Origin of giant wave ripples in snowball Earth cap carbonate

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ABSTRACT

The most extreme climate transitions in Earth history are recorded by the juxtaposition of Neoproterozoic glacial deposits with overlying cap carbonate beds. Some of the most remarkable sedimentary structures within these beds are sharp-crested (trochoidal) bedforms with regular spacing of as much as several meters that are often interpreted as giant wave ripples formed under extreme wave conditions in a nonuniform postglacial climate. Here we evaluate this hypothesis using a new bedform stability diagram for symmetric oscillatory flows that indicates that the first-order control on the formation of trochoidal rather than hummocky bedforms is sediment size, not wave climate. New measurements of bedform wavelengths and particle sizes from the ca. 635 Ma Nuccaleena Formation, Australia, indicate that the giant ripples are generally composed of coarse to very coarse sand; most are within the trochoidal bedform stability phase space for normal wave climates. Moreover, numerical simulations of flow over fixed bedforms show that symmetric trochoidal ripples with a nearly vertical angle of climb may be produced over long time periods with variable wave climates in conjunction with rapid seabed cementation. These data reveal that, rather than extreme wave conditions, the giant wave ripples are a consequence of the unusual mode of carbonate precipitation during a global carbon cycle perturbation unprecedented in Earth history.

INTRODUCTION

Neoproterozoic ice ages and subsequent postglacial hothouses mark the most extreme climates in Earth history (e.g., Kirschvink, 1992). Weathering fluxes, primary productivity, and the carbon cycle were severely perturbed during these intervals (e.g., Hoffman et al., 1998), and the physical stratigraphic record of snowball Earth deglaciation is correspondingly exceptional, particularly of the late Neoproterozoic Marinoan event (e.g., Kennedy, 1996). In many localities, meter- to decimeter-thick cap carbonate units spanning the ca. 635 Ma terminal deglaciation to early postglacial transition feature 1–4 strata-bounded sets of long, regularly spaced (~1–6 m wavelength), symmetric cuspatte sedimentary structures (Fig. DR1 in the GSA Data Repository1), referred to as trochoidal bedforms. Although a number of origins have been proposed (e.g., James et al., 2001), the leading hypothesis is that these strata are the result of wave ripples (e.g., Allen and Hoffman, 2005a; Jerolmack and Mohrig, 2005), albeit at a size substantially larger than most modern examples. Allen and Hoffman (2005a) inferred that the giant ripples formed under extremely large waves (wave periods, $T = 21–30$ s; wave heights, $H > 7.5–12$ m) that transported sediment in water depths of $h = 200–400$ m, a scenario unlike any wave conditions in modern ocean basins. Jerolmack and Mohrig (2005) countered that this interpretation may constitute one of many valid reconstructions, but did not consider the trochoidal ripple morphology, which Allen and Hoffman (2005b) contended requires extreme wave conditions. The heart of this debate revolves around assumptions used to invert geologic data, in particular the conditions under which trochoidal ripples form. Herein we develop a new stability diagram for large-scale bedforms developed under oscillatory flow and show that carbonate giant wave ripples are expected to have formed under normal wave conditions, given their coarse sediment sizes. Our findings have significant implications for reconstructing paleoenvironmental conditions from large-scale wave ripples, in particular during the Neoproterozoic, when climate extremes and diversification of multicellular life were extraordinary (e.g., Hoffman and Li, 2009; Pierrehumbert et al., 2011).

OSCILLATORY BEDFORM STABILITY

Our new bedform stability diagram is based in part on an exhaustive compilation by Pedocchi and Garcia (2009) that highlights, for purely oscillatory flow, a robust boundary separating large two-dimensional (2-D) trochoidal bedforms from hummocky bedforms as $U_c = 25\omega^*$, where $U_c$ is the near-bed maximum wave orbital velocity and $\omega^*$ is the particle settling velocity. Given this constraint and an orbital diameter, the stability-field boundary can be inferred from a unique combination of grain size and wave period (or orbital velocity, equivalently) (Fig. 1A). The orbital velocity is directly related to the near-bed orbital diameter, $d_o$ by definition (i.e., $d_o = U_c/T\pi$) and orbital diameter scales with bedform wavelength, $\lambda$, for large orbital bedforms following $\lambda = C_d d_o$, where $C_d = 0.65$ (e.g., Pedocchi and Garcia, 2009). To complete the bedform-stability phase space, we calculate the boundary for incipient sediment motion following Young and Yin (2006), and for upper plane bed as $\tau_r = 3$ (where $\tau_r$ is the Shields number) based on our reanalysis of experimental data in purely oscillatory flow (Dumas et al., 2005; Cummings et al., 2009). Results for a typical example case where $d_o = 3.07$ m (i.e., $\lambda = 2$ m) show that, for wave conditions comparable to modern observations during fair weather and storms (i.e., $T < 15$ s), bedforms are expected to be hummocky for grain sizes $D < 0.2$ mm, approximately equivalent to fine sand and finer, or alternatively, the bed state is predicted to be planar (Fig. 1A). For the same wave conditions, trochoidal bedforms occur for $D > 0.5$ mm (coarse sand and coarser) except under very small wave periods (i.e., $T < 5$ s) where hummocks can develop.

Although experiments using oscillatory ducts can reproduce the entire parameter space in Figure 1A, the same is not true for surface gravity waves in the world’s oceans, which have physical limits. The shortest wave period corresponds to waves that are just steep enough to break (Muir Wood, 1969), $|H| > 0.142$ tanh $\left(2\pi h/L\right)$, where $H$ is wave height, $L$ is the wavelength, and $h$ is water depth (Fig. 1B). The longest possible period for waves of a given height is $T = C_22\pi U_c/g = 2\pi C_2\sqrt{H/g}$ (where $g$ is gravitational acceleration, and $C_2 = 1.5$ and $C_2 = 0.3$ are empirical coefficients), based on observations of fetch-limited conditions that span orders of magnitude in wind velocity (Bretshneider, 1959). These two bounds, along with Airy wave theory and a constraint on bedform wavelength, define the conditions under which wind-driven surface gravity waves produce symmetric oscillatory flow (Fig. 1B).
To perform a reconstruction, we require information on water depth, bedform wavelength, and sediment size (Figs. 1A and 1B). Water depth is the most difficult parameter to characterize from ancient deposits, and therefore we fold this uncertainty into the bedform stability diagram by recasting it in terms of sediment diameter and bedform wavelength (Fig. 1C), allowing for the full range of shelf water depths (h < 100 m; Fig. 1B). Thus, for some combinations of sediment size and bedform wavelength, multiple bed states are possible given the range of possible wave periods (or orbital velocities) observed for h < 100 m. This stability diagram (Fig. 1C) reconciles long-standing debates concerning the origin of large-scale oscillatory bedforms (e.g., Swift et al., 1983; Quin, 2011) and indicates that large trochoidal bedforms are favored for D > ~0.5 mm, whereas hummocky bedforms dominate the phase space for fine sand and very fine sand (D < 0.2 mm), regardless of wave climate and water depth. These predictions are supported by observations that meter-scale hummocky cross stratification occurs almost exclusively in fine and very fine sand (e.g., Dott and Bourgeois, 1982; Myrow et al., 2008), and that large 2-D trochoidal ripples typically occur in coarse sand and gravel (e.g., Leckie, 1988; Cummings et al., 2009).

**NEOPROTEROZOIC GIANT WAVE RIPPLES**

Our bedform stability model is similar to that used for paleohydraulic reconstruction of Neoproterozoic giant wave ripples by Allen and Hoffman (2005a); however, they assumed that trochoidal ripples form only at the threshold for sediment motion. Allen and Hoffman (2005a) reported D = 0.12 mm for giant ripples in the Mackenzie Mountains (Canada), and the threshold condition for this sediment size yields extremely large wave periods (T > 30 s) (e.g., Fig. 1A), and consequently extremely large water depths (h > 400 m) and wave heights (H > 20 m) (e.g., Fig. 1B).

A more plausible alternative to invoking extreme wave conditions is that the ripples formed under normal wave conditions, but in relatively coarse sediment (Fig. 1C). Bedform wavelengths are readily measured in outcrop, but measuring sediment diameters in diagenetically stabilized dolostone lithologies is more difficult. We compiled data from previous studies that reported measurements of wavelength and sediment size from large 2-D trochoidal wave ripples in Neoproterozoic cap carbonate deposits (Table DR1 in the Data Repository). To supplement these data, we measured bedform wavelengths and grain sizes from several ca. 635 Ma Australian cap dolostone units equivalent to the Nuccaleena Formation (Raub et al., 2007) that contain large trochoidal wave ripples. Bedform wavelengths were measured directly on dip slope–exposed bedding planes in the field, perpendicular to ripple axes. Sediment sizes were measured in thin section by transmitted-light and reflected-light microscopy, often using a white-card method (e.g., Zenger, 1979) to reveal relict grain textures in the recrystallized dolostone (Fig. 2).

The data show large mean sediment diameters (D > 0.5 mm) with clear examples of very coarse sand (D = 1–2 mm) (Table DR1), consistent with common reports of macropeloids in cap carbonate beds preserved elsewhere (e.g., James et al., 2001; Hoffman and Schrag, 2002). Given the observed bedform wavelengths, this places all but one of the observations in the predicted zone for trochoidal bedforms or in ambiguous domains of the solution space (Fig. 1C). Consequently, we conclude that large trochoidal ripples in snowball Earth cap carbonate beds are best explained by formation under normal wave conditions, and that a postglacial climate characterized by extreme sustained winds (e.g., Hoffman and Li, 2009) or heightened hurricane intensity (e.g., Pierre-humbert et al., 2011) is not necessary.

**DISCUSSION**

If the giant wave ripples common to Maroon cap carbonate deposits can be explained by normal wave climates given the observed coarse particle sizes, then why are these bedforms, which are abundant following the ca. 635 Ma deglaciation, not more common in the sedimentary record? We hypothesize that the answer is tied to the unique style of carbonate precipitation and deposition associated with Maroon cap carbonate. In silicilastic environments, large grains are rarely transported far from shore, and, with the exception of ravinement surfaces, most shelves are dominated by fine sand and mud; thus hummocky bedforms are associated with normal storm waves at shelfal depths (Fig. 1C) (e.g., Swift et al., 1983; Passchier and Kleinhans, 2005). Carbonate-rich settings do not have the same limitation because large grains can be produced in situ (or nearby), particularly after the evolution of animal and algal skeletons.

In addition to coarse grains, one of the most striking features of the cap carbonate giant wave ripples is a near-vertical direction of climb (Fig. DR1) (Allen and Hoffman, 2005a). This seems to imply formation under a steady wave climate, because nearly symmetrical waves...
are required to avoid net crest migration and preservation of dune-scale cross-stratification (e.g., Arnott and Southard, 1990). Although preferential north-south orientations of ripple crests suggest zonal winds (Hoffman and Li, 2009), it seems unlikely that fair-weather wave base was consistently more than an order of magnitude deeper than today and that wave climate remained exactly the same, even with zonal winds, over the time required to produce thick (0.5–2 m) ripple-laminated deposits at many locations globally. A similar problem exists if these deposits are to be explained by multiple storm events, and formation during a single storm event seems unlikely given the extremely high deposition rates that would be required (Jerolmack and Mohrig, 2005). Moreover, correlatable paleomagnetic reversals in cap carbonate units, including those studied over, correlatable paleomagnetic reversals in required (Jerolmack and Mohrig, 2005). More-extremely high deposition rates that would be a single storm event seems unlikely given the multiple storm events, and formation during exists if these deposits are to be explained by many locations globally. A similar problem thick (0.5–2 m) ripple-laminated deposits at zonal winds, over the time required to produce climate remained exactly the same, even with magnitude deeper than today and that wave base was consistently more than an order of 2009), it seems unlikely that fair-weather wave crests suggest zonal winds (Hoffman and Li, (e.g., Arnott and Southard, 1990). Although preservation of dune-scale cross-stratifi-ment (medium to coarse sand and coarser), choidal ripples form in relatively coarse sedi-ment (i.e., the equilibrium case), showing separation in lee of ripple crest (see text). Lengths of velocity vectors are proportional to magnitude of velocity. Linear color scale reflects relative velocity magnitude. Boundary conditions were free slip at upper boundary, no slip at bed, and periodic on side boundar-ies. Time-dependent velocity field was calculated with lattice Boltzmann method for turbulent flow (Reynolds numbers ranging from 10^4 to 3 x 10^6) using large-eddy closure (e.g., Aidun and Clausen, 2010). B: Normalized boundary shear stress (dimensionless) at instant shown in A. C: Normalized, time-averaged boundary shear stress (dimensionless) for five simulations with different values of λ/d_o. Stress is averaged over half wave cycle in which mean flow is to right. from that predicted to be in equilibrium with the ripple wavelength (λ/d_o = 0.65) to flows with λ/d_o ranging from 1.30 to 10.38. A comparison of the stress profiles (Fig. 3C) reveals that simulations with d_o different from the equilibrium case have a similar form, including the impor-tant characteristic that the steepest shear stress gradient is in the lee of the ripple crest. Thus, depositional patterns during transport events may have mimicked the inherited topography of the cemented or stabilized bed despite changes in wave conditions and potentially even changes in sediment-size inputs.

**CONCLUSIONS**

Bedform stability relationships for purely oscillatory flow show that large (λ > 1 m) tro-choidal ripples form in relatively coarse sediment (medium to coarse sand and coarser), whereas large hummocky bedforms require finer sediment, generally fine to very fine sand. Given the coarse sediment that composes cap carbonate giant wave ripples, the trochoi-dal bedforms are best explained as a result of normal wave climates without extreme winds...
or enhanced hurricanes. Instead, the important aspects of cap carbonate deposition that facilitated synthesis of these large bedforms were (1) production of large grains directly on the shelf (either produced in situ or drowned during post-glacial transgression) that allowed the stability of trochoidal ripples, and (2) high syndepositional cementation rates that allowed aggradation and preservation of these features. These anomalous cap carbonate deposition regimes must have been globally common, but regionally and temporally variable, since wave-ripple horizons within individual cap carbonate units are discrete. Thus, giant wave ripples are part and parcel of a larger suite of structures (e.g., Hoffman and Schrag, 2002) that point to significant perturbations of the carbon cycle that are unlike any other interval in Earth history.

ACKNOWLEDGMENTS

Lamb acknowledges support from the donors of the American Chemical Society Petroleum Research Fund. Fischer acknowledges support from the Agouron Institute. Raub was supported by National Science Foundation grant EAR-0739105. We thank Tony Prave, John Southard, and Paul Hoffman for informal reviews and delightful discussions. David Mohrig and Bob Dalrymple provided formal reviews that strengthened the final manuscript.

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Manuscript received 6 December 2011
Revised manuscript received 26 March 2012
Manuscript accepted 2 April 2012
Printed in USA
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Published in *Geology*, 2012.

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Table DR1. Giant wave-ripple sediment sizes and wavelengths from this study and others (James et al., 2001; Hoffman and Schrag, 2002; de Alvarenga et al., 2004; Halverson et al., 2004; Allen and Hoffman, 2005; Hoffman et al., 2007). Wave ripple deposits analyzed are distributed globally (e.g., Hoffman and Li, 2009). n refers to the sample size. The wavelength range represents the maximum and minimum of reported wavelengths. Wavelength mean is calculated as the median of the range if n is unknown. The grain size measurements were made in cap carbonates that contain giant wave ripples, although in few cases are wavelengths reported systematically and paired with directly constituent grain size photomicrographs or reported statistics. We excluded studies where reported grain size sampling could not be confirmed to be from wave-ripple horizons (Kennedy, 1996; James et al., 2005; Jiang et al., 2006; Corkeron, 2007; Fairchild and Kennedy, 2007; Halverson et al., 2007; Nedelec et al., 2007). Measured diameters in the 2-D thin section for this study were corrected to represent 3-D particle diameters (Kong et al., 2005), and the mean diameter by mass was calculated from the resultant size distribution. Our particle size estimates are imperfect as they only count rare preserved grains (Fig. 2).
Figure DR1. – Examples of a giant trochoidal wave ripple from the Nuccaleena Formation, Australia.
Figure DR2. Bedform stability diagram for linear pure oscillatory waves as a function grain diameter and bedform wavelength. This is the same as Fig. 1A in the manuscript, except here calculations are made assuming modern ocean conditions and siliciclastic sediment (water density $= 1028 \text{ kg/m}^3$, water viscosity $= 10^{-6} \text{ m}^2/\text{s}$ and particle density is 2650 $\text{ kg/m}^3$), rather than a warm ocean and carbonate grains. Changing these parameters has little effect on the stability boundaries. Ambiguity in the stability boundaries reflects uncertainty in the water depth ($1 < h < 100 \text{ m}$) and wave climate assuming Airy wave theory and conditions for wave breaking and fetch-unlimited seas. See text for details on bedform stability criteria. Some bedforms (e.g., hummocks, plane bed) may occur outside of our solution space, for example, in the surf zone where waves are asymmetric and nonlinear. Source codes to reproduce this diagram with different inputs of densities, water viscosity, and water depths of interest can be obtained from the Data Repository.
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