Marine Geology 371 (2016) 130–148

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Large-scale sediment waves and scours on the modern seafloor and their implications for the prevalence of supercritical flows

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ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form 16 November 2015
Accepted 21 November 2015
Available online 26 November 2015

Keywords:
Bedform
Supercritical flow
Sediment wave
Scour
Sedimentary processes

ABSTRACT

Large-scale (20 m to 7 km wavelength) bedforms are common on the seafloor, yet there is a lack of consensus on how they form and thus what to call them. We conducted statistical analysis on a dataset of 82 seafloor bedforms that span a range of water depths and environments. The data form three distinct groups: 1) small-scale (20–300 m wavelength) sediment waves with mixed relief made of medium sand to cobble-sized sediment that form in confined settings, which we call *small sediment waves*; 2) large-scale (300–7000 m wavelength) sediment waves with mixed relief made of fine-grained sediment that form in relatively unconfined settings, which we call *large sediment waves*; and 3) large-scale fully enclosed depressions in the seafloor, which we call *scours*. There is a statistically significant data gap in the size of bedforms between small sediment waves and large sediment waves that does not appear to be a sampling artefact. This data gap probably results from the environments in which sediment waves form being either confined (e.g. channel or canyon) or unconfined (e.g. open slope). Bedform migration direction is available for 36% of the data and includes small and large-scale sediment waves; of these examples all are shown to migrate up-current. Up-current migration is indicative of supercritical flow; thus this data suggests that supercritical flows operate in a wide range of environments and can generate both small and large sediment waves. Therefore, we suggest that small and large sediment waves form by similar processes despite the gap in bedform wavelength and sediment size. The migration direction for scours remains unknown. Scours may form from similar processes to small and large sediment waves, or alternatively they may be a completely separate bedform type that form when erosive flows exploit pre-existing defects in the seafloor. This novel statistical analysis of a global database shows that up-current migrating bedforms associated with supercritical flow are unusually widespread, and are recognised at two distinct scales.

1. Introduction

Sediment-laden flows in the ocean are poorly understood because there are few direct observations of these types of flows (Talling et al., 2015). As a result, much of what is known about sediment-laden flows is based upon the analysis of deposits that they leave behind in the geological record and on the modern seafloor. Large-scale (up to 7.2 km wavelengths), undulating bedforms, are one of the most distinct, widespread, and frequently described features on the deep seafloor (Flood and Shor, 1988; Piper and Savoye, 1993; Wynn and Stow, 2002; Gong et al., 2012) (Fig. 1). Despite abundant literature on these seafloor features there is a general lack of consensus on how they should be interpreted, what the bedforms reveal about how they are formed, or indeed how they should be classified.

The recognition of large-scale bedforms on the deep seafloor has increased over the last six decades due to the advent of advanced seafloor mapping techniques (Wynn et al., 2014). The last global review of seafloor bedforms was conducted in 2002 (Wynn and Stow, 2002); however, in the last 13 years technology has progressed sufficiently for numerous, mainly shallower water examples (<500 m water depth) of bedforms to be identified and studied (e.g. Paull et al., 2010; Babonneau et al., 2013; Hughes Clarke et al., 2014) along with many additional examples in deep water (e.g. Arzola et al., 2008; Gong et al., 2012).

Here we conduct a global analysis of seafloor bedforms using a much larger dataset than any previous study. In an attempt to avoid bias, we initially make no assumptions about how the bedforms formed but instead compile a dataset of observable bedform parameters (wave height, wavelength, slope angle, environmental setting, system size, water depth and crest shape). This dataset is then analysed visually and statistically to define clusters of bedforms with similar characteristics, which forms the basis for a classification scheme. We go on to use our dataset to infer how the different groups of bedforms were formed.

1.1. Terminology

A wide range of terms has been used to describe seafloor bedforms; however, there is no general consensus on terminology. For example,

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http://dx.doi.org/10.1016/j.margeo.2015.11.009
0025-3227/

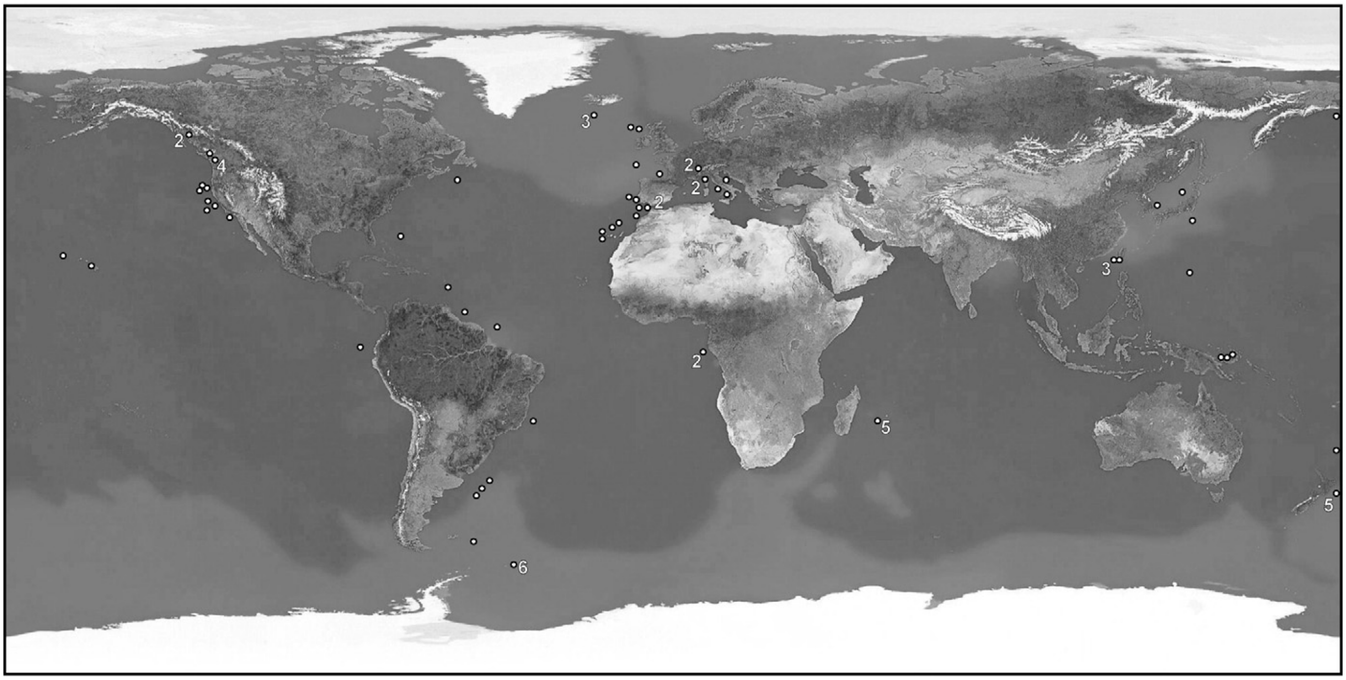

Fig. 1. Map showing global distribution of seafloor bedforms used in this study.

the same bedform may be classified differently by different authors (e.g. sediment waves versus crescent shaped bedforms for the same features in Monterey Canyon; Smith et al., 2007; Paull et al., 2010). Below, we outline a set of terms that we will use throughout this contribution (Fig. 2).

We define a *topographic feature* as any morphological feature on the seafloor. Further classification comes from considering the overarching formation mechanisms. A *bedform* is formed by interaction of a flow with the seafloor, including turbidity currents, thermohaline bottom currents, and tidal flow (Wynn and Stow, 2002; Gong et al., 2012; Sumner et al., 2013). The term *bedform* encompasses seafloor features of any scale that span the range from negative to positive relief in relation to the overall seafloor. We define *slope creep bedforms* as features that form by deformation of the seabed under the influence of gravity, which may be initiated by events such as earthquakes (Lee and Chough, 2001).

The bedforms considered in this contribution can be further divided into *sediment waves* and *scours* according to the prevalence of erosion. Sediment waves are typically tens of metres to a few kilometres in wavelength and several metres in wave height (Wynn et al., 2000b). Sediment waves are created by a combination of deposition and erosion, and their crests are positive relative to the surrounding region of seafloor. Thus it is possible for sediment waves, prior to investigation of this data set, to be further divided into: 1) depositional bedforms, where deposition is dominant and the majority of the bedform is elevated above the regional seafloor, and 2) mixed bedforms if the sediment wave is formed from a combination of erosion and deposition (Fig. 2). The grain size of sediment waves is variable, ranging from mud-size (Lewis et al., 1998), through sand-size (Kenyon and Belderson, 1973) to gravel-size (Shor et al., 1990). We use the term sediment wave to encompass all of the above forms regardless of grain size. Sediment waves have been documented globally and in a range of different submarine environments including continental shelves (e.g. Cattaneo et al., 2004), continental slopes and rises (e.g. Ediger et al., 2002), abyssal-plains (e.g. Flood and Giosan, 2002), deltas (e.g. Hill, 2012; Hughes Clarke et al., 2014), canyons and channels (e.g. Arzola et al., 2008) and volcanic flanks (e.g. Wright et al., 2006). Sediment waves can be further classified according to their grain size and the type of flow that formed them (Wynn and Stow, 2002). *Coarse-grained turbidity current sediment waves* are commonly formed by confined flows in submarine canyons or channels, or from expanding flows in channel-lobe transition zones (Mulder and Alexander, 2001; Faugères et al., 2002; Wynn et al., 2002; Arzola et al., 2008). *Fine-grained turbidity current sediment waves* have been inferred to form beneath unconfined turbidity currents, most notably on the backslopes of channel levees (Lewis et al., 1998; Migeon et al., 2000; Nakajima and Satoh, 2001; Normark et al., 1980, 2002). Both *coarse- and fine-grained bottom current sediment waves* form in unconfined settings where bottom currents are prevalent (Lonsdale and Malfait, 1974; Flood and Shor, 1988; Manley and Caress, 1994; Cunningham and Barker, 1996; Gong et al., 2012; Kuang et al., 2014).

Scours are predominantly erosional bedforms, although they may have localised areas of deposition. They are characterised by enclosed depressions, which cut into (and lie below) the surrounding region of seafloor. Scours are predominantly found in deep-water settings on the margins and at the mouths of submarine canyons and channels, such as the Eel Fan (Lamb et al., 2008; Paull et al., 2014), Agadir Canyon Mouth (Huvenne et al., 2009; Macdonald et al., 2011), Horseshoe Valley (Terrinha et al., 2009; Duarte et al., 2010; Macdonald et al., 2011), Setúbal Canyon Mouth (Lastras et al., 2009; Macdonald et al., 2011), and Whittard Channel margin (Macdonald et al., 2011). Shallower water examples of scours have been found on channel levees and back slopes, such as the Monterey East Channel (Fildani et al., 2006). Scours can occur as linear trains (Fildani et al., 2006; Covault et al., 2014; Zhong et al., 2015), individual isolated depressions (Macdonald et al., 2011; Paull et al., 2014), or form areas of complex erosion (Macdonald et al., 2011).

The crests of bedforms typically migrate over time. The direction of migration provides insight into the flow-state (sub or supercritical) and type of flow that created the bedform. Crests can migrate along slope, up-current (towards the flow source), or downslope (away from flow source). The planform crest shape of flow bedforms can vary between individual bedforms within a system and can be linear, crescentic (with limbs pointing up or downslope), or sinuous (Fig. 3).

The term *crescent shaped bedform* was recently introduced to describe coarse-grained bedforms that have a crescent shaped crest in plan view (Paull et al., 2010). Crescent shaped bedform has subsequently been used to describe bedforms with a broader range of