coarse sand) would be well below $p = 0.8$, which means that this grain size would always be transported as suspended load.

We also examine the influence of Froude number on Rouse number (Fig. 4C). For all $Fr > 1$, suspended-load conditions obtain exclusively. For $Fr = 1$ and given grain size and roughness length, the Rouse number would be <0.8 for all flow depths >13 m, 13 m being realistic for overland flow of impact-generated tsunami waves (Weiss and Wünneman, 2007; Korycansky and Lynett, 2007).

Minimum flow depth also can be approximated by $2H$ (H is bed-form height). Because many of the "chevrons" have heights of >4 m, we cut off our diagram at depth $h = 8$ m (Fig. 4), and many of these large bed forms have heights >10 m, giving flow depths of at least 20 m.

None of the conditions specified generates pure bed-load transport ($p > 2.5$) (Fig. 4), which also is the condition for bed-form stability. Most of the conditions specified result in pure suspended-load transport ($p < 0.8$). For example, if we take a "chevron" made of 1 mm sand, having a bed-form height of 10 m (therefore a minimum flow depth of 20 m) and assume a k_s of 1 m, the Rouse number for $Fr = 1$ is 0.7 and for $Fr = 2$ is 0.4. Many of the "chevrons" are found at elevations of >50 m (up to 200 m) above sea level (Kelletat and Scheffers, 2003; Abbott et al., 2006b). If these "chevrons" really were subaqueous, under such flow depths bed-load transport is not possible (Fig. 4).

CONCLUSIONS

We have presented three lines of argument that reject the mega-tsunami hypothesis for "chevron" bed forms. First, these features are common in the interiors of continents and along smaller bodies of water (Fig. 1). Second, the long axes of many of these "chevrons" are inconsistent with wave-refraction patterns, for example in southern Madagascar (Fig. 3). Finally, we can exclude bed-load transport conditions for virtually all flows specified by the hypothesis (Fig. 4). The extraordinary claim of "chevron" genesis by mega-tsunamis cannot withstand simple but rigorous testing.

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