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Unit bar architecture in a highly-variable fluvial discharge regime: Examples from the Burdekin River, Australia

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ABSTRACT

Unit bars are relatively large bedforms that develop in rivers over a wide range of climatic regimes. Unit bars formed within the highly-variable discharge Burdekin River in Queensland, Australia, were examined over three field campaigns between 2015 and 2017. These bars had complex internal structures, dominated by co-sets of cross-stratified and planar-stratified sets. The cross-stratified sets tended to down-climb. The development of complex internal structures was primarily a result of three processes: (i) superimposed bedforms reworking the unit bar avalanche face; (ii) variable discharge triggering reactivation surfaces; and (iii) changes in bar growth direction induced by stage change. Internal structures varied along the length and across the width of unit bars. For the former, down-climbing cross-stratified sets tended to pass into single planar cross-stratified deposits at the downstream end of emergent bars; such variation related to changes in fluvial conditions whilst bars were active. A hierarchy of six categories of fluvial unsteadiness is proposed, with these discussed in relation to their effects on unit bar (and dune) internal structure. Across-deposit variation was caused by changes in superimposed bedform and bar character along bar crests; such changes related to the three-dimensionality of the channel and bar geometry when bars were active. Variation in internal structure is likely to be more pronounced in unit bar deposits than in smaller bedform (for example, dune) deposits formed in the same river. This is because smaller bedforms are more easily washed out or modified by changing discharge conditions and their smaller dimensions restrict the variation in flow conditions that occur over their width. In regimes where unit bar deposits are well-preserved, their architectural variability is a potential aid to their identification. This complex architecture also allows greater resolution in interpreting the conditions before and during bar initiation and development.

Keywords Bedform, cross-stratification, dune, fluvial, internal structure, unit bar.

INTRODUCTION

Unit bars, first defined by Smith (1974), were defined as: “relatively unmodified bars whose morphologies are determined mainly by depositional processes”. In many rivers, they contribute to the formation of larger compound bars (Miall, 1977). Unit bars and their deposits have been recorded in rivers described as braided (Smith, 1972, 1974; Cant & Walker, 1978; Lunt & Bridge, 2004; Sambrook Smith *et al.*, 2006; Reesink & Bridge, 2011; Lunt *et al.*, 2013; Parker *et al.*, 2013), wandering (Wooldridge & Hickin, 2005; Rice *et al.*, 2009) and meandering (Levey, 1978; Bridge *et al.*, 1995; Fielding *et al.*, 1999). Unit bars form in a wide range of different climatic regimes, from hot arid (Williams, 1971; Hassan *et al.*, 2009), to hot seasonal (Coleman, 1969; Bridge & Lunt, 2006), to temperate (Smith, 1972, 1974; Jackson, 1976; Levey, 1978; Bridge *et al.*, 1995; Reesink & Bridge, 2011), to sub-arctic (Collinson, 1970). Unit bars also form with a wide range of bedload grain sizes, with many published examples formed of sand (Collinson, 1970; Smith, 1972; Jackson, 1976; Sambrook Smith *et al.*, 2006; Ashworth *et al.*, 2011; Reesink & Bridge, 2011) and of gravel (Smith, 1974; Lunt & Bridge, 2004; Lunt *et al.*, 2004; Rice *et al.*, 2009).

Several mechanisms of unit bar formation have been identified. Unit bars are often forced to develop (‘*forced unit bars*’) by channel non-uniformity (Leopold & Wolman, 1957; Cant & Walker, 1978; Smith, 1971) or by unsteadiness of flow or sediment flux (Jopling, 1966; Smith, 1971; Lunt & Bridge, 2007), but can also develop spontaneously under certain conditions as ‘*free unit bars*’ (Callander, 1969; Seminara & Tubino, 1989; Tubino *et al.*, 1999). Whilst the former type of unit bar can be solitary to periodic in nature, the latter type tends to have a periodicity (for example, alternate bars).

Once initiated, unit bars grow through a combination of vertical accretion (Jopling, 1966; Bridge *et al.*, 1995; Wooldridge & Hickin, 2005; Lunt & Bridge, 2007), lateral accretion (Collinson, 1970; Crowley, 1983; Reesink & Bridge, 2011), upstream accretion (Goff & Ashmore, 1994) and downstream accretion (McKee, 1957; Jopling, 1961, 1963, 1965a,b; Collinson, 1970). Because unit bars can exist over weeks, months or several years, often surviving through multiple changes in discharge (Smith, 1974; Wooldridge & Hickin, 2005; Parker *et al.*, 2013), bar growth can be sporadic, linked to discrete discharge events. As unit bars develop, they often tend towards a tabular profile, consisting of a long, very shallow dipping (upstream or downstream) to horizontal stoss, and a much shorter, more steeply dipping lee (Fig. 1).

Downstream movement of a unit-bar lee face forms sedimentary structures, which herein are called the foreset component of the unit bar deposit. This is often underlain by a thinner bottomset and passes up into a thin topset (Fig. 1). Bottomsets form from the deposition or reworking of sediment downstream of the bar lee whilst topsets form from the deposition or reworking of sediment on the bar stoss. Of these three components that make up unit bar deposits, foresets often predominate (Fig. 1). Despite the original definition of a unit bar proposing that they form mainly by deposition, in cases where other relatively large bedforms are superimposed upon a unit bar, erosion can play an important role in defining unit bar internal structure.

Large dunes, which can reach comparable scales to unit bars in certain rivers, can generate similar internal structures as they migrate. However, there are a few key differences between unit bars and dunes that make them discretely different bedforms. In rivers in which both unit bars and dunes form, the heights of unit bars tend to be greater than those of dunes (Jackson, 1976; Lunt *et al.*, 2004, 2013). This is because for dunes, their equilibrium height is suggested to scale to flow depth (Yalin, 1964; Allen, 1982), whilst unit bar height is a function of discharge, the sediment transport rate and the sediment character (the ‘profile of equilibrium’ concept of Jopling, 1966). Formation mechanisms of dunes and unit bars also differ. Dunes form only through spontaneous development (Kennedy, 1963; Richards, 1980; Seminara, 2010; Vesipa *et al.*, 2014) within a relatively narrow range of flow and sediment conditions (Costello, 1974; Harms *et al.*, 1975; Allen, 1982; Southard & Boguchwal, 1990; Van den Berg & Van Gelder, 1993). Extended time outside these conditions leads to washout and replacement (for example, upper plane bed; Bridge & Best, 1988) unless they are rapidly sub-aerially exposed. The narrower range of existence conditions lessens their ability to exist over great changes in discharge relative to that of unit bars formed in the same river.

Despite the ability of unit bars to exist over relativity large changes in flow, previous research on unit bars in modern rivers has tended to focus on European and North American rivers where the discharge regime is often relatively steady. In addition, experimental flume research focusing

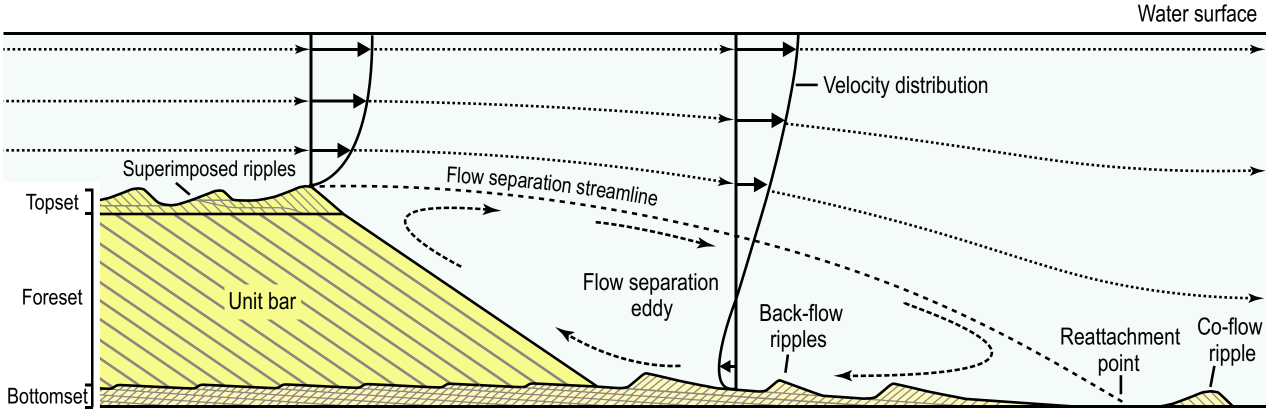


Fig. 1. Schematic representation of the internal structure of a classic (simple) unit bar.

on bedforms, such as unit bars, has often been conducted with one or more of the major variables (for example, flow velocity, flow depth, discharge and sediment input rate) held steady (Guy *et al.*, 1966; Costello & Southard, 1981; Baas, 1994, 1999; Leclair, 2002; Reesink & Bridge, 2007). This bias towards the study of relatively steady river (and flume) systems leads to uncertainty as to whether such research is applicable to more variable discharge flow regimes. Herein, a summary of the current understanding of unit bar internal structures, primarily based on descriptions from relatively steady modern rivers and flume studies, is presented; this is followed by a description and discussion of the internal structures of unit bars formed in the highly-variable discharge Burdekin River, Australia. This is undertaken to answer the following questions:

1 What internal structures are present within unit bars formed in the highly-variable discharge Burdekin River?

2 How do the internal structures observed compare to published descriptions from rivers with steadier discharge?

3 What are the likely reasons for the differences in internal structure that are observed?

Answering these questions will improve understanding of the internal structures of unit bars in a wide variety of discharge regimes and, particularly, in very variable discharge regimes. It will also help in the interpretation of ancient deposits of such rivers.

Unit bar architecture – the state of the art

High-angle planar cross-stratification (Fig. 2A) is a commonly identified foreset structure within unit bars in modern rivers (Collinson, 1970; Smith, 1970, 1972, 1974; Cant, 1978; Cant & Walker, 1978; Levey, 1978; Crowley, 1983; Ashworth *et al.*, 2011; Reesink & Bridge, 2011) and flumes (McKee, 1957; Jopling, 1961, 1963, 1965a,b, 1966; Johansson, 1963; McCabe & Jones, 1977; Reesink & Bridge, 2007, 2009). Single sets of high-angle planar cross-stratification develop when a unit bar with a lee-side avalanche face migrates downstream and can be formed of sand (McKee, 1957; Jopling, 1963, 1965a,b) or gravel (Johansson, 1963; Reesink & Bridge, 2007). Dependent on the flow conditions and sediment character and flux, cross-stratification can be angular (dip angle relatively consistent, cross-strata contacting the lower bounding surface at a relatively high angle; e.g. Jopling, 1963, 1965a; Tillman & Ellis, 1968; Reesink & Bridge, 2007, 2009; Herbert *et al.*, 2015) or tangential (cross-strata dip declines towards the base of the set, contact with the lower bounding surface is tangential; e.g. Jopling, 1963, 1965a; Tillman & Ellis, 1968; Reesink & Bridge, 2007, 2009; Herbert *et al.*, 2015). The change within one set from angular to tangential has been linked to increasing flow velocity, increasing bed shear stress and an increasing ratio of flow depth above the stoss to flow depth in the trough (Jopling, 1963, 1965a; Tillman & Ellis, 1968; Reesink & Bridge, 2009).

Superimposed bedforms influence cross-stratum characteristics, leading to changes in grain size, thickness and grain sorting. The position of the most downstream superimposed bedform relative to the brink of a unit bar's avalanche face is an important control (Reesink & Bridge, 2007, 2009; Reesink, 2018). If the trough of a relatively small superimposed bedform coincides with the unit-bar brink point, a fine-grained

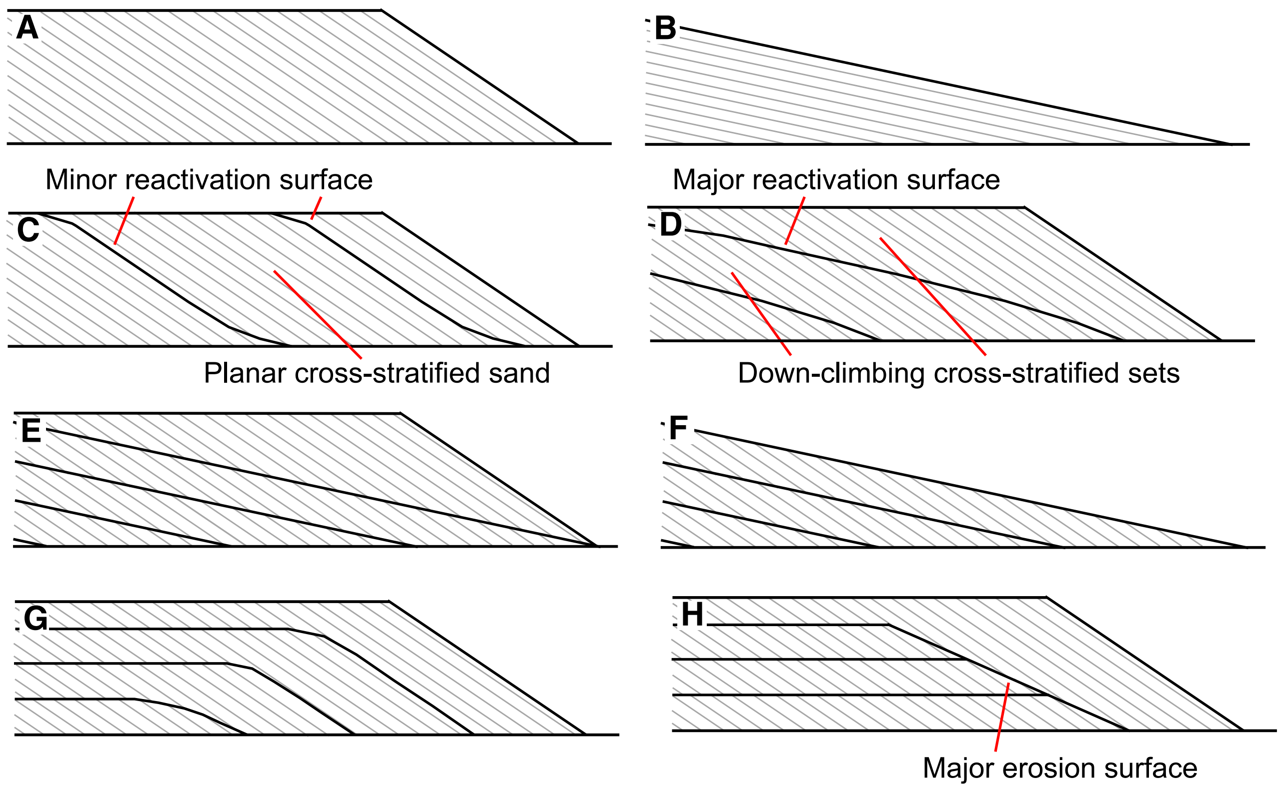


Fig. 2. Schematics showing possible unit bar internal structures in flow-parallel section. (A) Planar tabular cross-stratified deposit. (B) Low-angle planar tabular cross-stratified deposit, formed by the downstream migration of a unit bar with a low-angle lee. (C) Planar cross-stratified deposit with minor reactivation surfaces. (D) A deposit with major, convex upward reactivation surfaces, which bound down-climbing cross-stratified sets. (E) A deposit with major, planar reactivation surfaces, which bound down-climbing cross-stratified sets. (F) Compound-cross stratification, formed by superimposed bedforms migrating over a unit bar with a low-angle lee face, creating down-climbing cross-stratified sets where set boundaries dip more steeply than the mean slope of the channel reach. (G) Co-set of planar cross-stratification, with underlying sets terminating and amalgamating with the overlying sets. (H) Co-set of planar cross-stratification, the lower three sets of which are bounded by an erosional truncation surface. The top set is reactivated the truncated bar. Key descriptive terms used herein are highlighted.

drape can form on the unit bar lee, leading to the development of a fine-grained cross-stratum. Conversely, when a relatively small superimposed bedform moves over a unit bar brink, a bedload-dominated cross-stratum develops with its cross-sectional area related to the size of the superimposed bedform (Reesink & Bridge, 2009).

Planar stratification and low-angle cross-stratification (Fig. 2B) have also been recorded within unit bar deposits (Smith, 1974; Bridge *et al.*, 1995; Fielding *et al.*, 1999). Their formation has been linked to the growth of unit bars with low-angle lee slopes (Smith, 1974) or low heights (Fielding *et al.*, 1999). Growth patterns early in the development of unit bars can greatly influence the chance of low-angle cross-stratification development. Hein & Walker (1977) suggested that when downstream accretion dominates early bar development, the formation of an avalanche face can be prevented and thus planar and low-angle cross-stratification is more likely. In contrast, Bridge *et al.* (1995) suggested that a high rate of vertical accretion was important in the development of upstream and downstream dipping low-angle cross-stratification within a preserved unit bar in the South Esk River, Scotland. Unit bars containing low-angle cross-stratification are rare in flume studies, although it has been recorded forming where suspended sediment deposition in the trough dominates over bar-lee-face grain flows (Jopling, 1966) or if the flow over a unit bar is deflected towards the bed (Johansson, 1963, produced with a deflection plate in the flow). Small amounts of planar stratification and low-angle cross-stratification can be found within the deposits of bars dominated by high-angle cross-stratification, with its generation linked to erosion of the unit-bar avalanche face during low stage conditions (Reesink & Bridge, 2011).

The internal complexity of avalanche-face unit bars (containing high-angle cross-stratification) can be increased by the development of reactivation surfaces (Collinson, 1970; McCabe & Jones, 1977; Reesink & Bridge, 2007, 2009; Reesink, 2018). These downstream-dipping erosion surfaces have a range of geometries from relatively planar to convex up or down. Dip angles range from close to the angle of repose (near parallel to the cross-stratification; Fig. 2C) to low-angle surfaces that cross-cut cross-stratification (forming a co-set; Fig. 2D and E). In unidirectional flows, reactivation surfaces develop through interactions between bedforms (Allen, 1973), flow reattachment scour of superimposed bedforms eroding a host bedform's avalanche face (Allen, 1973; McCabe & Jones, 1977; Levey, 1978; Reesink & Bridge, 2007, 2009) or avalanche-face erosion during falling stage (Collinson, 1970; Smith, 1974; Reesink & Bridge, 2011). Only the last of these formation mechanisms requires variable discharge. The position of a unit bar within a channel is important for the falling stage trigger, preferentially affecting unit bars, or parts of bars, located high in the channel, which are more likely to be sub-aerially exposed at low stage (Reesink & Bridge, 2011).

Migration of superimposed bedforms over a bar with a low-angle lee can form compound cross-stratification (Allen, 1982). It consists of multiple sets of cross-stratification bound by relatively shallow-dipping set boundaries, forming a co-set (Fig. 2F) and was first described in detail by McKee (1963). Whilst structurally similar to multiple low-angle reactivation surfaces (for example, Fig. 2E), the formation mechanisms differ. With compound cross-stratification, the pre-existing low-angle bar lee allows for superimposed bedforms to migrate over the bar with minimal bar-lee erosion. Compound cross-stratification can be analysed to infer characteristics of the host and superimposed bedforms. Allen (1973, 1982) and Banks (1973) modelled the generation of compound cross-stratification, and proposed that the relative thickness of individual down-climbing cross-stratified sets relative to the compound set thickness is controlled by the ratio of superimposed bedform height to bar height. Almeida *et al.* (2016a) proposed a method to estimate the geometry of compound cross-stratified unit bars from measurements of pairs of cross-strata and cross-strata set boundaries.

Flow and sediment-flux unsteadiness during the movement and growth of unit bars has been found to alter their internal structure, often increasing complexity; although, as yet, it has not been researched to a great extent. Unsteadiness can trigger vertical accretion, leading to the incorporation of topsets into a unit bar. Unit bar vertical accretion has been observed in flume experiments conducted over a rising stage. Lower vertical accretion rates can lead to the incorporation of ripple-derived or dune-derived cross-stratification, or planar stratification (Jopling, 1963, 1966; Lunt & Bridge, 2007). Higher rates can trigger superimposed unit bars, which once amalgamated into the host bar create a deposit containing multiple, stacked, planar cross-stratified sets (Jopling, 1966). Planar cross-stratified sets can amalgamate together, forming a smaller number of thicker sets downstream (for example, Fig. 2G; Jopling, 1966), or multiple sets can be truncated by one reactivation surface, formed due to erosion and subsequent reactivation of the avalanche face (for example, Fig. 2H; Williams, 1971, fig. 11A). Flow unsteadiness can also trigger changes in foreset shape (Jopling, 1965a), soft sediment deformation (Harms *et al.*, 1963; Levey, 1978), the generation of wave ripples and 'beach' deposits (containing low-angle cross-stratification) formed by partial sub-aerial exposure of the bar (Collinson, 1970; Reesink & Bridge, 2011) and the lateral accretion of bars, often through amalgamation of dunes (Bristow, 1987; Ashworth *et al.*, 2000) and ripples (Collinson, 1970, fig. 22; Reesink & Bridge, 2011).

FIELD SITE, METHODS AND TERMINOLOGY

The research presented herein aims to build upon previous work and provide a better understanding of the role of flow and sediment-flux unsteadiness on unit bar architecture. Research focuses on a single river, the highly-variable discharge Burdekin River, in north Queensland, Australia. The Burdekin River, which has a 130 000 km^2 catchment, has great inter-annual discharge variability, with short-duration, large discharge events separated by long periods of little flow. Heavy rain, associated with monsoon troughs and tropical cyclones, causes the river level to rise rapidly to a peak, with discharge reaching up to three orders of magnitude greater than base flow, followed by a similarly rapid decline (Alexander *et al.*, 1999; Amos *et al.*, 2004).

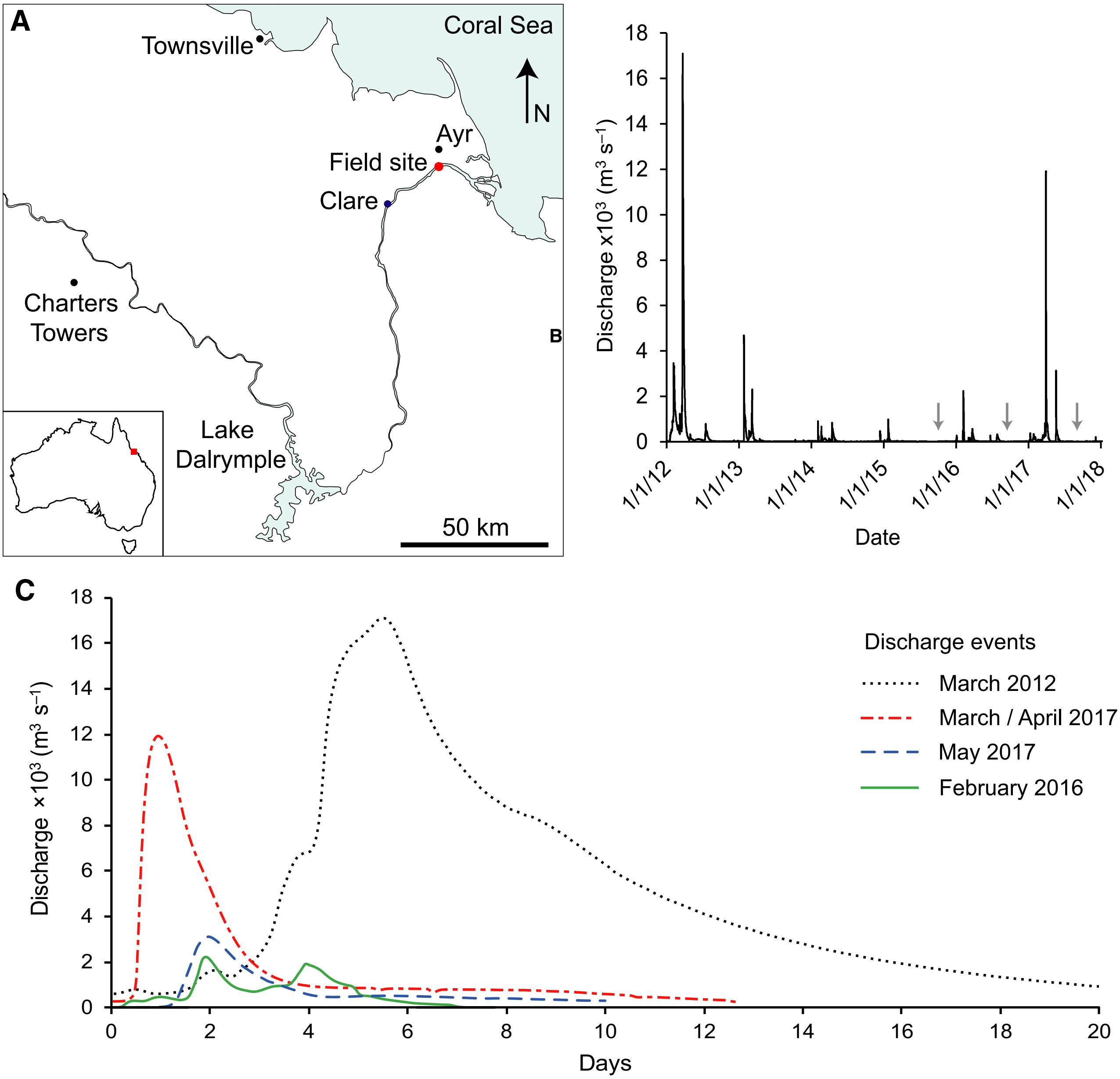


Fig. 3. (A) Map of the lower Burdekin River, the field site is denoted by the red circle. (B) Burdekin River discharge (between 1 January 2012 and 1 January 2018) recorded at Clare. Data from the State of Queensland Department of Natural Resources, Mines and Energy. Grey arrows denote approximate timing of the three field campaigns. (C) Discharge of events that formed/altered unit bars observed over the three field campaigns versus event duration.

Over much of the year, most of the channel bed is sub-aerially exposed, with the flow limited to the lowest elevations. The riverbed predominantly consists of a gravelly coarse sand that is often sculpted into trains of bars, dunes and antidunes (Fielding & Alexander, 1996; Alexander & Fielding, 1997). Gravel sheets and ridges are observed locally (Alexander & Fielding, 1997) and more laterally extensive (hundreds of metres) gravel sheets are infrequently present. Drapes of finer sand and mud have been observed within local topographic lows of the dry bed.

Prolonged exposure of large areas of riverbed allows for vegetation growth, which subsequently influences sedimentary processes (Fielding *et al.*, 1997; Nakayama *et al.*, 2002). The amount and size of vegetation is controlled by duration between inundation events. Some areas

Fig. 4. Satellite photographs of the Burdekin River at the Inkerman Bridge field site taken in: (A) December 2011; (B) October 2013; (C) February 2016; and (D) August 2017. Part (A) is courtesy of the DigitalGlobe Foundation; parts (B) and (D) are from Google, Centre national d'études spatiales and Airbus; and part (C) is from Google and DigitalGlobe.

of the bed may be emergent for several years, allowing dense growth of saplings and grasses to become established.

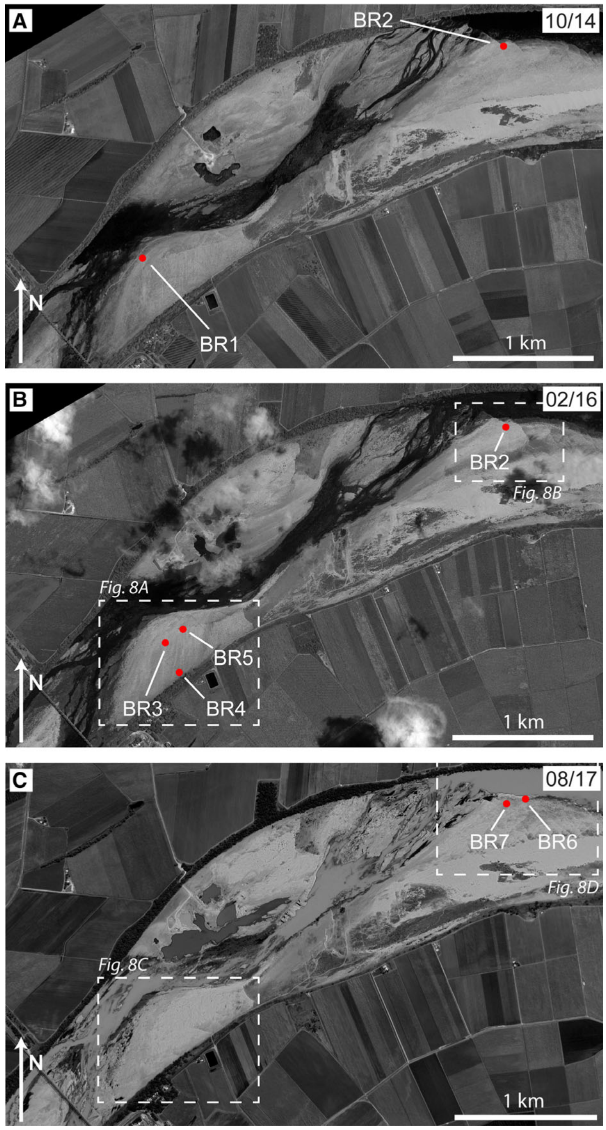


Fig. 5. Satellite photographs of the Burdekin River field site taken in: (A) October 2014; (B) February 2016; and (C) August 2017. Examined bars are denoted by red circles. Fieldwork was conducted in August 2015 (BR1 and BR2), August 2016 (BR2 to BR5) and July 2017 (BR6 and BR7). Parts (A) and (B) are courtesy of the DigitalGlobe Foundation and part (C) is from Google, Centre national d'études spatiales and Airbus.

The highly-variable discharge of the Burdekin River, with large areas of emergent channel bed during the dry season, make it possible to examine moderate to high stage bars and smaller bedforms directly. In addition, other advantages include the flashy nature of discharge, which leads to minimal reworking of relatively large bedforms (such as unit bars) prior to sub-aerial

Table 1. List of trenches dug into unit bars over the 2015, 2016 and 2017 field campaigns.

Bar	Year	Trench	Trench length (m)	Bar height at trench (m)	Orientation	GPS co-ordinates
BR1	2015	–	2·0	0·40	055°	19°38·1369′S 147°23·9990′E
BR2	2015	Trench 1	2·6	0·22	094°	19°37·2505′S 147°25·5281′E
	2016	Trench 2	1·5	0·25	075°	19°37·2397′S 147°25·5391′E
		Trench 3	3·1	0·50	080°	–
BR3	2016	–	4·4	0·40	044°	19°38·1212′S 147°24·0868′E
BR4	2016	–	4·0	0·35	060°	19°38·2328′S 147°24·1503′E
BR5	2016	–	3·7	0·45	011°	19°38·0639′S 147°24·1640′E
BR6	2017	–	5·6	0·45	040°	19°37·2206′S 147°25·6198′E
BR7	2017	Trench 1	3·3	0·40	049°	19°37·2504′S 147°25·5504′E
		Trench 2	2·2	0·43	041°	–

exposure; the coarse sediment grade, which minimises aeolian reworking; and the low population density, which reduces the likelihood of modification of the emergent bed by human activity.

Field work was undertaken at a single field site 17 km upstream of the river mouth, beneath and downstream of the Inkerman Bridge (19°38′8·58″S 147°24′14·40″E; Fig. 3A). The field site is at the downstream end of a nearly straight 10 km long reach. Over this reach, the channel varies from 500 to 1500 m wide and is 800 m wide at the bridge. At the field site, the channel bed is easily accessible, and has been a site of sedimentological study since 1998 (Amos *et al.*, 2004; Fielding *et al.*, 2005; Alexander & Fielding, 2006).

Between 2012 and 2017, the Burdekin River had great inter-annual discharge variability (Fig. 3B). Over this time, two large discharge events (>10 000 m^3 s^{-1}) were recorded at the Clare gauging station *ca* 25 km upstream of the field site (Fig. 3A), occurring in March 2012 (24-day duration) and March 2017 (three-day duration). There was little rain between March 2012 and March 2017 and only three smaller discharge events occurred (between 2000 m^3 s^{-1} and 5000 m^3 s^{-1}; Fig. 3B). A small discharge event also followed the March 2017 event (May 2017; Fig. 3B and C). All of the small discharge events were much less than bank full (*ca* > 12 000 m^3 s^{-1}).

At the field site, large channel-bed changes occurred in the longer-duration discharge event in March 2012, including downstream movement of large compound bars and a change in position of the base flow stream (Fig. 4A and B). Subsequent discharge events formed, altered or washed out unit bars and smaller bedforms, but caused minimal change to the large compound bars. Between 2012 and 2017, aggregate extraction modified the northern portion of the channel bed locally (Fig. 4C and D).

During each campaign, unit bars were photographed and measured. Trenches were dug in some of the unit bars, parallel to palaeoflow indicators preserved on the bar's stoss sides and away from areas modified by human activity (such as tyre tracks). Trenches were dug with the aim of exposing the entire thickness of the deposit of a unit bar (i.e. down to its bottomset) at its avalanche face. Thus, the trenches were similar to those previously dug into unit bars formed in less variable discharge fluvial regimes (e.g. Reesink & Bridge, 2011), allowing for easier contrast and comparison to previous work. During trench excavation, the exposed internal structure was periodically measured and photographed. The length of the trenches was primarily controlled by the distance into the bar reached before the dry-sand trench walls

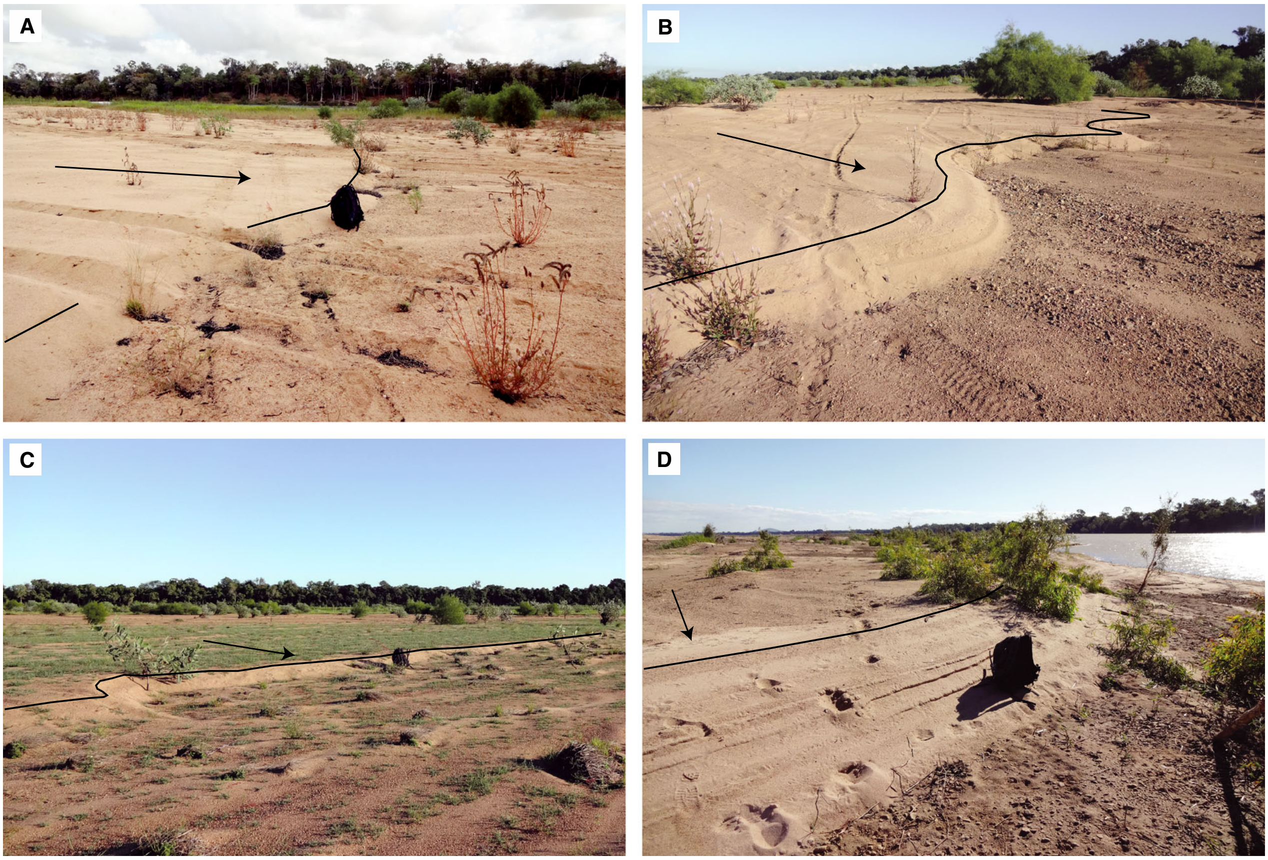


Fig. 6. Photographs of some of the trenched Burdekin River unit bars examined over the 2015, 2016 and 2017 field campaigns. Bars: (A) BR2 in 2015; (B) BR2 in 2016; (C) BR3; and (D) BR6. Backpack in parts (A), (C) and (D) is 0·45 m high. The unit bar in part (B) is *ca* 0·4 m high (0·35 m towards the centre, 0·5 m towards the top right). Solid black lines denote the bar crest. Arrows denote flow direction when bars were last active.

collapsed. For the 2015 and 2016 field campaigns, grain size of strata was evaluated in the field using a hand lens and grain-size comparator. In the 2017 campaign, sediment samples were collected, from which grain-size was measured using sieves.

Over the field campaigns, ten trenches were dug into seven unit bars (called Bars BR1 to BR7 herein): two in 2015, five in 2016 and three in 2017 (Fig. 5; Table 1). Some of the unit bars trenched in 2015 migrated downstream in the February 2016 discharge event, one of these (Bar BR2) was trenched again in 2016. For Bars BR2 and BR7, two trenches were dug in close proximity into their avalanche face to observe lateral variation in internal structure along the crest; these trenches were 7·0 m and 4·6 m apart, respectively.

Photographs of the trench walls were used to generate 3D models of the unit bar exposures (using the software package Agisoft Photoscan®; Agisoft LLC, St. Petersburg, Russia), which were then converted into high-resolution images. Aerial photographs of the field site were collected using an unmanned aerial vehicle [DJI Phantom 2 (DJI, Shenzhen, China) with a gimballed Hero 4 Black camera (GoPro, San Mateo, CA, USA)]; all flights were conducted with permission from the Civil Aviation Safety Authority of Australia. A satellite imagery grant, provided by the DigitalGlobe Foundation, along with satellite images accessed using Google Earth Pro, allowed observation of how the channel bed and exposed unit bars developed at the field site.

For the descriptions of the internal structures observed in the bars, the term down-climbing cross-stratified sets is used herein (following the approach of Reesink & Bridge, 2011) to describe the geometry of sets of cross-stratification in unit bars that downlap set bounding surfaces (i.e. downcurrent-descend) and have a decline in set elevation downstream (for example, Fig. 2D).

Table 2. External character and history of the trenched unit bars examined over the 2015, 2016 and 2017 field campaigns.

Bar	Year	Crestline	Superimposed bedforms	Associated vegetation	Formation, migration and washout history
BR1	2015	Lobate	Washed out dunes	Localised shrubs on stoss	Formed prior to the 2015 field campaign. Washed out by the February 2016 discharge event
BR2	2015	Lobate	None	Localised grasses on stoss	Formed prior to the 2015 field campaign. Migrated less than *ca* 50 m in the February 2016 discharge event. Washed out in the 2017 discharge events
	2016	Lobate	None	Localised shrubs on stoss	
BR3	2016	Straight	None	Extensive grasses and localised shrubs on stoss	Formed prior to the 2015 field campaign. Migrated less than *ca* 25 m in the February 2016 discharge event. Washed out in the 2017 discharge events
BR4	2016	Lunate	None	Extensive grasses on stoss	Formed prior to the 2015 field campaign. Migrated less than *ca* 5 m in the February 2016 discharge event. Washed out in the 2017 discharge events
BR5	2016	Lobate	Washed out dunes	Localised grasses and shrubs on stoss	Formed prior to the 2015 field campaign. Migrated less than *ca* 30 m in the February 2016 discharge event. Migrated less than *ca* 70 m in the 2017 discharge events. Extant as of August 2017
BR6	2017	Lingoid	None	Localised shrubs on stoss	Formed in the 2017 discharge events. Extant as of August 2017
BR7	2017	Lobate	None	None	Formed in the 2017 discharge events. Extant as of August 2017

The term 'compound cross-stratification' has been used by other authors to describe such a structure; however, this term is avoided herein because it can imply a particular formation mechanism (i.e. migration of bedforms over a bar with a low-angle lee). In addition, the terms minor reactivation surface and major reactivation surface are used herein to describe reactivation surfaces that have minimal cross-cutting (for example, Fig. 2C) and major cross-cutting (for example, Fig. 2D) relationships with cross-strata, respectively. Surfaces that cross-cut multiple sets are herein termed major erosion surfaces (for example, Fig. 2H).

RESULTS

External geometry and migration

Observed unit bars were up to hundreds of metres long and wide, had amplitudes that ranged from 0·2 to 2·5 m and had bar crests that varied from straight to lobate. Key characteristics of the seven trenched unit bars examined over the field campaigns, some of which are shown in Fig. 6, are detailed in Table 2.

Of the trenched unit bars, superimposed bedforms were only present close to the avalanche faces of Bars BR1 and BR5. These bedforms had low amplitudes (<50 mm) and long wavelengths (>1 m). Whilst the dimensions of the superimposed bedforms made them difficult to see from ground level, they could occasionally be observed in satellite photographs. Superimposed bedforms are clearly visible in photographs taken just after the February 2016 discharge event, with many observed on the stoss of Bar BR2 and surrounding bars (Fig. 7). These superimposed bedforms ranged in length from <1 m to >15 m, with this varying both along, across and between the bars.

Some of the larger unit bars persisted over the discharge events that occurred between the field campaigns (Fig. 8; Table 2). Bars BR2, BR3, BR4 and BR5 avoided washout over the relatively small February 2016 discharge event. Migration distances were generally greater for bars closer to the base flow stream (i.e. at lower elevations), with Bar BR2, located near the southern channel bank, only migrating a few metres (Fig. 8A and B). Bar BR5 also avoided washout during the larger 2017 discharge events, migrating a greater distance over the channel bed than in 2016 (Fig. 8A and C).

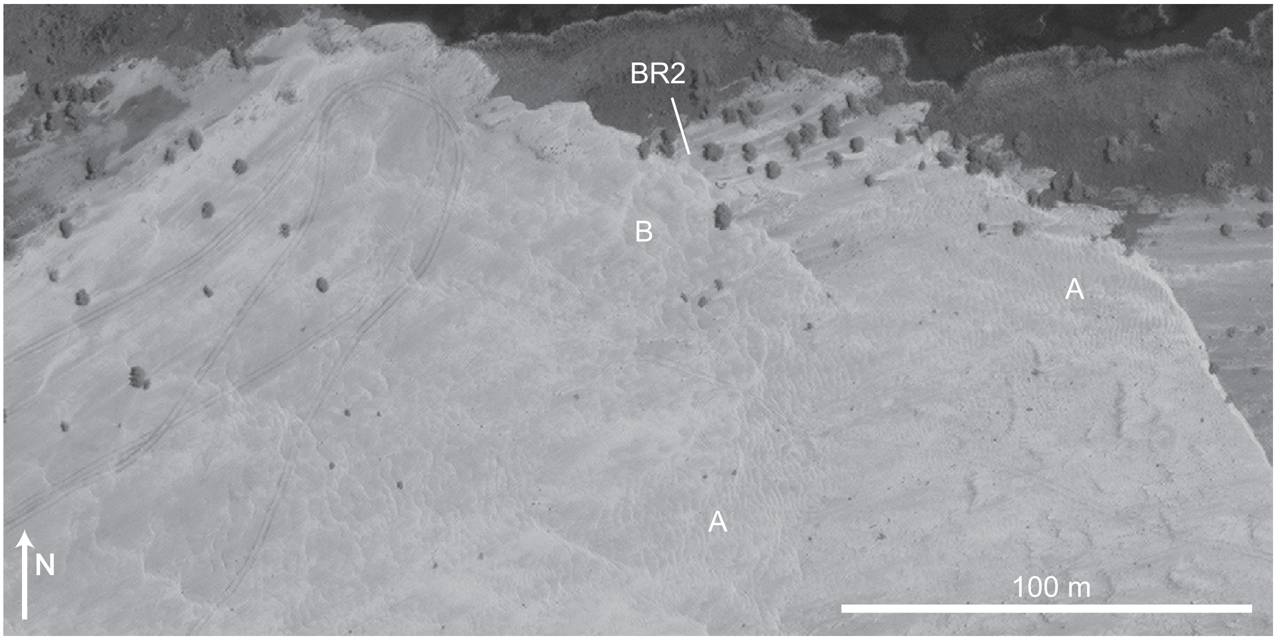


Fig. 7. Satellite photograph of superimposed bedforms on unit bar BR2 and surrounding unit bars after the February 2016 discharge event. Regions of shorter and longer wavelength bedforms can be seen at 'A' and 'B', respectively. Satellite image courtesy of the DigitalGlobe Foundation.

Internal structure

The internal structure and facies of the seven trenched unit bars was complex, containing multiple planar-stratified and cross-stratified sets that varied in thickness and dip angle (Figs 9, 10, S1 and S2). The internal structure varied both vertically and along the bar. The foreset structures observed are categorised into seven component facies, of which three form a major and four a minor proportion of the unit bar deposits (Fig. 10). The more predominant facies are: (i) single sets of relatively thick planar cross-stratified sand; (ii) co-sets of down-climbing cross-stratified sand; and (iii) co-sets of relatively thin planar-stratified or cross-stratified sand. More minor component facies are: (iv) climbing back-flow ripple deposits; (v) thin mud drapes; (vi) thin beds of structureless sand; and (vii) muddy gravel.

Single, relatively thick (<0·4 m) sets of planar cross-stratified sand were a major component present in eight of the trenches. This facies often contained multiple minor reactivation surfaces (for example, Bar BR2 – trench 1, BR4 and BR6; Fig. 10). Its proportional volume differed greatly between bars, ranging from being the predominant component of Bar BR2 in trench 2, to absent in Bar BR3. Where present, planar cross-stratified deposits were only observed at the downstream ends of unit bars.

The dominant facies in many of the trenched bars (for example, Bars BR1, BR3, BR6 and BR7) consisted of co-sets of stacked, relatively thin (<0·3 m), downstream-dipping cross-stratified sets (Fig. 10). The sets within the co-sets dipped at between 4° and 20° downstream. This facies was most predominant at the upstream end of trenches. In some of the bars, multiple co-sets developed, bounded by downstream dipping major erosion surfaces (for example, Bars BR3, BR6 and BR7 – trench 1; Fig 10). In most of the bars, down-climbing cross-stratified deposits changed downstream at reactivation surfaces into planar cross-stratified deposits (for example, Bars BR4, BR6 and BR7 – trench 2; Fig. 10) and/or upstream into relatively thin sets of planar-stratification or cross-stratification (for example, Bars BR3, BR5 and BR7 – trench 1; Fig. 10).

Co-sets of relatively thin (<0·1 m) planar-stratified or cross-stratified sand were observed at the tops of all the trenches. The sets often changed downstream into thicker down-climbing cross-stratified (for example, Bars BR3 and BR5; Fig. 10) or planar cross-stratified (for example, Bars BR1, BR4 and BR7 – trench 2; Fig. 10) sets.

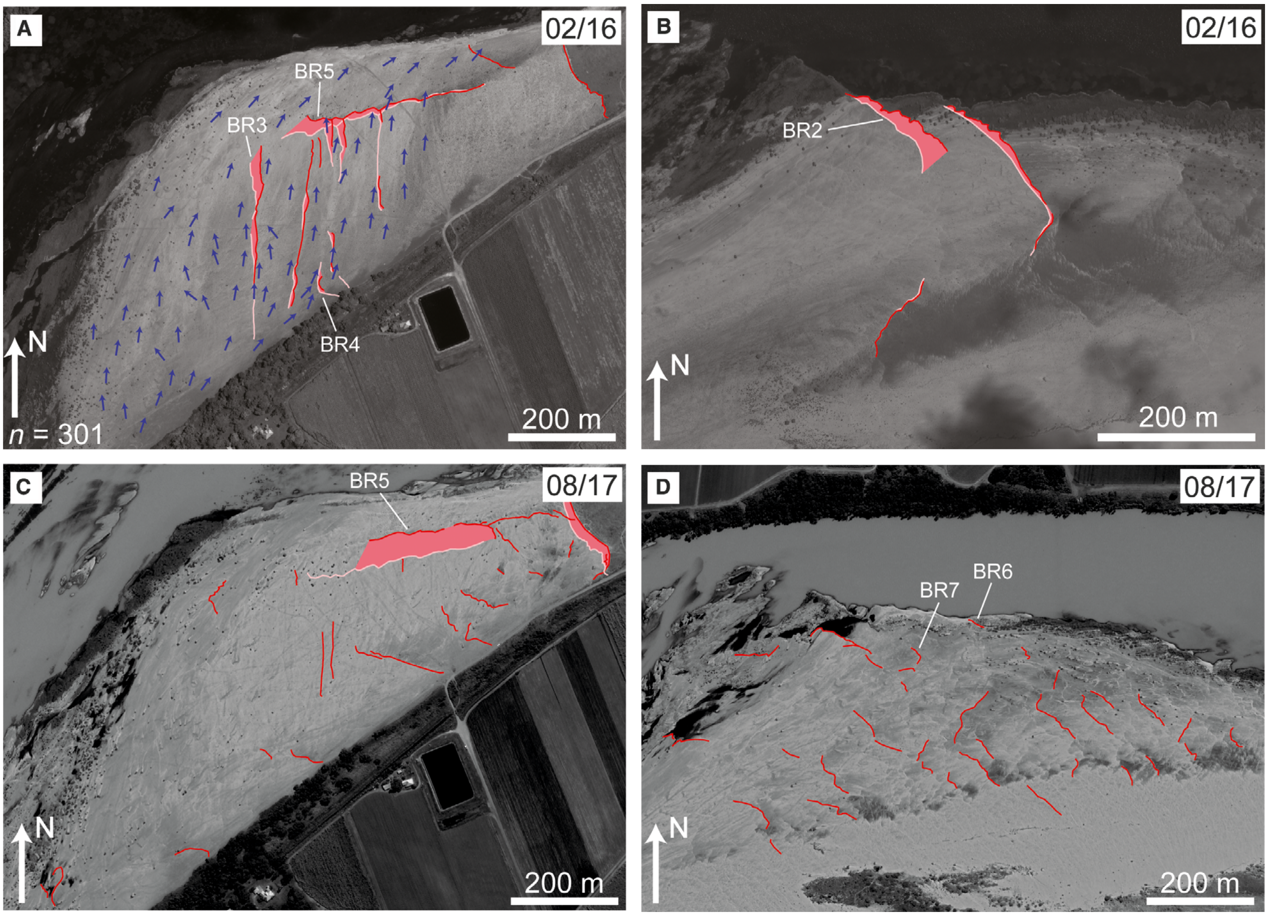


Fig. 8. Satellite photographs of the Burdekin River field site taken in: (A) and (B) February 2016; and (C) and (D) August 2017. Parts (A) and (C) are upstream whilst parts (B) and (D) are downstream (see Fig. 5). Red lines denote crests of major bars, pink lines denote the crest position of the same bars in the previous year and light red shading denotes areas of bar growth. Arrows on part (A) denote flow directions of the February 2016 discharge event reconstructed from sediment tails (cf. Nakayama *et al.*, 2002; Herbert & Alexander, 2018). Parts (A) and (B) are courtesy of the DigitalGlobe Foundation and parts (C) and (D) are from Google, Centre national d'études spatiales and Airbus.

Where this change occurred, the lower bounding surface of the set transitioned into a major reactivation surface, for the former, or minor reactivation surface, for the latter.

Thin mud drapes (<20 mm) were observed bounding a major and a minor reactivation surface in Bar BR4. Climbing back-flow ripple deposits were observed in three bars at the base of down-climbing cross-stratified sets (Bars BR2 – trench 3, BR6 and BR7 – trench 1; Fig. 10). In trenches 2 and 3 of Bar BR2, unit bar deposits overlay thin beds of structureless sand and muddy gravel (diameter <100 mm), respectively. The climbing back-flow ripple deposits along with the thin basal beds of structureless sand and muddy gravel are likely bottomset deposits.

Within Bar BR2, the internal structures within the bar differed greatly between the two trenches (7 m distance). A single planar cross-stratified deposit dominated trench 2, contrasting markedly to the multiple down-climbing cross-stratified sets in trench 3 (Fig. 10). This variation in

Fig. 9. Photogrammetric models of trenches dug into unit bars examined over the 2015, 2016 and 2017 field campaigns. Trenches were dug parallel to local palaeoflow indicators. Vertical and horizontal scales are the same. The colour of the photogrammetric reconstructions is dependent mainly on the light conditions; the large contrast difference representing north (darker) and south (lighter) side trench faces. For the 2017 unit bars, plots denote grain size against cumulative percentage for samples of the upper foreset (<0·1 m from the deposit top), lower foreset (<0·1 m from the deposit base) and trough. All samples were collected within 1 m of the bar avalanche face.


2015
BR1
BR2 - trench 1
2016
BR2 - trench 2
BR2 - trench 3
BR3
BR4
Mud-draped reactivation surfaces
1 m

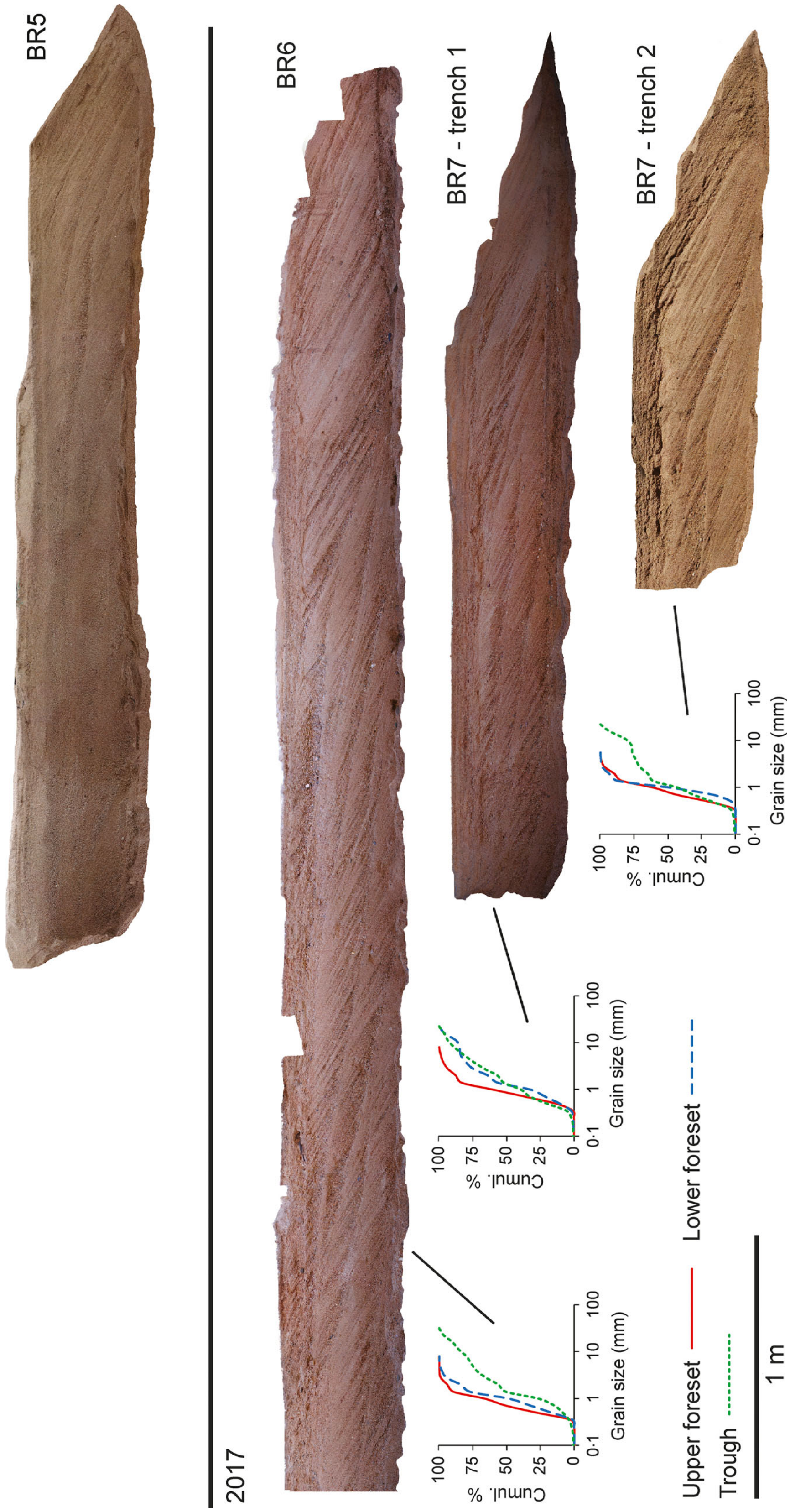
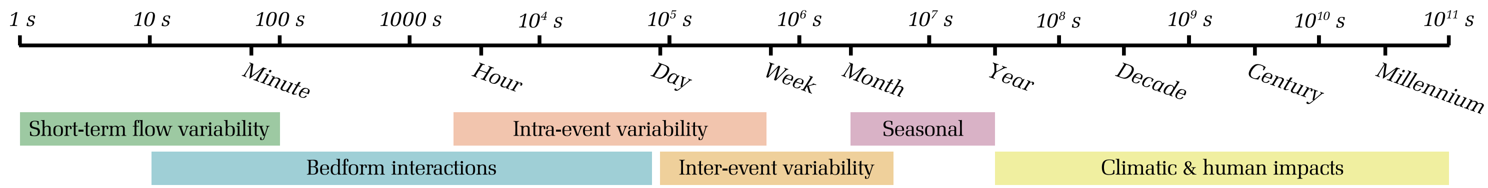


Fig. 9. Continued.

Table 3. Classification of unsteadiness found in purely fluvial systems.

Timeline



Types	Short-term flow variability	Bedform interactions	Intra-event variability	Inter-event variability	Seasonal	Climatic & human impacts
Description	Highly localised, short duration flow unsteadiness.	Localised changes in flow and sediment conditions induced by the migration of relatively small bedforms.	Changes in flow and sediment conditions during an individual discharge event.	Unsteady fluvial conditions spanning multiple discharge events.	Unsteady fluvial conditions resulting from seasonal weather patterns. For example, wet versus dry season in the tropics, summer versus winter in temperate and arctic climates.	Unsteady conditions induced by long-term (> 1 year) climatic cycles, changing climates and human modification of river channels and their catchments.
Principal driving processes:	Turbulent flow Vortex shedding Wake flapping Bolder displacement Biological activity	Ripple migration Dune migration Antidune migration	Catchment shape Catchment size Groundwater flow predominance Rainfall magnitude and duration	Rainfall location magnitude, duration & timing Dam outflow Groundwater flow predominance	Changes in precipitation through the year Snow melt in cold climates Vegetation growth	Climatic oscillations Solar activity Volcanic activity Global warming Land use change Dam construction
Unsteady variables:	Flow velocity Sediment transport	Flow velocity Flow depth Sediment transport Sediment flux to and from the bed.	Discharge Flow velocity Flow depth Sediment characteristics Sediment transport Sediment flux to and from the bed	Discharge Flow velocity Flow depth Sediment characteristics Sediment transport Sediment flux to and from the bed	Discharge Flow velocity Flow depth Sediment characteristics Sediment transport Sediment flux to and from the bed	Discharge Flow velocity Flow depth Sediment characteristics Sediment transport Sediment flux to and from the bed

Table 4. Internal structures within unit bar deposits attributable to different types of unsteadiness within a fluvial system. Each category of unsteadiness, except short-term flow variability, may also contain changes induced by the shorter period categories.

Unsteadiness		Unit bar structural changes	Formation mechanism	Example(s)
Short-term flow variability	Foreset	Cross-strata character variation	Turbulent eddies control suspended sediment deposition and can initiate, accelerate or decelerate grainflows.	Reesink & Bridge (2009)
		Undulations on cross-strata	Transient back-flow ripples, formed by high velocity packets, climb up bar lees and preserve on cross-stratum.	Herbert *et al.* (2015)
	Bottomset	Back flow ripple development	High-velocity packets from vortex shedding and wake flapping within flow separation zone.	Herbert *et al.* (2015); Fig. 10
		Co-flow ripple development	High-velocity packets downstream of flow separation zones.	Herbert (2017)
		Locally variable ripple direction	Ripple fans formed by short duration, high velocity packets influenced by secondary currents.	Herbert (2017)
Bedform interactions	Foreset	Cross-strata grain size variation	Periodic avalanching of bedload, supplied by superimposed bedforms, down the unit bar lee.	McCabe & Jones (1977)
		Cross-strata thickness variation	Periodic avalanching of bedload, supplied by superimposed bedforms, creating thicker cross-stratum.	Reesink & Bridge (2007)
		Reactivation surfaces	Superimposed bedforms washing out the unit bar lee.	McCabe & Jones (1977); Fig. 10
	Bottomset	Back-flow ripple development	Superimposed bedforms alter flow separation geometry and the turbulent magnitude within.	Herbert *et al.* (2015)
Intra-event	Foreset	Vertical accretion/ stacked sets	Changing conditions raise the ‘profile of equilibrium’, inducing vertical accretion.	Jopling (1966); Fig. 10
		Changes in foreset shape	Weak flow separation eddy forming angular foresets, strong flow separation eddy sculpting tangential foresets.	Jopling (1965a)
		Changes induced by transient back-flow ripple development	Transient back-flow ripples may start forming at certain flow velocities, generating foreset undulations and altering cross-strata grain size.	Herbert *et al.* (2015)
	Bottomset	Changes in bottomset character	As flow conditions change flow processes and sediment transport alter, thus altering trough deposition.	Herbert & Alexander (2018)
Inter-event	Foreset	Reactivation surfaces	Formation of reactivation surfaces during low flow conditions.	Collinson (1970); Fig. 10
		Aeolian reworking	Sub-aerial exposure allowing aeolian reworking of bar tops and lees.	Collinson (1970)
		Bioturbation structures	Sub-aerial exposure allowing reworking of bar tops and lees by fauna.	Reesink & Bridge (2011)
	Bottomset	Mud drape development	Deposition of fine-grained sediment in the trough during calm conditions.	Herbert & Alexander (2018)
		Antecedent gravels	High energy conditions transporting large gravels prior to unit bar formation or migration into an area.	Herbert & Alexander (2018)
		Dunes & antidunes	Development of bedforms in the troughs of unit bars during low flow.	Reesink & Bridge (2011)
		Wave-generated structures	Waves generated by wind altering trough sediments during low-flow conditions.	Collinson (1970)
		Aeolian reworking	Sub-aerial exposure allowing aeolian reworking of the bar troughs.	Herbert & Alexander (2018)
		Bioturbation structures	Sub-aerial exposure allowing reworking of the bar troughs by fauna.	Herbert & Alexander (2018)
Seasonal	Foreset and bottomset	Aeolian reworking	Sub-aerial exposure allowing aeolian reworking of the bar.	Refer to inter-event
		Vegetation	Longer-term sub-aerial exposure allows for the development of vegetation on the exposed channel bed.	Fielding *et al.* (1997); Fig. 6
		Sediment tails	Vegetation may not be washed out by small discharge events allowing for the formation of sediment tails.	Nakayama *et al.* (2002)
		Bioturbation structures	Longer-term exposure may allow significant reworking of the channel bed by fauna.	Herbert & Alexander (2018)

internal structure is suggestive that Bar BR2 may have contained great widthwise structural heterogeneity. The two trenches in Bar BR7 also demonstrated spatial variation in internal structure, but on a smaller scale than in Bar BR2. This included differences in the number, shape and position of reactivation surfaces (Fig. 10). The lesser difference observed in Bar BR7 may have been, in part, due to the trenches being closer together than in Bar BR2, separated by only 4·6 m of crestline.

DISCUSSION

The internal structures observed within the Burdekin River unit bars compare well with the complex internal structures observed by Williams (1971) in bars formed in ephemeral streams of central Australia and to unit bars in more perennial North American rivers suggested to have formed under variable discharge (Jackson, 1976; Reesink & Bridge, 2011). However, they differ markedly from many unit bars formed under relatively steady discharge conditions, where single, laterally extensive sets of planar cross-stratification often dominate (Collinson, 1970; Smith, 1970, 1972; Cant, 1978; Cant & Walker, 1978; Ashworth *et al.*, 2011).

Flume studies focusing on unit bar development have found that internal complexity can relate to initial unit bar development (Jopling, 1966; Herbert, 2017). However, as the Burdekin River unit bars existed over multiple discharge events and were much longer than flume-derived bars, it is unlikely that trenches cutting through their deposits at their downstream terminal avalanche faces contained any structures related to their initial formation. Instead, the complexity within the unit bars is primarily related to superimposed bedforms reworking the unit bar avalanche face, variable discharge triggering reactivation surfaces (for example, avalanche face erosion during falling stage) and changes in bar growth direction (for example, vertical accretion) induced by stage change during bar migration. The influence of each control differs between bars, resulting in the differences in internal structure.

Down-climbing cross-stratified deposits were found throughout the trenched unit bars; however, more abundantly at their base and towards the upstream end of trenches (Fig. 10). The down-climbing cross-stratified deposits were often the oldest deposit exposed in a trench, and formed relatively early during the most recent bar reactivation (or formation) event or possibly during a previous high-discharge period. They formed through the incorporation of superimposed bedform deposits into the unit bar. The superimposed bedforms observed on Bars BR1 and BR5 were 17% and 11% of the unit bar height, respectively, but they probably had a much greater amplitude during bar migration, when water levels were high. This allowed major reactivation surfaces to form, on to which superimposed bedforms downlapped (Fig. 11A). Towards the end of discharge events, as depth declined, superimposed bedform height probably reduced (Fig. 11B), with dunes eventually replaced by upper (or lower) plane beds (Fig. 11C). As superimposed bedform height declined, reactivation surface development would change to the minor type (Fig. 11B), and eventually cease entirely (Fig. 11C). This explains why bar deposits often changed from down-climbing cross-stratified sets, bounded by major reactivation surfaces, into a single planar cross-stratified set containing only minor reactivation surfaces in the downstream direction (Fig. 10). It also explains why superimposed bedforms were only infrequently observed on the unit bars (see Table 2). This idea is supported by previous observations of large trains of washed out (flattened) dunes in the Burdekin River (Fielding *et al.*, 1999).

Temporally changing superimposed bedform height also explains the planar-stratified and cross-stratified co-sets observed towards the top of unit bar deposits (Fig. 10). Scour depth tends to decrease with dune height (Leclair, 2002). Thus, as dune height declined towards the end of the discharge events, scour of the bar stoss also declined (Fig. 11B). This promoted the preservation of multiple thin, but laterally extensive sets within unit bar topsets; these are the preserved lowest parts of migrating superimposed bedforms present towards the end of a discharge event (Fig. 11C).

Unsteady fluvial conditions can induce vertical accretion, which leads to the incorporation of superimposed bedform deposits into the bar top (McKee, 1957; Jopling, 1963, 1966; Lunt & Bridge, 2007). This may explain the high proportion of thin planar-stratified or cross-stratified sets in Bar BR5 (up to 50% at the upstream end of the Bar BR5 trench) and Bar BR3.

Climbing back-flow ripple deposits were found locally at the base of some of the down-climbing cross-stratified sets (Fig. 10). Their localised and infrequent occurrence suggests a relatively short-duration change in either bedform, flow or sediment transport conditions (Herbert & Alexander, 2018). These deposits may have resulted from an increase in back-flow velocity in the lee of a superimposed bedform, induced by increased mean flow velocity (Herbert *et al.*, 2015). Alternatively, they could relate to an increase in the sediment deposition rate downstream of the superimposed bedform.

Where present, superimposed bedforms varied in character across the width of unit bars (for example, Fig. 7). This could explain some of the variation in foreset structure observed across Bar BR2 (Fig. 10), as changes in superimposed bedform height can alter the likelihood of reactivation surface development or the character of any topset deposits. Bottomset character also varied across the width of Bar BR2, from structureless sand to muddy gravel. This probably relates to the antecedent bed conditions and differences in flow pattern in the trough across the width of the bar while it was active; the latter controlled by variations in superimposed bedform height and the geometry and orientation of the bar's lee (for example, Bar BR2 in Fig. 6B).

Some of the reactivation surfaces observed within the bars probably formed because of discharge variability, where erosion of the avalanche face was induced by a decline in water levels; for example, the mud-draped reactivation surfaces in Bar BR4 (Figs 9 and 10), where mud was likely deposited during slow flows at relatively low stage. This interpretation is supported by the relatively small migration distance of Bar BR4 in the February 2016 discharge event (Fig. 8A). The major mud-draped reactivation surface possibly separates deposits laid down over two different discharge events, with only the downstream most *ca* 2 m deposited in February 2016. The existence of this and similar mud-draped reactivation surfaces in the Burdekin River emphasises that they may not always be a reliable indicator of tidal influence (cf. Martinius & Van Den Berg, 2011).

The effects of fluvial discharge variation and flow unsteadiness on unit bar internal structure

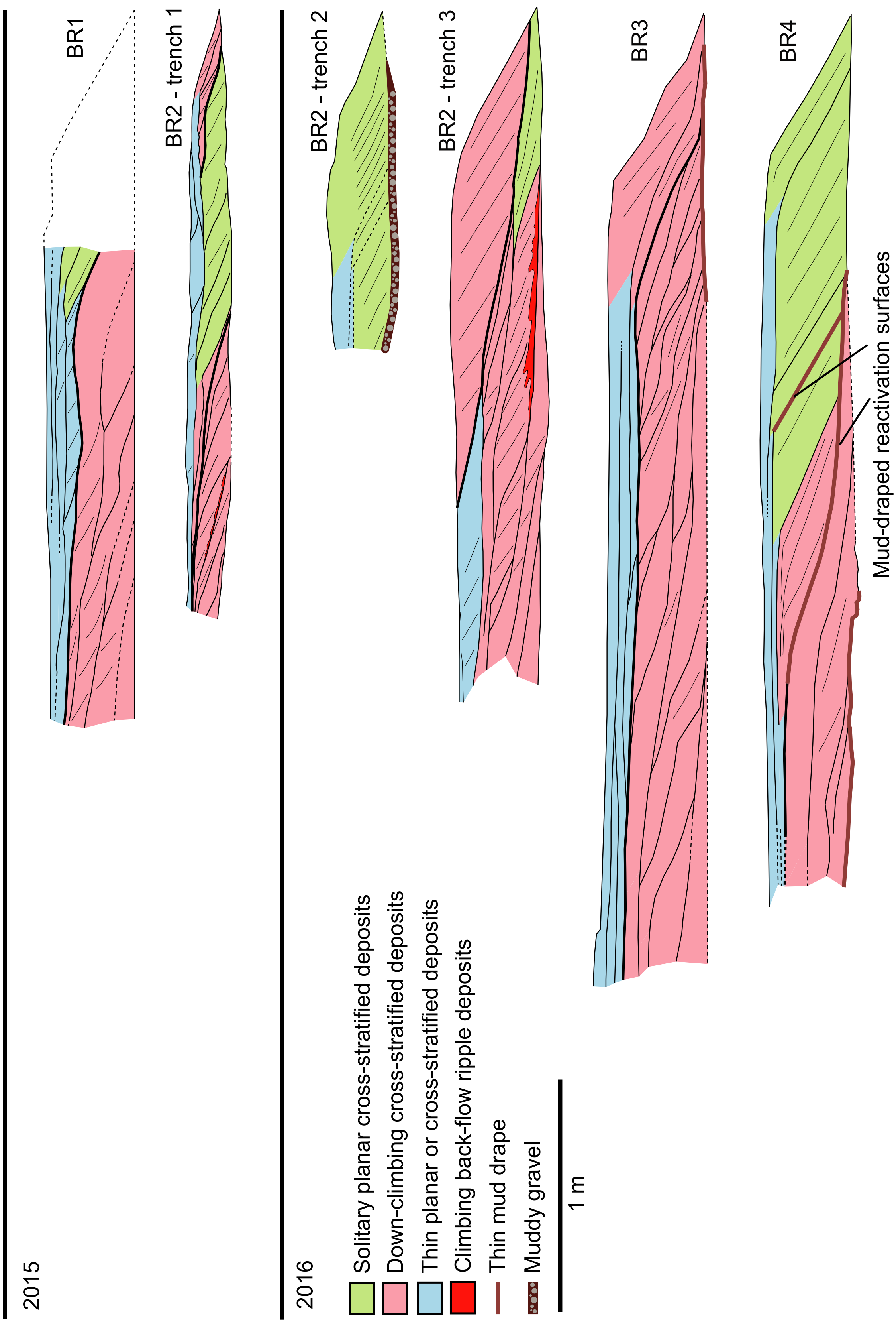
The complexity and variation in the internal structure of unit bars within the Burdekin River is, in part, a result of the river's highly unsteady discharge and sediment load (Alexander *et al.*, 1999; Amos *et al.*, 2004). Localised unsteadiness can be caused by turbulent events, migration of bedforms up or down a channel, bank collapse, entrainment of boulders (Alexander & Cooker, 2016), wave breaking (for example, in association with antidunes; Froude *et al.*, 2017) and wind gusting, as well as other factors. Unsteadiness in rivers occurs over a wide range of timescales, herein split into six categories, each with different processes driving unsteadiness (Table 3). Each of these different scales of unsteadiness can influence the structure and growth of unit bars (Table 4; Figs 12 and 13); however, the first four (shorter duration) categories are focused on specifically herein.

Short-term flow variability

On the shortest timescales, unsteadiness is dominated by localised short-term flow variability, which occurs even in steady discharge rivers (Table 3). The shortest periods of unsteadiness relate to relatively small turbulent eddies (Nezu & Nakagawa, 1993). Larger and more coherent eddies form through interactions between the flow and boundary structures, such as circular columns (for example, plant stems and bridge piers in rivers; Bloor, 1964; Williamson, 1996), or bedforms (Kostaschuk, 2000). Biological activity (for example, movement of fauna) also contributes to turbulence generation.

Turbulent eddies can initiate, accelerate, decelerate or lift up grain flows, locally altering cross-strata (Reesink & Bridge, 2009). In the trough of bedforms, packets of high velocity flow drive sediment transport and can form back-flow ripples (Fig. 12A and B; Table 4; Herbert *et al.*, 2015). As found in the Burdekin River unit bars, such ripples can be preserved (for example, Bar BR2 – trench 3, Bars BR6 and BR7 – trench 1; Fig. 10).

Fig. 10. Schematics of the internal structure of trenched unit bars examined over the 2015, 2016 and 2017 field campaigns. Cross-strata are denoted by fine solid lines; set bounding surfaces and external geometry are represented by solid lines; and major reactivation and erosion surfaces that bound a transition in deposit character are denoted by bold solid lines. Dashed lines are extrapolations of probable structure where surfaces were not visible.


2015
2016
BR1
BR2 - trench 1
BR2 - trench 2
BR2 - trench 3
BR3
BR4
Mud-draped reactivation surfaces
Solitary planar cross-stratified deposits
Down-climbing cross-stratified deposits
Thin planar or cross-stratified deposits
Climbing back-flow ripple deposits
Thin mud drape
Muddy gravel
1 m

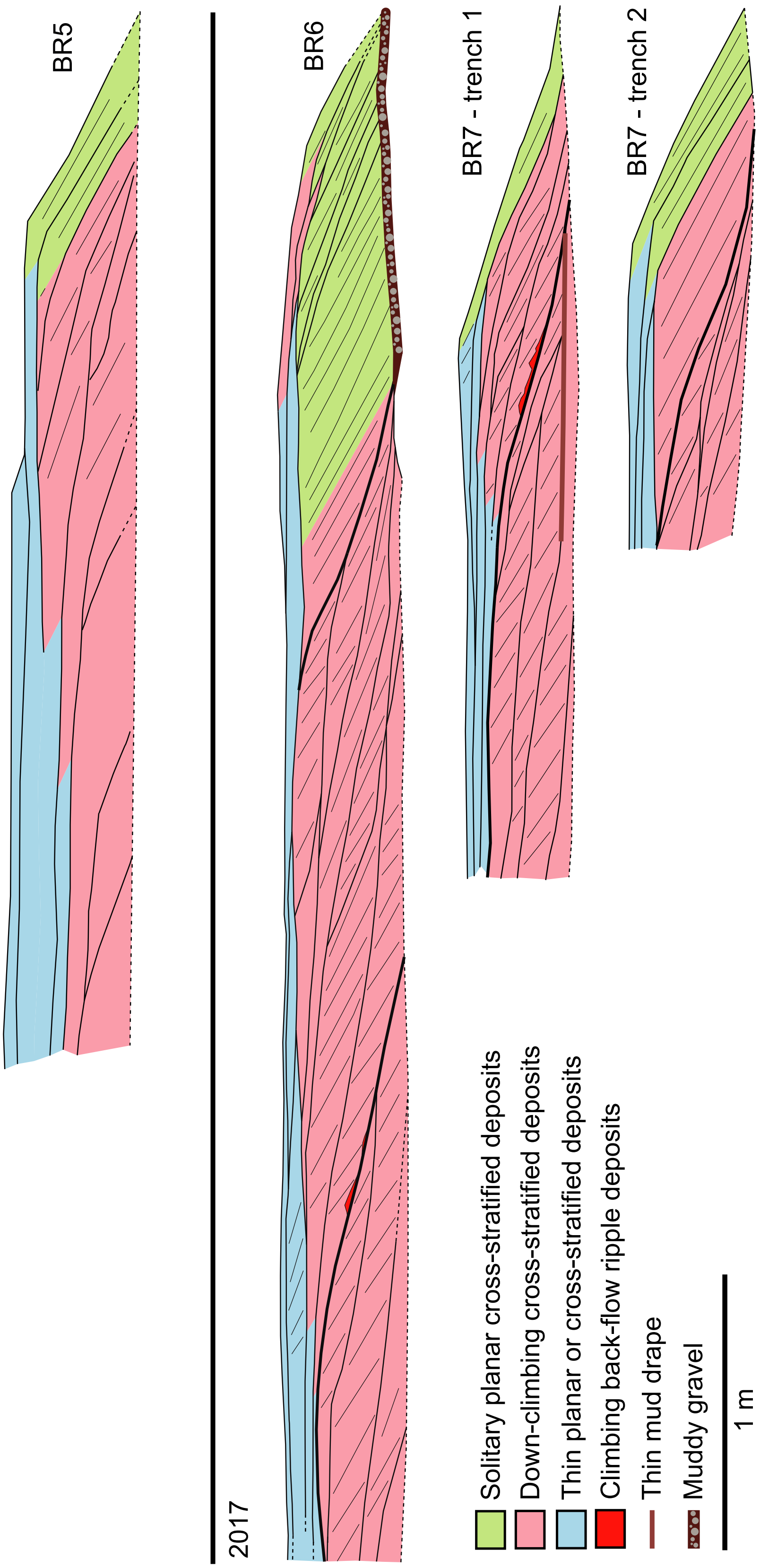


Fig. 10. Continued.

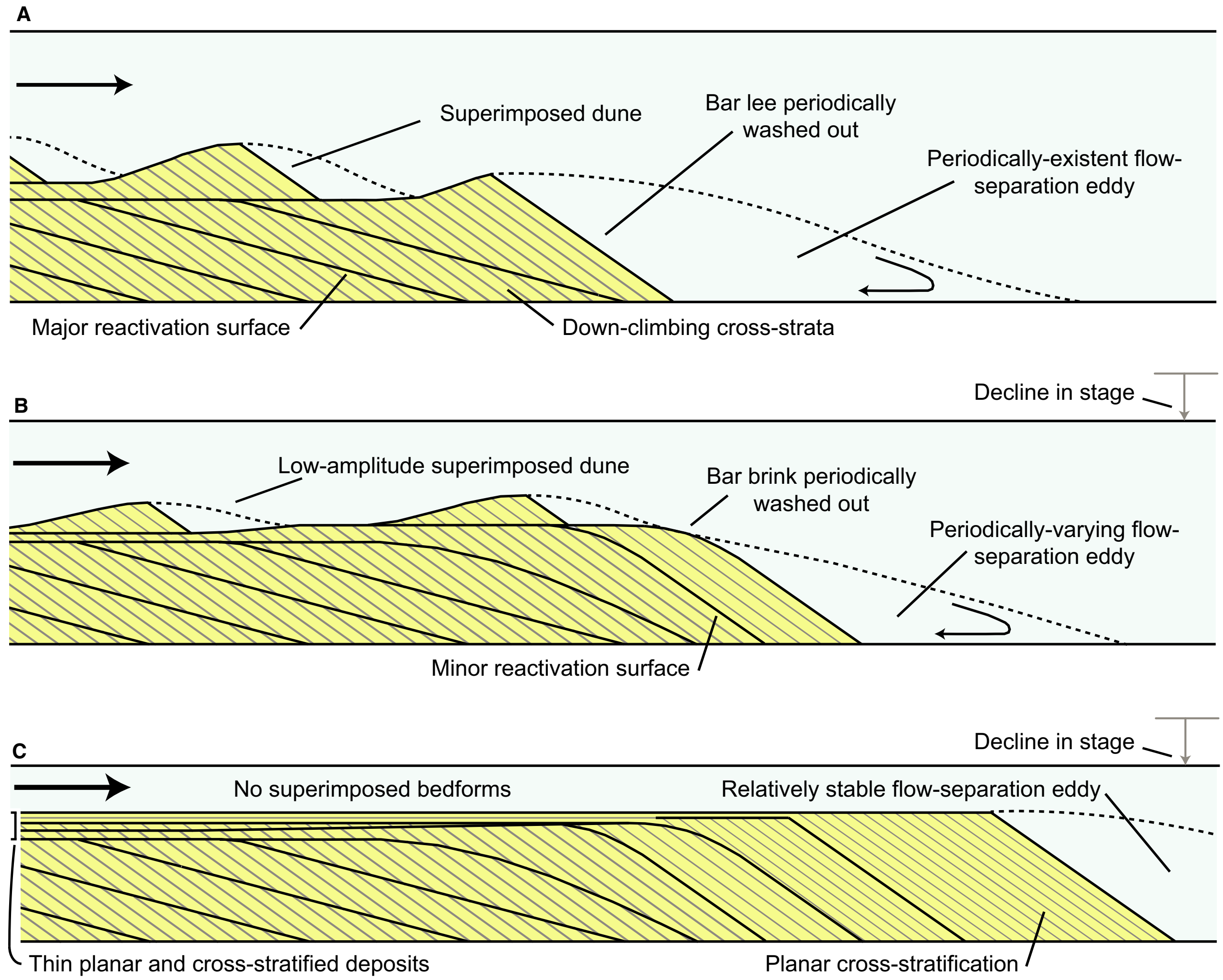


Fig. 11. Schematics of the likely changes to superimposed bedforms and unit bar foreset structure over the declining limb of a discrete discharge event in the Burdekin River. (A) Peak discharge. (B) Mid-way through the decline. (C) Towards the end of a discharge event.

Unsteadiness over and between bedforms

Unit bar deposits often contain structures formed by bedform-derived unsteadiness (Fig. 12C to F; Table 3). Unsteadiness caused by bedform migration is observed in a stationary reference frame (i.e. a fixed point). However, when considering a simple bedform-covered bed under constant discharge, zones of scour and deposition move with the bedforms (i.e. are not fixed). As a result, any preserved deposits appear to record only relatively steady conditions, because at the site of deposition (which was not fixed) conditions varied little. Allen (1973) suggested that changes in bedform geometry and sporadic amalgamation over time would cause some, relatively minor, variation in deposits. However, bedforms that feature superimposed bedforms better preserve evidence of bedform-derived unsteadiness. This is because the superimposed bedforms tend to have a higher migration rate, creating unsteady conditions in the host's lee (McCabe & Jones, 1977; Reesink & Bridge, 2007, 2009).

Small superimposed bedforms (Fig. 12C and D) can alter cross-strata thickness (McCabe & Jones, 1977; Reesink & Bridge, 2007, 2009; Reesink, 2018), control open-framework gravel cross-strata development (Rust, 1984; Lunt & Bridge, 2007) and alter the geometry of, and turbulence within, the host bedform flow separation zone (Fernandez *et al.*, 2006). In cases where superimposed bedforms are relatively large (height >25% of the host bedform height), scour generated at their flow separation

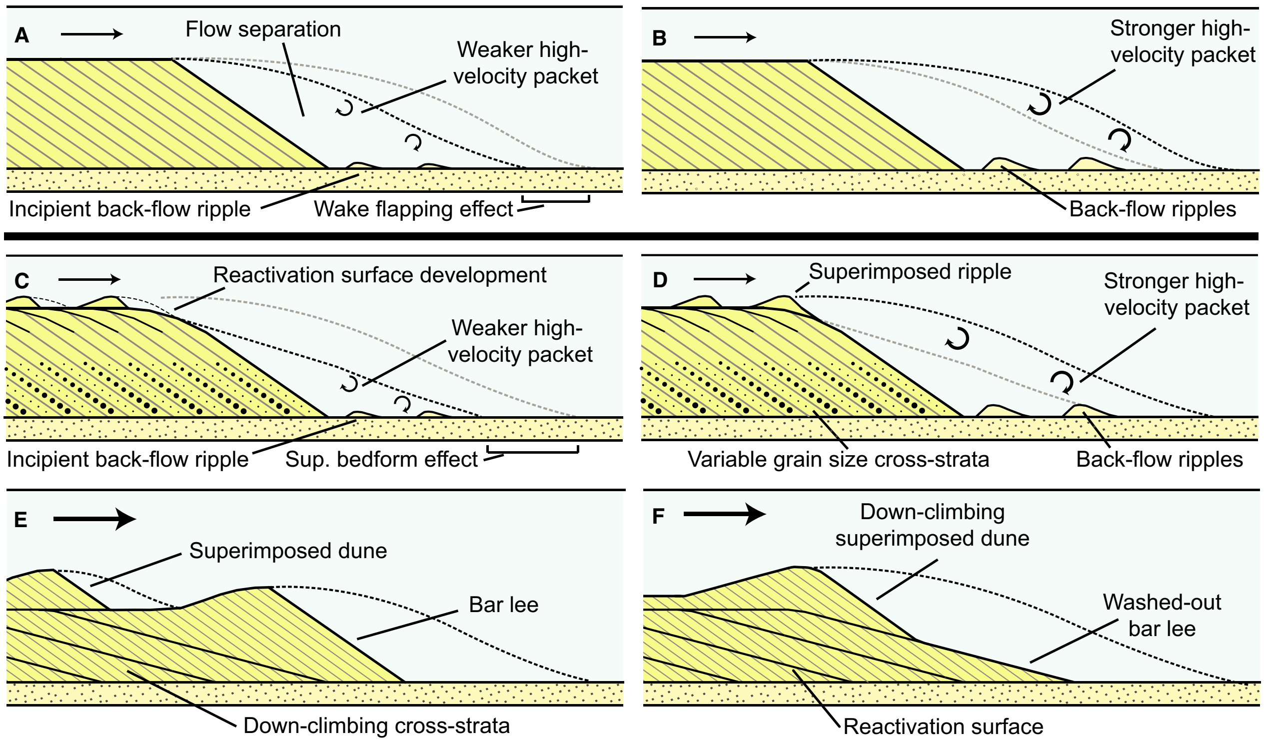


Fig. 12. Schematics denoting possible unit bar internal structures formed by relatively short-term flow and sediment transport unsteadiness in relatively steady and unsteady discharge regimes. (A) and (B) Short-term turbulent flow variability. (C) and (D) Relatively small superimposed bedforms interacting with a unit bar. (E) and (F) Relatively large superimposed bedforms interacting with a unit bar. Stippled basal layer is an antecedent bed.

reattachment point can wash out some or all of the host bedform's lee-side avalanche face, generating reactivation surfaces (McCabe & Jones, 1977; Reesink & Bridge, 2009; Reesink, 2018). Larger superimposed bedforms induce greater washout of the host bedform lee, forming major reactivation surfaces that cross-cut most, if not all, of the foreset (for example, Figs 2D, 2E, 12E and 12F). This can drive the formation of down-climbing cross-stratification, as seen in the Burdekin River unit bars (for example, Fig. 10).

Unsteadiness within single discharge events

Individual discharge events vary greatly in frequency, magnitude and duration. In any discharge event, flow velocity, water depth and sediment transport recorded at a fixed point vary over time (Table 3). Generally, these tend to increase as the flood waxes and decline as it wanes, although sediment transport may be out of phase with discharge (Leopold & Emmett, 1976; Lisle, 1989; Amos *et al.*, 2004). This unsteadiness alters bedform character accretion, migration and washout.

Changing flow velocity can alter foreset shape (Jopling, 1965a; Tillman & Ellis, 1968; Reesink & Bridge, 2007, 2009; Fig. 13A and B; Table 4), trough deposition and reworking (Herbert *et al.*, 2015; Fig. 13A and B; Table 4), and unit bar vertical accretion or erosion (Jopling, 1966; Lunt & Bridge, 2007; Fig. 13A and B; Table 4). Vertical accretion can lead to the incorporation of superimposed bedform deposits into unit bar deposits (Fig. 13A and B). The geometry of preserved vertical accretion deposits within a unit bar depends, at least in part, on the magnitude, duration and timing (including lag between water and sediment changes) of unsteadiness (Herbert, 2017). Intra-event unsteadiness may also alter superimposed bedforms over time (Figs 11, 13C and 13D). In the Burdekin River unit bars, temporal changes in superimposed bedform character altered unit bar foresets (for example, reactivation surface abundance and geometry) along the bar (Figs 10 and 11).

Unsteadiness over successive discharge events

Unsteadiness during the transition from high to low discharge, and vice versa, affects unit bar

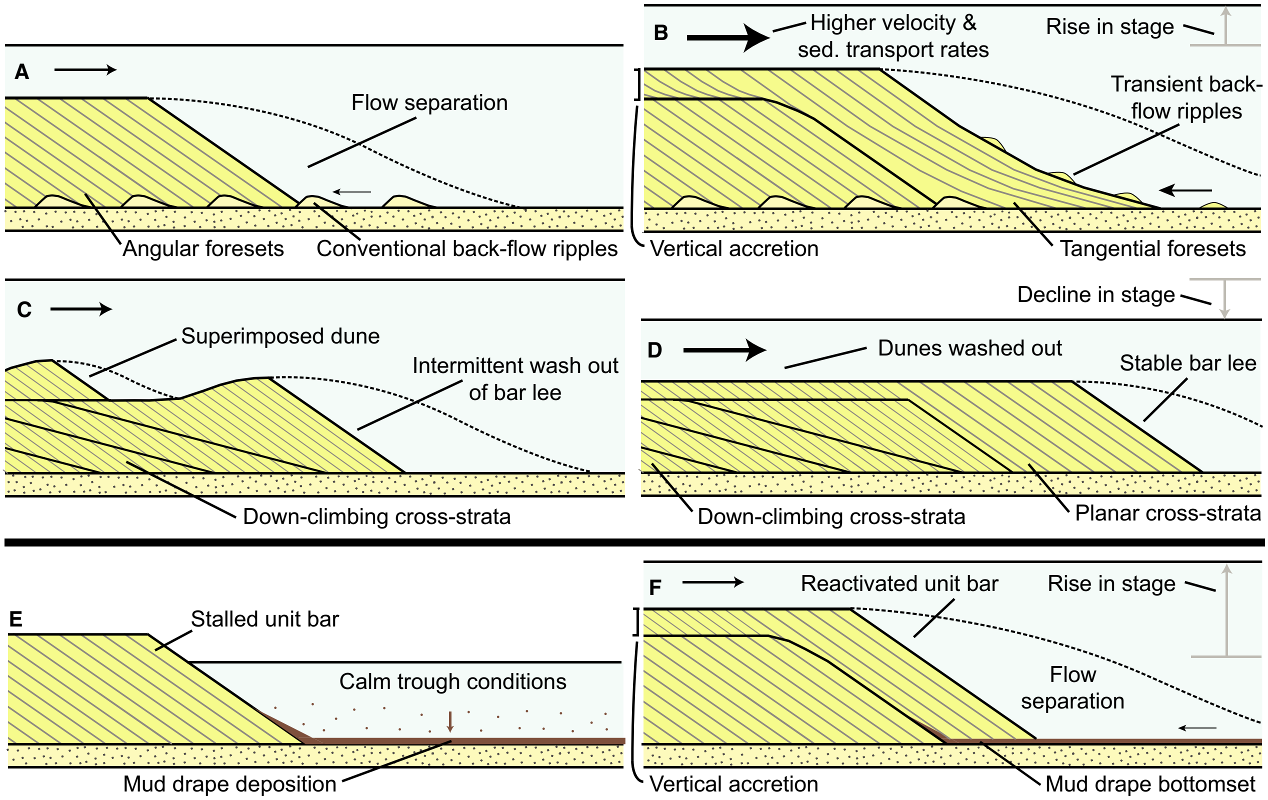


Fig. 13. Schematics denoting possible unit bar internal structures formed by relatively long-term flow and sediment transport unsteadiness in relatively unsteady discharge regimes. (A) and (B) Rising stage over a discharge event. (C) and (D) Falling stage over a discharge event. (E) and (F) A transition from base flow to discharge event flow.

structure (Fig. 13E and F; Table 4). In perennial rivers, bars may remain submerged in base flow conditions, but in highly-variable discharge regimes, many bars will become partially or totally emergent (for example, Fig. 6), allowing sub-aerial modification, such as aeolian reworking of fine sediment (as found by Collinson, 1970). Due to the coarse sediment grade at the Burdekin River field site, such reworking was only rarely observed (for example, localised reworking of fine-grained trough deposits). Partial emergence of unit bars can lead to trough channelisation (Reesink & Bridge, 2011; Herbert & Alexander, 2018) or deposition of suspended sediment (Herbert & Alexander, 2018). When such bars are re-submerged, trough deposits formed during bar inactivity are likely to be preserved. For example, the muddy gravel facies at the base of Bar BR2 was probably partly deposited (mud deposition) during low-flow conditions. In addition, reactivation of a bar that was partially or totally emergent leads to the development of a major reactivation surface within the foreset. Such surfaces can be mud draped if silt and clay are deposited on the inactive avalanche face during low flow, as appears to have been the case in Bar BR4 (Figs 9 and 10).

Longer-term unsteadiness: discharge variability

Seasonal variability, climatic change, human interference and other factors (Table 3) cause river discharge variability over longer timescales (which is a large-scale unsteadiness in the flow). This will also influence unit bar, compound bar and river deposit architecture. Possible effects of one of these, seasonal variability, on fluvial architecture is described in Table 4.

The differences in the effects of unsteadiness on unit bars and dunes

Unit bars and dunes differ greatly in their ability to persist through changing conditions. Unit bars often persist over great changes in discharge and sediment transport rate (Tillman & Ellis, 1968; Collinson, 1970; Smith, 1974; Wooldridge & Hickin, 2005; Reesink & Bridge,

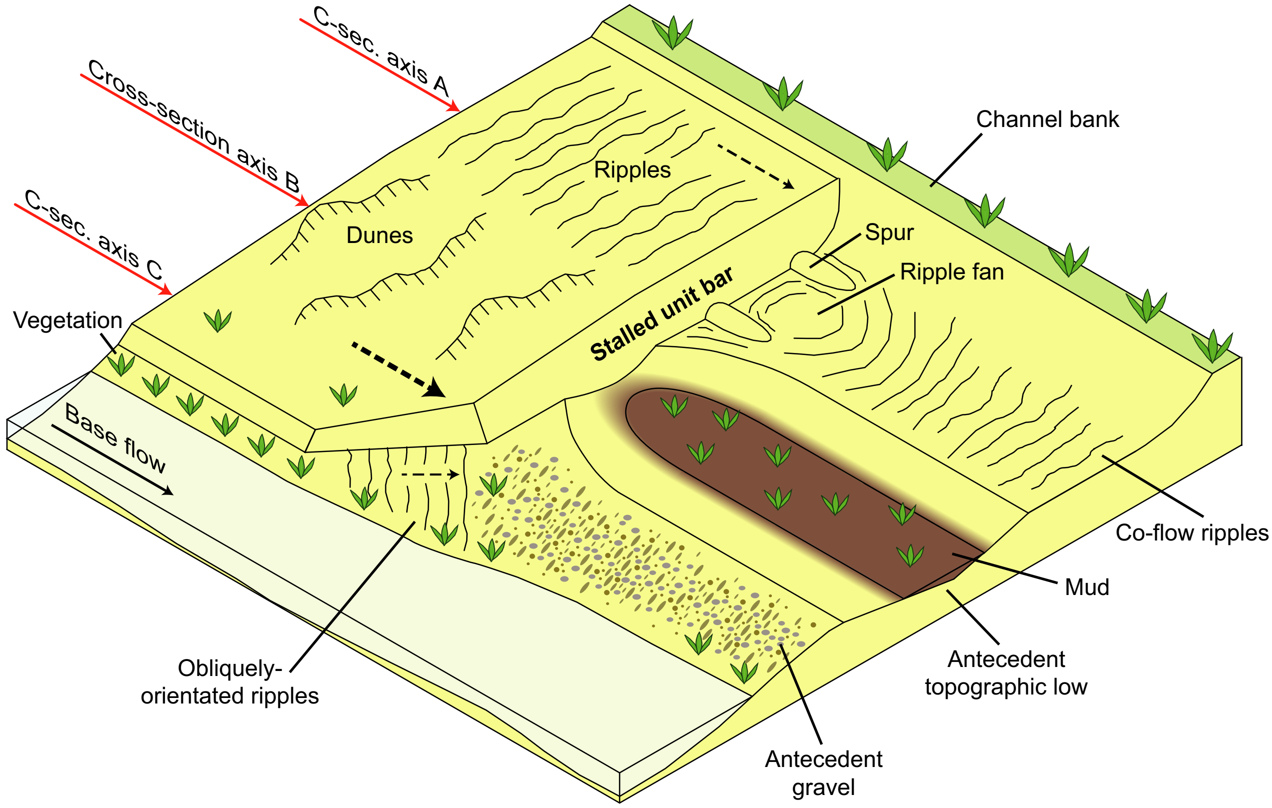


Fig. 14. Schematic noting possible cross-stream variation in unit bar character in a highly-variable discharge fluvial system. The black arrow denotes current flow. Dashed black arrows denote flow when the unit bar was last active. Red arrows relate to the schematic cross-sections in Fig. 15.

2011; Parker *et al.*, 2013). As conditions change, unit bar internal structure also changes (Figs 12 and 13; Table 4). The persistence of forced unit bars relates to how they form, as a structure generated as the bed adjusts to changing sediment transport and flow. Such unit bars can grow or move as long as accommodation space is available (i.e. the 'profile of equilibrium' is above the antecedent bed; Jopling, 1966; Smith, 1971). As a result, they can persist across all the categories of unsteadiness discussed above. Free unit bars (for example, alternate bars) form sporadically, controlled by the channel width, slope and grain size (Jaeggi, 1984; Tubino *et al.*, 1999). Consequently, they may persist through a narrower range of conditions than forced unit bars. Changes in discharge alter the channel width to depth ratio, potentially taking conditions out of the zone of free unit bar development (Rodrigues *et al.*, 2015).

In contrast, dune development occurs in a relatively narrow range of flow conditions, restricting the magnitude and timescale of unsteadiness through which they persist, relative to unit bars. Thus, downstream variation in the internal structure of individual dune deposits (their bottomset, foreset and topset components) tends to be less than in unit bar deposits formed within the same river. Dunes are unlikely to preserve structures recording long-period unsteadiness. However, they may form structures indicating short-period unsteadiness (for example, short-term flow variability and bedform interactions). This might not apply to very large dunes, such as those examined in Almeida *et al.* (2016b), both because their large sediment volume may take longer to remobilise as conditions change and because they can behave as bars at low flow stage.

Effects of the three-dimensionality of channels and unit bars on unit bar internal structure

The across-deposit heterogeneity in the Burdekin River unit bars is related to two scales of

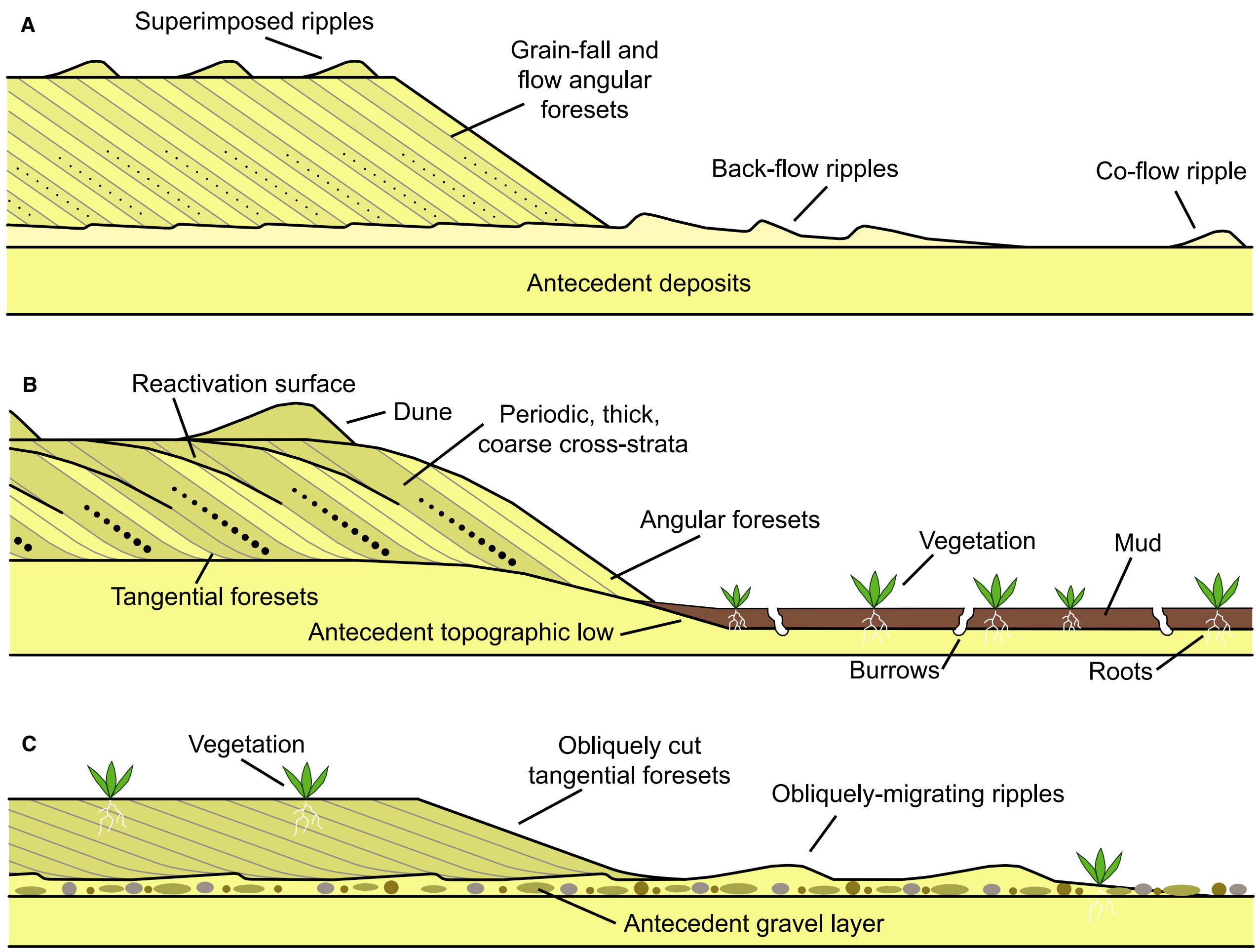


Fig. 15. Schematics denoting possible cross-stream variation in unit bar character along the three cross-sections of the unit bar avalanche face in Fig. 14. (A) Downstream cross-section close to the bank. (B) Downstream cross-section close to the midpoint between the bank and base flow channel. (C) Downstream cross-section close to the base flow channel. Lighter and darker yellows within bar deposits denote finer and coarser deposits, respectively.

variation in space: (i) channel scale non-uniform properties of the channel bed and flow; and (ii) bedform scale non-uniform properties caused by the three-dimensional unit bars themselves, which alter flow and sediment transport locally.

Change in channel width, depth, slope and direction along their length, vegetation and other surface roughness elements lead to non-uniform flow and sediment transport. This is amplified in highly-variable discharge regimes by the growth of trees on the channel bed at low stage. All of these factors can affect a bar's structure by, for example, causing variation in the size and type of superimposed bedforms across a bar (Figs 7, 14 and 15).

Unit bar geometry controls the internal structure of bars (Collinson, 1970; Smith, 1972; Reesink & Bridge, 2011). The internal complexity tends to increase as bar three-dimensionality increases. Conditions at the downstream end of highly lobate or variable-height unit bars can be highly localised across the bar (Fig. 14). For example, changes in unit bar height alter the degree to which superimposed bedforms interact with the bar lee face (for example, causing minor or major reactivation surface development, forming thick cross-strata) and alter the geometry and strength of the flow separation zone, together increasing across-deposit heterogeneity (Fig. 15). Lateral variation in flow separation zone geometry and strength probably contributed to the change in the bottomset character across Bar BR2 by altering the grain size and flux of sediment reaching the trough at different sites along its width.

Preservation of unit bar deposits

Preservation of unit bar deposits is an important consideration when interpreting the rock record. The Burdekin River observations suggest that the structure of a single unit bar deposit can vary greatly both along and across channel. Poor preservation could lead to loss of some depositional elements of this variation.

Lunt *et al.* (2013) and Parker *et al.* (2013), observed a lot of erosional truncation within preserved unit bar deposits in the South Saskatchewan River, Canada (a river with moderate peak discharge variance; Fielding *et al.*, 2018). Parker *et al.* (2013) observed truncation in thickness (*ca* 20% thinner than formative bedform), length (*ca* 32% shorter) and width (*ca* 60% narrower) once unit bars amalgamated into and were preserved within compound bars. Unit bar truncation occurred over a range of flood magnitudes. Lunt *et al.* (2013) noted greater amounts of truncation in unit bar deposits beneath the modern channel basal erosion surface, with losses of up to 90% of the predicted unit bar length. In both studies, truncation led to avalanche face deposits being only a minor component of preserved unit bars, found only at their downstream margins (e.g. Parker *et al.*, 2013, fig. 7).

In the Burdekin River, the highly unsteady conditions lead to unit bars containing only a small amount of simple avalanche face deposits (as deposit complexity was increased by frequent reactivation surfaces and vertical accretion deposits). The poor preservation potential of simple unit bar avalanche face deposits (single sets of planar cross-stratification, as in Fig. 1) in the moderately-variable discharge South Saskatchewan River and its poor formation potential, independent of its preservation, in the highly-variable discharge Burdekin River suggest that such structures within ancient deposits are likely to be infrequent, except when formed by rivers with low discharge variability. Instead, multiple thinner sets of planar-stratification or cross-stratification (potentially down-climbing) are likely to be more abundant.

CONCLUSION

Unit bars in the Burdekin River, examined by digging trenches into the bar lee face, contained complex deposits dominated by co-sets of relatively thin, planar-stratified or cross-stratified sets which, for the latter, tended to down-climb. Internal structures altered along the length of unit bars, with laterally restricted avalanche face deposits (a single planar cross-stratified set) tending to develop only at their downstream ends. The complex and varying internal structures developed primarily as a result of: (i) superimposed bedforms reworking the unit bar avalanche face; (ii) variable discharge triggering reactivation surfaces; and (iii) changes in bar growth direction induced by stage change. Internal structures were also found to vary laterally across unit bars, related to changes in superimposed bedform character and unit bar geometry along the crest of unit bars.

Fluvial unsteadiness was found to be a key contributor in controlling unit bar architecture. Four categories of fluvial unsteadiness greatly influenced the development of unit bar internal structures in the Burdekin River:

1 Short-term flow variability, related to turbulence generation, which supported the development of back-flow ripples that were incorporated into unit bars.

2 Interactions between superimposed bedforms and the avalanche face of unit bars, which led to the development of down-climbing cross-stratified sets that dominated bar deposits.

3 Fluvial unsteadiness over a single discharge event, which induced vertical accretion and the incorporation of topsets into unit bars. It also altered the character of superimposed bedforms, thus influencing the processes related to shorter-period fluvial unsteadiness.

4 Fluvial unsteadiness over multiple discharge events, which contributed to the development of major reactivation surfaces, relatively complex bottomsets and mud drapes.

A high degree of variation both along and across unit bar deposits is probably characteristic of unit bars, and unlikely with the deposits of smaller bedforms (for example, dunes), because they often wash out between discharge events and their smaller dimensions limit variation in fluvial conditions across their width. In regimes where unit bar deposits are well-preserved, variability in their architecture has the potential to aid with their identification and allow for detailed interpretations of the conditions before and during bar initiation and development.

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Supporting Information

Additional information may be found in the online version of this article:

Fig. S1. High resolution photogrammetric models of trenches dug into Bars BR1 to BR4. Trenches were dug parallel to local palaeoflow indicators. Vertical and horizontal scales are the same. The colour of the photogrammetric reconstructions is dependent mainly on the light conditions; the large contrast difference representing north (darker) and south (lighter) side trench faces.

Fig. S2. High resolution photogrammetric models of trenches dug into Bars BR5 to BR7. Trenches were dug parallel to local palaeoflow indicators. Vertical and horizontal scales are the same. The colour of the photogrammetric reconstructions is dependent mainly on the light conditions; the large contrast difference representing north (darker) and south (lighter) side trench faces. For the 2017 unit bars, plots denote grain size against cumulative percentage for samples of the upper foreset (<0·1 m from the deposit top), lower foreset (<0·1 m from the deposit base) and trough. All samples were collected within 1 m of the bar avalanche face.