Long-lived deepwater antidunes: Outcrop description of low-angle undulating, symmetric, upflow accreting bedforms within supercritical dominated slope deposits in the Fish Creek-Vallecito Basin, Late Miocene Gulf of California

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Abstract

Antidunes are a fixture in the Froude supercritical realm of bedform stability diagrams but are generally short-lived features in modern open channel settings. Interpreted antidune outcrop examples are thus restricted to environments conducive to rapid deceleration and sedimentation such as washover fans, glacial outburst flows, and pyroclastic ash-surges. In deepwater environments, evidence from modeling, seafloor bathymetric studies, and direct turbidity current observation increasingly suggests that sediment gravity flows often reach Froude supercritical flow states along moderately steep basin-margin slopes. While turbidity currents are net depositional, antidunes have generally been assumed not to preserve in deepwater deposits out of bias to their open channel ephemerality.

Spatially extensive slope turbidites of the Fish Creek-Vallecito Basin in the Anza Borrego Desert State Park of southern California reveal a variety of bedsets containing low-angle, symmetrical, undulating bed geometries that stack opposite to paleocurrent indicators. The turbidites, developed on steep marginal slopes during the initial opening of the Gulf of California, contain three primary facies: 1) 10-45 cm thick, medium-grained, normally graded sandstone beds, 2) 1-15 cm thick, fine-grained sands interbedded with silty mudstones, and 3) 50-100 cm thick laminated silty mudstones. 5-10 m-thick bedsets are composed of ~20-30 sigmoidal beds. Beds emerge tangentially as thin, flat, and fine-grained sediments that then transition downflow into thicker, coarser, upstream inclined sediments before transitioning back into thinner, finer deposits that flatten and/or recline downflow as a full waveform. Waveforms are 3-7 m in amplitude, 75-100 m in wavelength with dip angles generally <10°. Bioturbated (1-3 cm) mudstone caps to sandstones indicate that bedding geometries and stacking patterns were sustained across flow events through time. Bedforms are interpreted as antidunes, the first such-recognized preserved, long-lived, large-scale antidunes in a deepwater setting.

Background, Introduction, & Motivation

- Deepwater slope environments are important both as repositories of sediment and as the surface down which sediments are transported to the basin floor. Oftentimes, slopes are often assumed as low-energy sites of mud accumulation (Galloway, 1998) as focus is applied to channelized corridors of sediment erosion and bypass. This study examines an exception to the assumption, **deepwater slope systems that actively aggrade sand-rich deposits**.
- One active process of particular importance is the occurrence of **Froude supercritical sediment gravity flows** (hereon 'supercritical flows'). Flows become supercritical when the inertial forces (velocity) exceed the gravitational forces acting on the flow (Eqn 1). This distinction has important ramifications for slope and basin fill evolution. Conceptually, supercritical flows travel at velocities greater than the phase speed a wave would travel at the free interface. Thus, disturbances to the flow will not be translated or "felt" upflow.

$$Fr_d = \frac{U}{\sqrt{\frac{\rho_s - \rho_a}{\rho_s} gh}}$$

$$Densimetric\ Froude\ Number (Fr_d) = \frac{Intertial\ Forces}{Gravity\ Forces}$$

$Fr_d < 1$ → "Subcritical" flow; $Fr_d \approx 1$ → "Critical" flow
$Fr_d > 1$ → "Supercritical" flow

U = depth averaged velocity
ρ_s = sediment-laden fluid density
ρ_a = ambient fluid density
g = gravitational acceleration
H = flow thickness

Equation 1: Densimetric Froude Number, from Komar (1971)

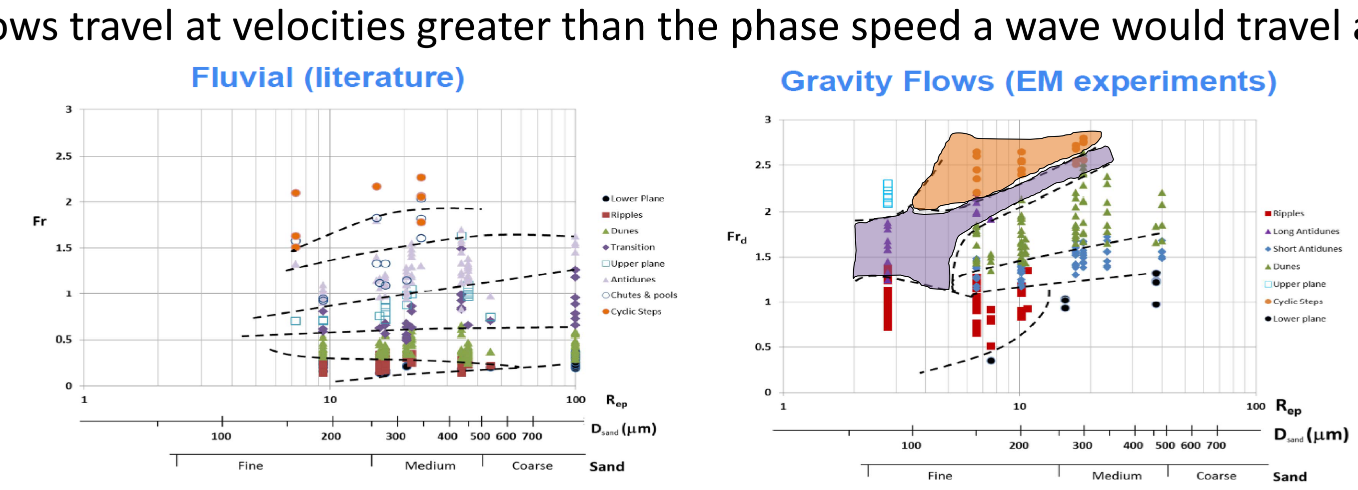
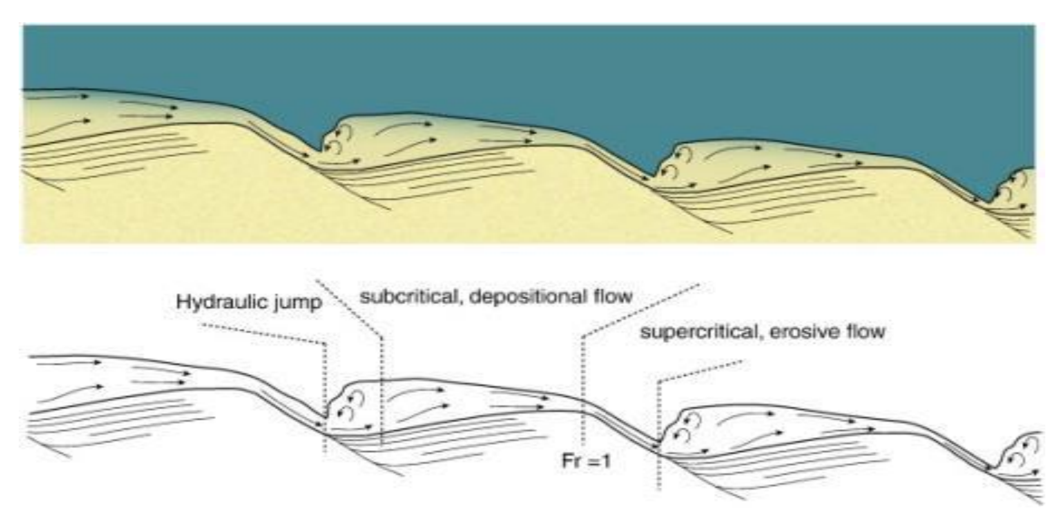


Figure 1: Bedform regime diagrams forming from dilute density flows in flume experiments for fluvial (open channel; left) and sediment gravity flows (subaqueous; right) (from Fedele et al., 2016). For gravity flows, cyclic steps (orange) form in higher ranges of Froude values than those for upstream migrating (here 'long') antidunes (purple). They are thought be the primary end members of known supercritical bedforms.

- Komar (1971) and Hand (1974) first postulated **sediment gravity flows should become supercritical over any deepwater gradients exceeding 0.5°.** Such gradients are **common** along modern basin slopes (Covault et al., 2016)
- An important implication of flows being supercritical is that, in encountering an upcoming obstacle/topography, **subcritical flows accelerate/erode** past while **supercritical flows decelerate/deposit sediment**.
- Hence, end member bedforms of supercritical flow regimes –**antidunes and cyclic steps** (Fig. 1) - **uniquely migrate upflow** (Fedele et al., 2016).
- At a flow transition from super to subcritical, **internal hydraulic jump** occurs – flow quickly decelerates and thickens, promoting rapid sedimentation and deformation of underlying bedding (e.g. Postma & Cartigny, 2014; Fig. 1).
- Deepwater supercritical flows and bedforms remained mostly theory until **advancements in geophysical imaging techniques** allowed researchers to analyze basin bathymetries at resolutions high enough to observe bedforms. These **studies revealed the common modern occurrence of features interpreted as bedforms evolved under supercritical flow conditions** (e.g. Cartigny et al., 2011; Covault et al., 2014, Symons et al., 2016; Fig. 4).
- Despite the apparent frequency that supercritical bedforms appear in modern deepwater, **recognition and characterization of their occurrence in the rock record is rare and poorly characterized**.

Antidunes, Cyclic Steps, and the Rock Record

- **Cyclic step** bedforms (Fig. 2) are, by definition, **bound up and downflow by hydraulic jumps** (Parker & Izumi, 2000).
- **Antidunes** form where the flow is steadily critical to supercritical and **in-phase with bed topography** (Kennedy, 1963).
- Differences between antidunes and cyclic steps in deepwater:
  - Cyclic Steps are thought to be "**Long-wave**" (length:height >15) and to **leave depositional record** (Kostic, 2011) - sharply erosional surfaces and massively bedded deposits linked to hydraulic jumps (e.g. Postma & Cartigny, 2014)
  - Antidunes are argued to be "**short-wave**" (length:height < 10), **ephemeral** bedforms, only preserved where very high sedimentation rates (Kostic, 2011)
- Given their assumed ephemerality, **deepwater slope antidunes have not been previously documented**.
- Modern and preserved antidunes have been primarily recognized in shallow, open channel environments (Fig. 3). Outcrop examples are restricted to environments conducive to rapid deceleration and sedimentation such as waning flood waters in fluvial channels (e.g. Alexander & Fielding, 1997), alluvial fans (e.g. Power, 1961), washover fans (Barwis & Hayes, 1985), fan deltas (e.g. Postma & Roep, 1985), glacial outburst flows (e.g. Lang & Winsemann, 2013), and pyroclastic ash-surges (e.g. Schmincke et al., 1973). The only deepwater examples are of isolated centimeter (cm)-scale bedforms within a single turbidite event bed (Skipper, 1971; Prave & Duke, 1990; Mulder et al., 2009).
- The **present work** aims to enhance the body of work on preserved supercritical bedforms by describing sedimentological **characterstics of thickly developed slope antidunes in outcrop** of the Lycium Member (Mbr) of the Latrania Formation in the Fish Creek-Vallecito (FCV) Basin of the Anza Borrego Desert State Park, San Diego County, California.



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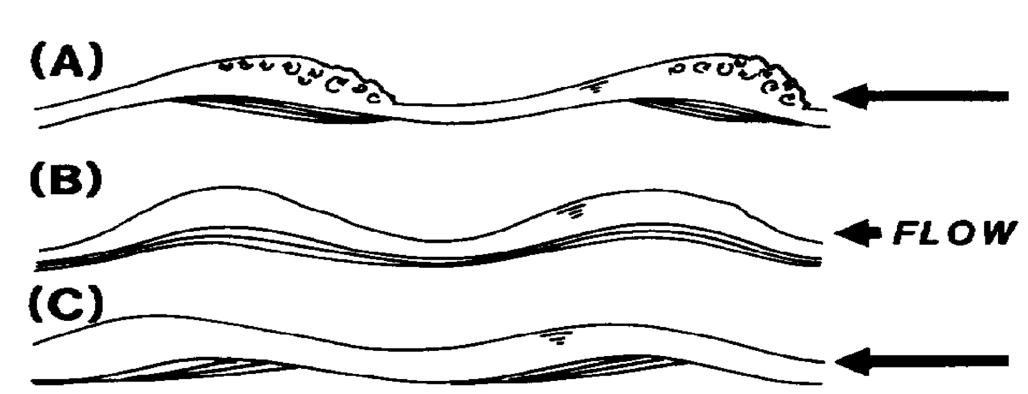

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Figure 2: (Top Left) Schematic example of sediment gravity flow alternating between supercritical and subcritical states with intervening hydraulic jumps (Cartigny et al, 2014). The bedforms represented are cyclic steps, supercritical bedforms bound at both ends by hydraulic jumps. (Top Right) Example of a hydraulic jump in open-channel river system. (Bottom Left) Schematic illustration of idealized antidunes in open channel showing backset (A), aggrading (B), and foreset (C) dominated cross strata with varying phases of flow (Allen, 1982). (Bottom Right) Antidunes occurring in thin flow along beach.

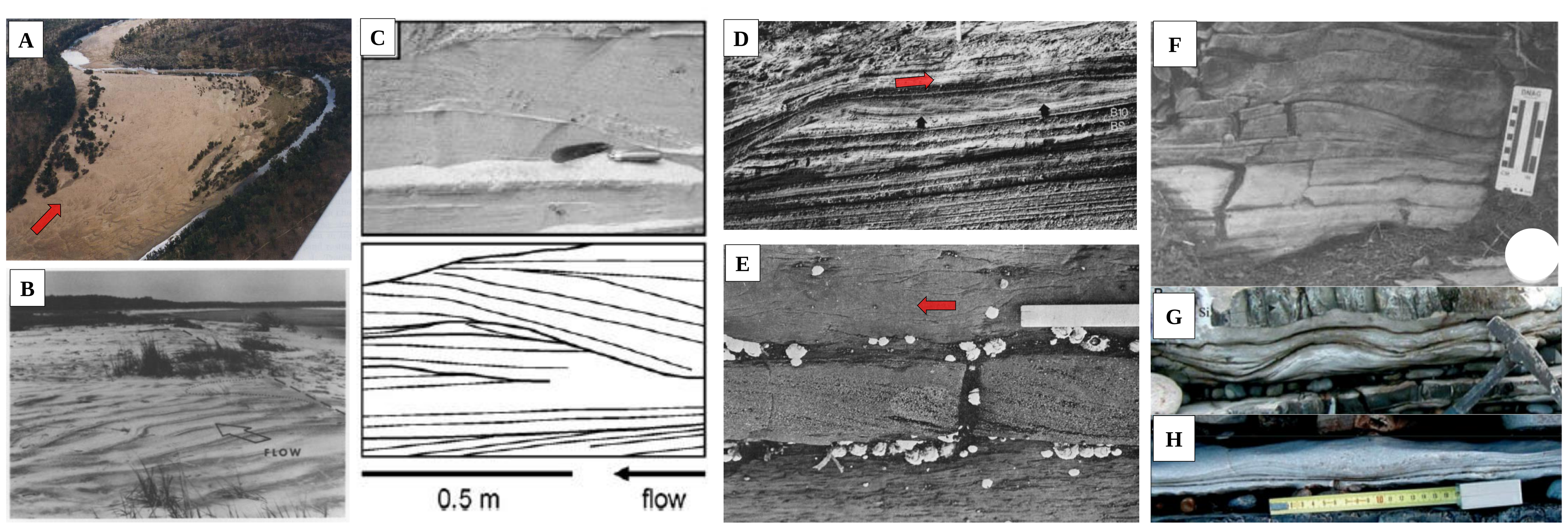

Figure 3: Interpreted antidunes in modern environments and ancient rock record. Red arrows indicate flow direction (if known) where not otherwise stated. (A) Recent fluvial antidunes (dark bands, bottom center) formed during peak flood (Alexander & Fielding, 1997). (B) Antidunes on washover fans (Barwis & Hayes, 1985). (C) Photo & sketch of antidunes in glacial outburst flood deposits (Lang & Winsemann, 2013). (D) Small antidunes (black arrows) deposited during a pyroclastic surge (Schmincke et al., 1973). (E-H) Interpreted antidunes (E; Skipper, 1971) or hummocky cross-strata that can be argued as antidunes (F – Prave & Duke, 1990; G&H – Mulder et al., 2009).

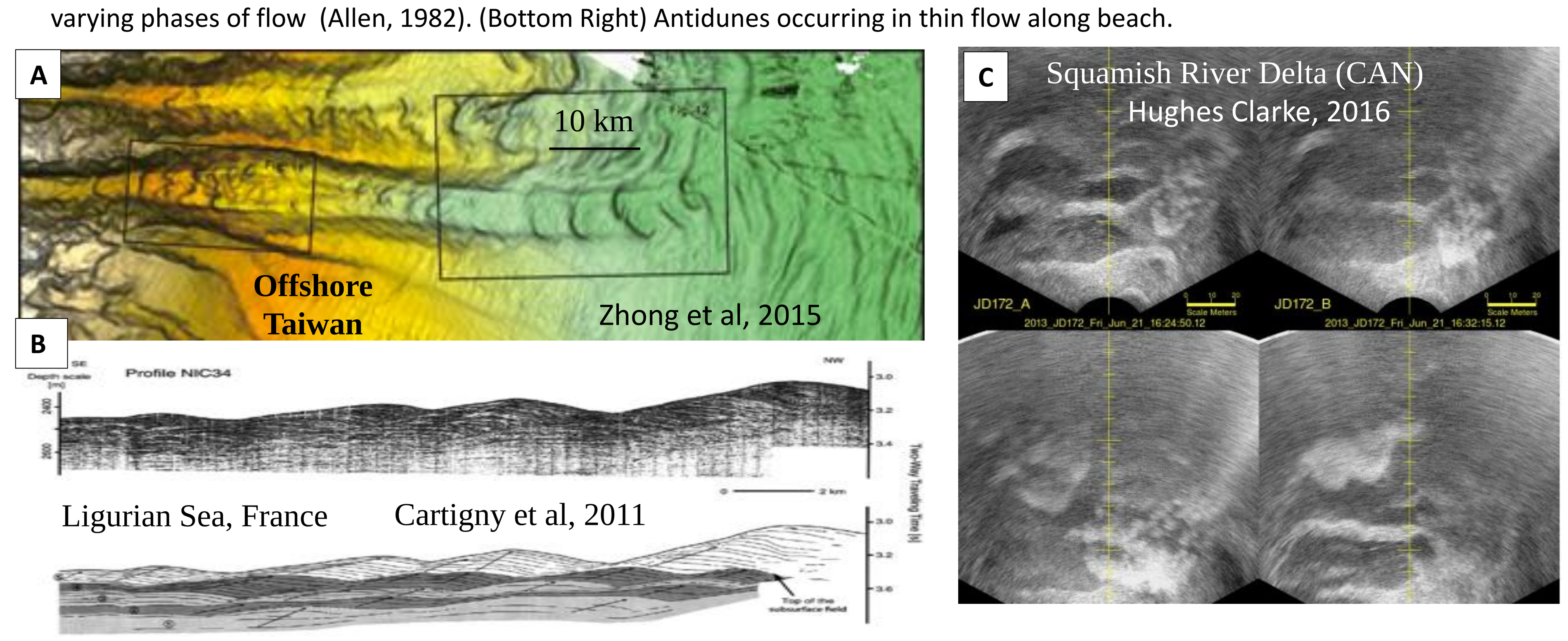

Figure 4: Modern examples of bathymetry interpreted to be composed largely of supercritical bedforms. (A) Bathymtery of deepwater channels. (B) Interpreted supercritical bedforms over slope-channel levee. (C) Direct image of supercritical turbidity flow.