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Anatomy of the buried Burdekin River channel across the Great Barrier Reef shelf: how does a major river operate on a tropical mixed siliciclastic/carbonate margin during sea level lowstand?

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Abstract

A large palaeochannel on the northeastern Australian continental shelf has been imaged by a series of shallow seismic reflection profiles. The buried channel forms an important Pleistocene route of the Burdekin River and extends almost continuously for ~ 160 km from the present coast to the outermost reef. The channel floor profile steps across the shelf with alternating segments of gentle gradient (flats) and steeper gradient (ramps). Channel sinuosity as interpreted from seismic records varies among segments between 1 and 1.72, with no consistent relationship between sinuosity and gradient. The lower and upper parts of the channel fill have different geometry and reflection character, suggesting channel excavation and initial filling occurred during a different regime than final filling. In one section of the shelf, about the − 50 m isobath, the channel is difficult to define and appears to have wandered significantly, either because it has been modified by shoreface erosion ca. 10.5 ka or because the river encountered a change in topography in front of karstified reefs. As the channel passes between the numerous outer shelf reefs, in water depths of 70–80 m, it becomes progressively smaller, conspicuously underfilled, and absent entirely over the outermost 10 km of the shelf. No discrete lowstand river mouth could be recognised on the present shelf edge. The elevations of flat segments on the channel floor profile show considerable similarity to published elevations of stillstands or brief rises in sea level attained during the long-term drawdown associated with the last glacial cycle (125–20 ka) and are interpreted to have formed during this stepwise drop in sea level. Channels were cut and partially filled during the fall and lowstand and then backfilled during the Holocene transgression. The ancestral channel of the Burdekin River therefore preserves a rare insight into the stratigraphic record of falling sea level during the last glacial.

Keywords: Great Barrier Reef; Australia; Pleistocene; Palaeochannel

1. Introduction

Lowstand rivers on exposed shelves play an important role in the evolution of continental margins. Generic depositional models (e.g., Van Wagoner et al., 1988; Posamentier et al., 1992) predict that rivers

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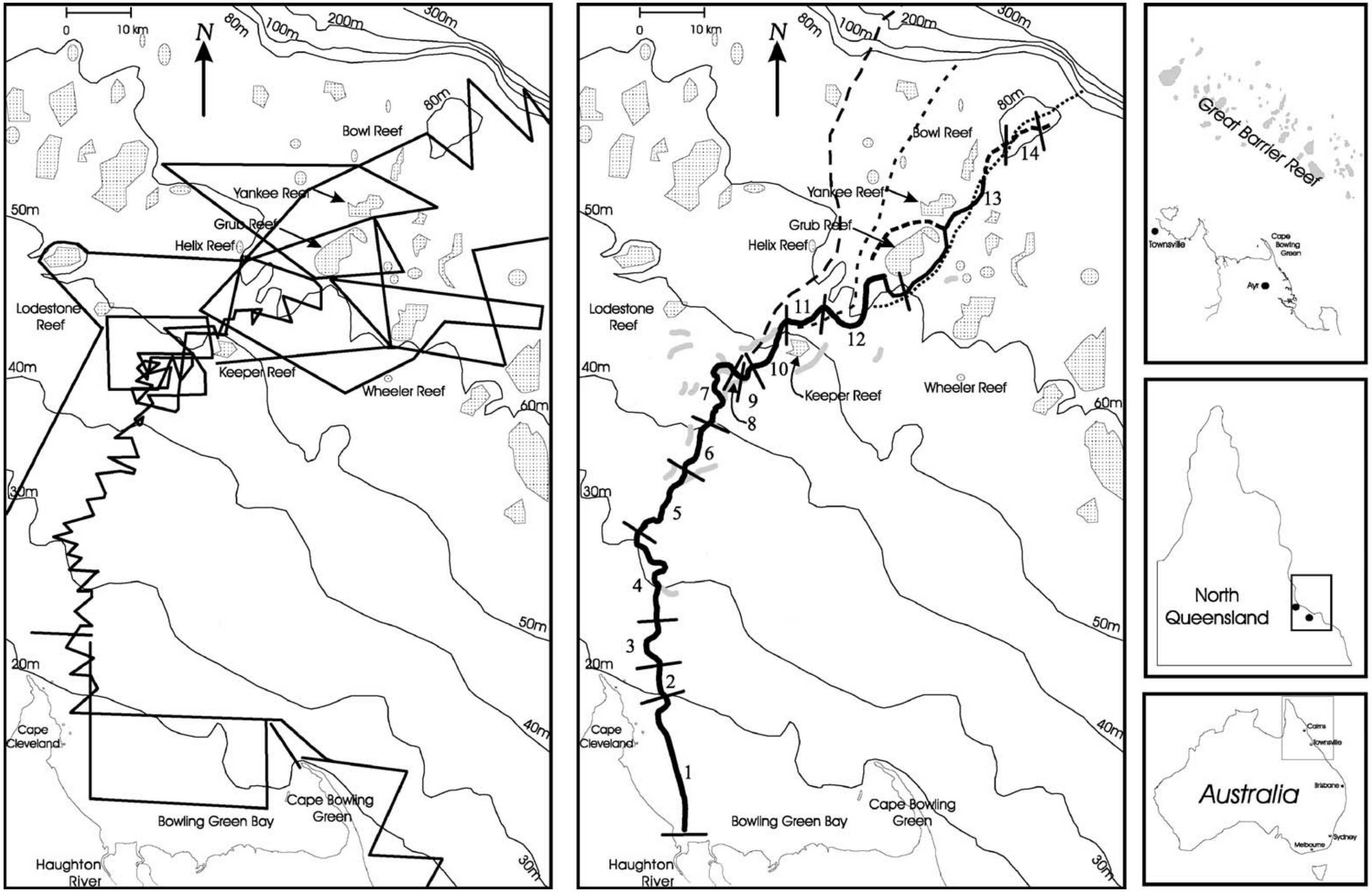

Fig. 1. The northeastern Australia margin showing tracks of our seismic surveys and the interpreted course of the palaeo-Burdekin. The solid black line indicates the path of the palaeochannel based on our surveys, with grey lines indicating tributary and other channels intersected. The long-dashed line indicates the channel course as interpreted by Harris et al. (1990), the short-dashed line indicates that of Johnson and Searle (1984), and the dotted line indicates the unpublished interpretation of Carr and Johnson (data held at School of Earth Sciences, James Cook University of North Queensland). Numbers correspond to channel course segments (Table 1). Bathymetric contours are taken from published maps and are considerably generalised seaward of the − 60 m isobath.

will incise exposed shelves perpendicular to the coast during falling sea level because such a fall will produce convex longitudinal channel profiles. However, shelf bathymetry and relative sea level change may complicate fluvial incision patterns significantly (Talling, 1998). One particularly interesting problem arises for tropical mixed siliciclastic/carbonate margins where, during sea level highstands, rivers discharge onto shelves rimmed by active carbonate banks or reefs. In contrast to well-studied siliciclastic margins, subaerially exposed carbonate hills on the outer shelf could modify cross-shelf gradients during lowstands, causing river avulsion (Woolfe et al., 1998) or incision parallel to the coast (e.g., Esker et al., 1998; Ferro et al., 1999).

The northeast Australian margin (Fig. 1), including the Great Barrier Reef (GBR) shelf, is the largest and perhaps best extant example of a tropical mixed siliciclastic/carbonate system. Seismic reflection profiles acquired between 1973 and 1980 show numerous buried channels on the shelf, presumably formed during lower sea level (Orme et al., 1978; Johnson et al., 1982; Searle, 1983; Johnson and Searle, 1984). Following basic sequence stratigraphic concepts, these workers and others (e.g., Harris et al., 1990; Carter et al., 1993) have liberally connected "palaeochannels" to show major rivers crossing the broad (50–100 km) GBR shelf during lowstand, roughly perpendicular to the coast. The extensive reef network on the outer shelf, active today and during the penultimate highstand, was exposed and karstified during the last lowstand (e.g., Marshall and Davies, 1984; International Consortium for Great Barrier Reef Drilling, 2001). Reconstructions of the exposed shelf on the northeast Australian margin thus have major lowstand rivers bisecting a significant topographical barrier with minimal or no interaction.

Available seismic lines across the GBR shelf typically lie at least 10 km apart, intersect palaeochannels at unknown orientations and show them without detailed internal structure. As emphasized by Woolfe et al. (1998), no study has continuously traced a palaeochannel across the shelf, so known channel intersections could represent a "discontinuous and complex array of channel segments" formed by estuarine entrenchment. With this explanation, and in contrast to generic depositional models, fluvial sediments might aggrade on a broad, reef-silled shelf during lowstands (Woolfe et al., 1998).

The Burdekin River (Fig. 1) dominates fluvial discharge on the northeast Australian margin, annually adding 9.8×10^9 m^3 of water and $3–9 \times 10^6$ tonnes of sediment to the GBR shelf (Neil et al., in press). These figures are nonetheless modest when taken in a global context and reflect the relatively subhumid climate, tectonic stability and great antiquity of the Australian landscape.

Connecting a few buried channels seaward of the modern Burdekin Delta, Johnson and Searle (1984) and Harris (1990) show the "palaeo-Burdekin" flowing northeast to the shelf edge. The two interpretations diverge on the outer shelf, however, with Johnson and Searle showing the channel passing west of Keeper and Grub reefs, while Harris (1990) plotted a some,-what different course due north from Helix Reef (Fig. 1). A further unpublished interpretation by Carr and Johnson (data and maps held by School of Earth Sciences, James Cook University) shows the palaeochannel passing east of Grub, Yankee and Bowl Reefs to the shelf edge (Fig. 1). In this study, we trace and characterise this palaeochannel to examine the fate of a major river on an archetypal tropical mixed siliciclastic/carbonate margin during lowstand.

2. Approach and methods

Cruises KG-00/2 and KG-01/2 of the RV *James Kirby* were dedicated to mapping palaeochannels seaward of the Burdekin River. Seismic reflection data were acquired for a total of 12 days using a side-mounted Datasonics CAP6600 CHIRP II acoustic profiling system, which generated a linear FM 2–7 kHz pulse with a dominant frequency of 3.5 kHz. The positions of surveyed lines were accurately determined using differential GPS. Working maps of channel location were compiled during cruises to facilitate navigation and efficiency.

Previous seismic work (e.g., Johnson and Searle, 1984; Orpin, 1999) indicated several palaeochannels immediately offshore of the Burdekin Delta, including a major channel north of the Haughton River (Fig. 1). However, given the variable quality and wide spacing of earlier seismic lines, the number, size and course of channels remained uncertain. In our first survey (KG-00/2), 2 days were spent acquiring a comprehensive suite of data on the modern Burdekin Delta front

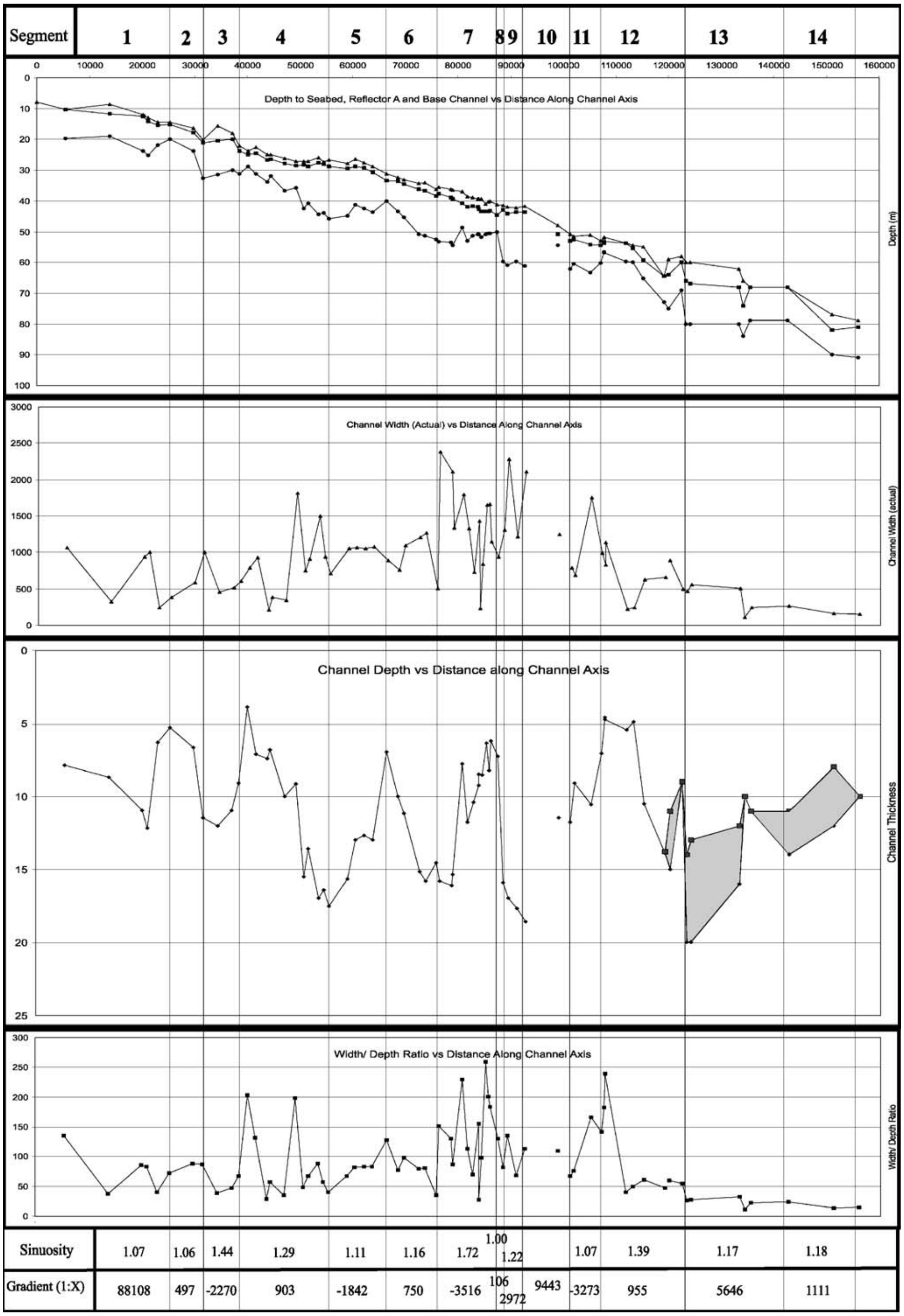

Fig. 2. Profile along the palaeo-Burdekin channel showing variations in channel floor elevation, top of channel fill, sea floor elevation and channel dimensions. Shaded area indicates regions where the palaeochannel is underfilled, i.e., where it has both a surface and a subsurface expression. Channel course segments (1 – 14) are as in Table 1.

to locate and characterise all palaeochannels extending from land. Four days were then spent following the most prominent palaeochannel by zigzagging short, closely spaced seismic lines. In this way, a trunk channel and some potential tributaries could be traced across the shelf to the GBR. In the second survey (KG-01/2), a pattern of lines was acquired to constrain possible channel courses over the outermost part of the GBR shelf.

Following the cruises, data were downloaded, processed and interpreted using the Kingdom software package. Although data quality was affected by sea surface conditions, which varied from dead calm to 3 m swells, the new seismic profiles are significantly better quality than previous work.

Several critical channel characteristics were determined from the seismic data, including apparent width, depth (calculated using p-wave velocity in water: 1500 m/s), cross-sectional profile and fill reflection character. Cross-sectional geometry and the orientation of accretionary bedsets in these mainly oblique intersections were then used to interpret the directional sense of curved reaches (cf. Willis, 1989) and to calculate true cross-sectional orientation and dimensions. From these data, channel sinuosity was estimated over the length of the survey. All of these properties have been plotted as a function of depth below present mean sea level (Australian Height Datum or AHD) and distance along the channel from the modern coastline (Fig. 2).

3. The palaeo-Burdekin channel

Surrounding the modern Burdekin Delta, one major buried channel < 1000 m wide and at least six minor buried channels < 200 m wide occur between the 10 and the 30 m isobaths (Fig. 1). As recognised by Johnson and Searle (1984), the dominant palaeochannel occurs in southwest Bowling Green Bay, directly offshore from the modern Haughton River mouth. However, the greater width and depth of this buried

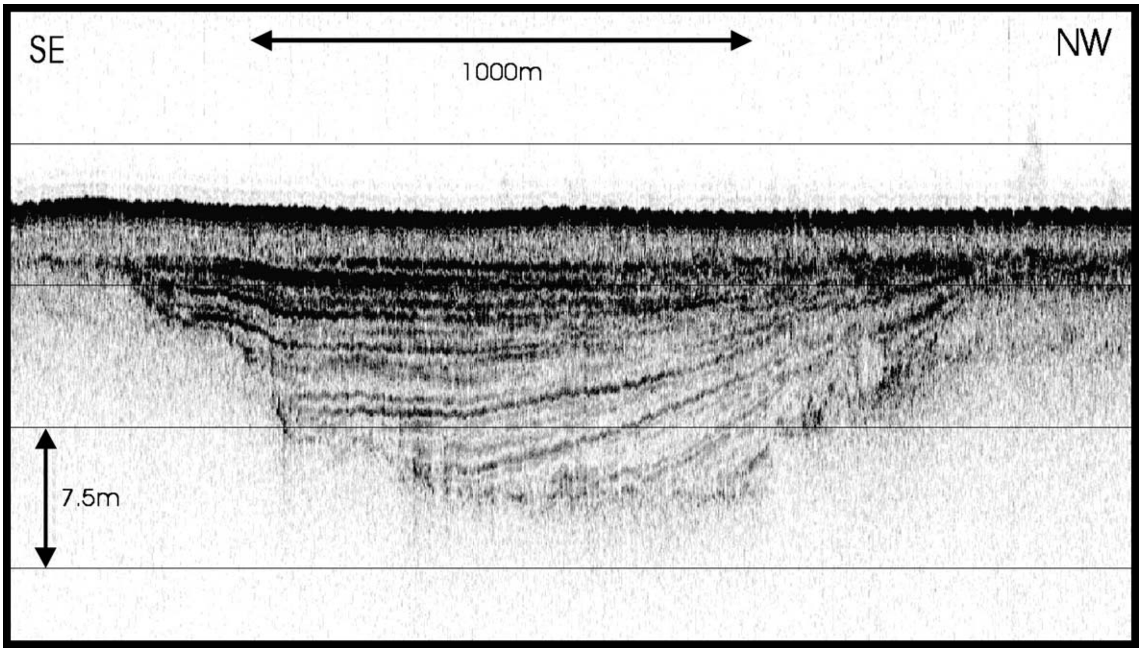

Fig. 3. Example of a channel cross-section from Line 35 on the middle shelf (Table 1, Segment 5). Note the asymmetrical cross-sectional geometry with large-scale dipping stratal surfaces interpreted as lateral accretion surfaces in the lower fill and the distinct character of the upper fill interpreted as having accumulated by backfilling during sea level rise. Vertical axis is in two-way time, converted to depth by assuming a p-wave velocity of 1500 m/s.

channel compare more closely to the modern lower Burdekin River, ∼ 55 km to the southeast. On the basis of geomorphological data and limited drilling on land, Hopley (1970) suggested the modern Haughton River is a principal Pleistocene channel of the Burdekin River. We concur with Johnson and Searle (1984) that a lowstand trunk channel of the Burdekin system lies beneath western Bowling Green Bay.

All palaeochannels around the Burdekin Delta are defined in part by a high amplitude reflector that can be traced from the relatively flat, elevated surfaces either side of the channel (interfluves) down into the channel floor (Fig. 3). On the interfluves, a < 5 m thick ragged blanket of sediment overlies this reflector. A high amplitude reflector, typically covered by a thin sediment layer and colloquially termed "Reflector A" (Orme et al., 1978 et seq.), has been identified on many seismic profiles across the GBR shelf. This reflector has been interpreted ubiquitously as a Pleistocene–Holocene disconformity/angular unconformity formed during lowstand (e.g., Orme et al., 1978; Johnson et al., 1982; Johnson and Searle, 1984; Carter et al., 1993). Most previous works (e.g., Johnson et al., 1982; Johnson and Searle, 1984; Carter et al., 1993) have suggested that palaeochannels on the GBR shelf incise into this surface. However, the continuity of the reflector from one interfluve into the base of the channel and onto the opposite interfluve suggests (though does not prove) that channels are not incised into Reflector A. Rather, channels formed during the period of time represented by the unconformity surface, filling partly during this time and partly during the Holocene transgression. The depth of channel forms and the relatively simple cross-sectional geometry of channel fills are comparable to modern channels onshore, which are better described as "entrenched" than "incised".

4. Cross-shelf channel profile and fill

The palaeo-Burdekin channel located in western Bowling Green Bay can be traced across the GBR shelf for ∼ 160 km from the modern coast to the outermost part of the shelf (Fig. 1). This major channel initially heads north before turning northeast at about the − 40 m isobath. The northeast trend is roughly perpendicular to the modern coast and to isobaths that probably approximate older shorelines. Although several small channels join the main channel, no major tributaries have been recognised. The channel becomes difficult to trace on the outermost shelf but can be mapped to within ca. 10 km of the shelf edge.

Properties of the palaeo-Burdekin channel change significantly across the shelf (Table 1). In particular, the channel floor gradient alternates between long, gently (or even negatively) sloping sections and shorter, steeper intervals. On this basis, we have divided the channel into 14 alternating "ramp" and "flat" segments (Fig. 2). Within most segments, channel widths and depths show a consistent trend (Table 1). Interpreted sinuosity within individual segments varies from 1 to 1.72, with no consistent relationship between gradient and sinuosity (Table 1 and Fig. 2). The outermost Segment 14 of our profile (Fig. 2) drops into ca. 80 m water, beyond which the seafloor shallows somewhat to the shelf edge, and no channel was evident. Segment 10, ∼ 9 km long and located around Keeper Reef (Fig. 1), initially posed a problem. Only local evidence of channelling was found around the west and northwest sides of Keeper Reef during KG-00/01, although a second channel was subsequently recorded on the southeast side of the reef during KG-01/02 (Fig. 1). The channel floor elevation in these channels is ca. − 60 m, similar to that in the immediately upstream Segment 9 and the downstream Segment 11, and on this basis, Segments 9–11 can be considered as one long flat reach. The channel can be interpreted to have avulsed or split into two coeval courses around the front of Keeper Reef, the first substantial reef structure encountered by the channel. A single, larger channel is reestablished at the start of Segment 11 and continues to the end of our survey (Fig. 1).

Channel geometry and fill vary considerably along the profile (Table 1). In many places, orthogonal cross-sections show a steeply incised (entrenched), generally asymmetrical channel with a stepped channel floor and deepest point (thalweg) located close to the steeper bank (Fig. 3). As noted by Johnson and Searle (1984), these channels often contain two units: a lower unit dominated by low reflectivity and reflectors that dip from the gently sloping bank to terminate against the steeper bank and an upper unit with high reflectivity and reflectors that dip symmetrically toward the channel axis

Table 1
Characteristics of the ancestral Burdekin palaeochannel in each of the segments recognised (Figs. 1 and 2)

Segment	Morphology	Gradient (1/*x*)	Width (m)	Depth (m)	Width/Depth	Cross-section	Sinuosity	Fill characteristics
1	Flat	88,108	250–1060	6.5–12	35–135	Variable (few data)	1.07 (min.)	Possibly mud dominated
2	Ramp	497	380–1000	5.5–11.5	70–90	Mostly narrow, symmetrical	1.06 (min.)	Possibly mud dominated
3	Flat	−2270	460–1000	4–11.5	40–205	Asymmetrical, LA with symmetrical upper part	1.44	Composite, ?coarse-grained lower part, muddy upper part
4	Ramp	903	210–1820	4–17.5	30–205	Slightly asymmetrical, minor LA, deep and steep sided	1.29	Composite, a/a
5	Flat	−1842	710–1070	7–17.5	40–130	Asymmetrical, LA, local anabranching	1.11 (min.)	Composite, a/a
6	Ramp	750	500–1270	7–16	35–130	Symmetrical to slightly asymmetric, anabranching channels rejoin to a single trunk channel	1.16	Composite, a/a
7	Flat	−3516	230–2380	6–16	30–260	< 4 symmetrical, anabranching channels	1.72	Composite, a/a
8	Ramp	106	950–1310	7–16	80–130	Slightly asymmetrical, steep sided	1.00	Composite, a/a
9	Flat	2972	1210–2280	16–19	70–135	Slightly asymmetrical, possible anabranching	1.22	Composite, a/a
10	?	9443	1250	11.5 (min.)	110	Channel deposits eroded, except in one profile, there anabranching	?	?
11	Flat	−3273	690–1750	7–12	70–165	Slightly asymmetrical, LA, steep sided	1.07	Composite, a/a
12	Ramp	955	220–1130	4.5–14	40–240	Asymmetrical, probably truncated by erosion	1.39	Composite, a/a
13	Flat	5646	113–890	9–20	14–59	Symmetrical to slightly asymmetrical	1.17	Underfilled to unfilled
14	Ramp	1111	149–259	10–14	14–18	~ Symmetrical	1.18	Underfilled

min. = minimum, LA = laterally accreted, a/a = as above.

(Fig. 3). Other orthogonal cross-sections show a steep-sided but symmetrical channel with a flat channel floor. As for asymmetrical channels, the lower parts of these channels typically have low reflectivity while the upper parts have higher reflectivity. In Segments 5, 6 and 7, two or more steep-sided, mainly symmetrical channels were found.

For nearly all cross-sections, regardless of channel geometry, the top of channel fill is concave-up (Fig. 3). This and the high reflectivity suggest upper parts of the channel contain mud. Because the thickness of the late Holocene sediment blanket varies along our profile, we agree with Johnson et al. (1982) that no significant relationship exists between modern bathymetry and palaeochannel location on the GBR shelf. An exception to this rule occurs on the outermost part of the channel course. Here, in Segments 13 and 14, the channel has both a surface and a subsurface expression (i.e., is underfilled) and in a small number of intersections has only a surface expression (i.e., no channel fill deposits could be recognised) (Fig. 2). Elsewhere on the outer shelf, a scalloped seafloor truncates reflectors associated with the channel. Holocene erosion may therefore have modified the palaeo-Burdekin channel in some parts of the shelf.

A detailed description and interpretation of channel geomorphology and fill character is given by Fielding et al. (submitted for publication).

5. Interpretation—a new perspective on the lowstand Burdekin

A single prominent channel, similar in size to that of the modern lower Burdekin River, extends across most of the GBR shelf nearly perpendicular to the modern coast and isobaths. Although channel width varies, it does not consistently widen downstream as is typical of estuaries. Indeed, the channel shows an abrupt decrease in width, and width/depth ratio, at the start of Segment 12 that persists to the downstream limit of the channel (Fig. 2). The lowstand Burdekin River flowed across the broad, exposed GBR shelf to within 10 km of the shelf edge (Fig. 1), entrenched into a Pleistocene surface over most of this reach. Asymmetrical channel cross-sections most likely formed through lateral accretion and progressive infilling of a meandering river. However, the limited horizontal extent of this accretion suggests minimal migration and meandering, an impression corroborated by channel sinuosity, which only reaches a maximum of 1.7 (Table 1). By contrast, symmetrical channel cross-sections most likely formed through incision and dominantly vertical accretion in relatively straight channels. Such channels occur in segments with relatively low sinuosities (1.05–1.2) (Table 1). Areas where multiple, mainly symmetrical channels were found (Segments 5, 6, 7 and possibly 10) (Table 1) may record anabranching of the lowstand Burdekin River into two or more coeval streams. The relatively straight/narrow channel and the steep channel banks suggest entrenchment into a compact substrate. Coring through the Holocene sediment blanket on the GBR shelf often reveals indurated Pleistocene sediment at shallow depths (e.g., Carter et al., 1993). In this context, the reflection character of accreted units suggests they are predominantly composed of coarse-grained sand. In general, though not ubiquitously, symmetrical channels characterise ramps whereas asymmetrical or anabranching channels characterise flats (Table 1). Assuming this channel floor profile faithfully records past channel gradients, downstream limits of ramps (upstream limits of flats) define knick points associated with headward erosion and incision.

The palaeochannel could not be linked directly to the shelf edge, despite thorough searching (Fig. 1). Indeed, our data indicate that over the outermost 10 km of the shelf, outboard from the mapped end of the channel, the seafloor rises from ca. − 80 to about − 60 to 70 m, presenting a topographic barrier to the channel. This can be interpreted in one of two ways: either (1) the channel dispersed its load within a topographic low inboard of the shelf edge and never discharged onto the lowstand (− 120 m) shoreline or (2) the channel aggraded to the point where it was able to spill over the barrier to discharge onto the lowstand shoreline, but its deposits were subsequently removed by erosion. Whichever of these options is favoured, the fact remains that no incised channel reaches the shelf edge.

Several workers (Johnson et al., 1982; Johnson and Searle, 1984; Carter et al., 1993) have inferred that palaeochannel incision (or entrenchment) occurred partly during late transgression (< 10 ka) when the sea crossed the shelf. Holocene sea level curves for the northeast Australian margin (e.g., Larcombe et al., 1995), though somewhat controversial (Harris, 1999), show several rapid rises separated by short-lived stillstands. In this sense, channel steps could reflect Holocene stillstands, the Burdekin River entrenching into indurated sediment on land while a delta composed of coarse-grained sediments covered the channel at sea (Johnson et al., 1982). However, except for Segment 10, the channel shows no significant change in plan geometry, width/depth ratio or internal fill as would be expected for estuarine or deltaic environments. Moreover, no sediment bodies were found having seismic characteristics indicative of a delta in close proximity to the channel (e.g., clinoforms downlapping onto Reflector A).

Instead, we strongly suggest the palaeo-Burdekin channel and Reflector A formed contemporaneously. We propose that steps in the channel floor formed during the protracted drawdown in sea level between ca. 125 and 18 ka. Channel flat elevations correspond to sea levels that remained constant or rose slightly over an extended interval of time (e.g., Talling, 1998). Emergent reef terraces on the Huon Peninsula, 1500 km to the north, suggest significant periods of sea level stasis or rise ca. 100, 80, 60, 40, 32 and 28 ka corresponding to past sea levels of − 20, − 20, − 45, − 62, − 68 and − 70 m, respectively (Pinter and Gardner, 1989; Chap-

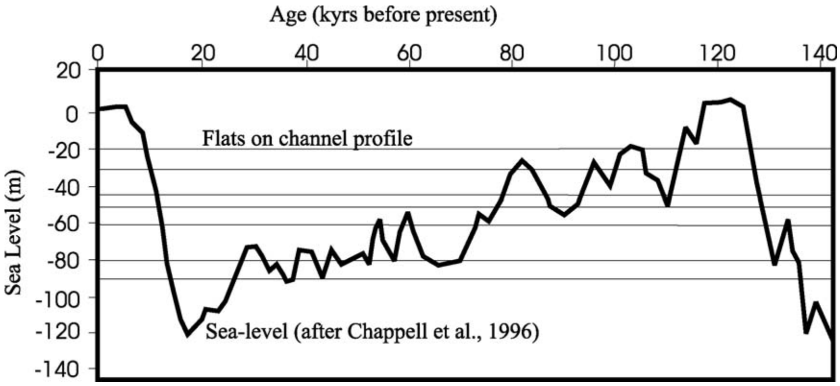

Fig. 4. Graph of sea level over the past 140 ka (from Chappell et al., 1996), showing the elevations of flat segments along the palaeo-Burdekin channel profile. There are numerous coincidences between the elevations of temporary stillstands between 105 and 55 ka and those of channel floor flat segments, suggesting a genetic relationship between the two parameters.

pell et al., 1996). Channel flat segments occur at −20, −31, −43, −51, −61, −80 and −90 m, some of which match past sea level stillstands (Fig. 4). The degree of coincidence is sufficient to suggest a relationship between the two parameters. In this scenario, the channel would incise (entrench) into the substrate during sea level lowering, then fill in part during the ensuing stillstand/temporary rise (e.g., lower fill in Fig. 3), before further sea level lowering caused renewed entrenchment, stripping and recycling of sediment further downstream. In this way, the stepped long profile would be constructed over the protracted and punctuated sea level drop lasting ca. 100 ka (Fig. 4). Upper fill units within the channel apparently accumulated in a stable channel of reduced size. In most cases, this fill is symmetrical, indicating vertical accretion. Unlike the lower unit of channel fill, fine-grained mud probably progressively backfilled the channel during channel abandonment.

Segment 10 lies between −42 and −51 m, a horizon that may correspond to a stillstand ca. 10.5 ka associated with the Younger Dryas (Larcombe et al., 1995; Harris, 1999). Significant shoreface erosion during the postglacial transgression provides an explanation for the apparent modifications to channels in Segment 10, although the fundamental cause of the changes in geometry and course of the river is probably the topographic barrier presented by Keeper Reef.

The apparent lack of a channel to the shelf edge and the noted rise in seafloor elevation close to the shelf edge suggest that the channel did not incise to the lowstand shoreline. Of the two plausible explanations given above, the most likely seems to be that channel sediments aggraded to the point where they spilled over the topographic barrier to reach the lowstand shoreline but were subsequently eroded during the early stages of postglacial sea level rise. The evidence for such a process of sediment stripping from the outermost shelf lies in the underfilled (to locally unfilled) character of palaeochannel intersections over Segments 13 and 14. If channels were never filled or were stripped of their sediment during the long-term drawdown in sea level, then it is difficult to explain the fully filled character of the palaeochannel elsewhere. A more plausible explanation is that coastal and shoreface erosion removed sediment from the lowermost part of the channel during the initial stages of the postglacial transgression, but then as the transgression gained pace the channel was backfilled passively and preserved more or less intact by rapid marine flooding. This explanation is also consistent with recent suggestions that maximum sediment delivery to the continental slope in this region was not during lowstand but rather during the early stages of the postglacial transgression (Dunbar et al., 2000).

6. Summary and implications

We have examined in unprecedented detail the lowstand channel of a major river across an archetypal tropical mixed siliciclastic/carbonate shelf system and suggest that no available model adequately explains its basic characteristics. In contrast to previous inferences but as might be predicted from some models (e.g., Talling, 1998), the Burdekin River entrenched into a partially indurated surface during the episodic drop of sea level associated with the last glacial lowstand. This entrenchment proceeded through an extensive reef network but ceased before reaching the lowstand shoreline at the present shelf edge. The inferred Pleistocene drainage system is therefore an entrenched channel (as opposed to incised valley) system, despite having formed during a lowstand that exposed the shelf edge (cf. Posamentier, 2001). The relatively low sinuosity and simple internal structure of the channel are consistent with the rapid rates of short-term sea level fall implied by Fig. 4 and with the cohesive nature of the substrate (cf. Begin, 1981; Wood et al., 1992), and the amounts of downcutting are consistent with other examples worldwide from this period (see review by Schumm, 1993). The complex pattern of variation recorded in the Burdekin palaeochannel indicates that the river was in a state of disequilibrium for much of the last glacial cycle.

The downstream decrease in channel size and ultimately its termination may reflect a largely undocumented process whereby lowstand rivers aggrade in front of karstified reefs. Whether or not this is valid, significant amounts of terrigenous sediment are currently missing from the outermost parts of the palaeochannel, presumably having been exported to the slope during the early stages of the postglacial transgression. This response is completely opposite to predictions from generic depositional models in which minimal siliciclastic accumulation occurs on the slope during transgression (e.g., Van Wagoner et al., 1988; Posamentier et al., 1992). Clearly, many more data pertaining to lowstand channels in a variety of climatic, tectonic and physiographic settings must be acquired before generalisations about river response to sea level lowering can be confidently made.

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