Abstract

The formation of incised valleys on continental shelves is generally attributed to fluvial erosion under low sea level conditions. However, there are exceptions. A multibeam sonar survey at the northern end of Australia’s Great Barrier Reef, adjacent to the southern edge of the Gulf of Papua, mapped a shelf valley system up to 220 m deep that extends for more than 90 km across the continental shelf. This is the deepest shelf valley yet found in the Great Barrier Reef and is well below the maximum depth of fluvial incision that could have occurred under a – 120 m, eustatic sea level low-stand, as what occurred on this margin during the last ice age. These valleys appear to have formed by a combination of reef growth and tidal current scour, probably in relation to a sea level at around 30–50 m below its present position.

Tidally incised depressions in the valley floor exhibit closed bathymetric contours at both ends. Valley floor sediments are mainly calcareous muddy, gravelly sand on the middle shelf, giving way to well-sorted, gravely sand containing a large relict fraction on the outer shelf. The valley extends between broad platform reefs and framework coral growth, which accumulated through the late Quaternary, coincides with tidal current scour to produce steep-sided (locally vertical) valley walls. The deepest segments of the valley were probably the sites of lakes during the last ice age, when Torres Strait formed an emergent landbridge between Australia and Papua New Guinea. Numerical modeling predicts that the strongest tidal currents occur over the deepest, outer-shelf segment of the valley when sea level is about 40–50 m below its present position. These results are consistent with a Pleistocene age and relict origin of the valley.

Based on these observations, we propose a new conceptual model for the formation of tidally incised shelf valleys. Tidal erosion on meso- to macro-tidal, rimmed carbonate shelves is enhanced during sea level rise and fall when a tidal, hydraulic pressure gradient is established between the shelf-lagoon and the adjacent ocean basin. Tidal flows attain a maximum, and channel incision is greatest, when a large hydraulic pressure gradient coincides with small channel cross sections. Our tidal-incision model may explain the observation of other workers, that sediment is exported from the Great Barrier Reef shelf to the...
adjacent ocean basins during intermediate (rather than last glacial maximum) low-stand, sea level positions. The model may apply to other rimmed shelves, both modern and ancient.

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**Keywords:** Great Barrier Reef; Gulf of Papua; tidal currents; continental shelf; submarine valleys; sea level change; Quaternary

1. Introduction

The creation of continental shelf submarine valleys and the accommodation space of most transgressive estuarine systems is generally attributed to the erosion and incision of the shelf by rivers (or by glaciers on high latitude shelves) under low sea level conditions (e.g., Dalrymple et al., 1994). However, in some cases, shelf valleys are formed by processes unrelated to rivers. Examples include valleys cut by shelf-edge slumps and mass flows (e.g., Jansen et al., 1987) and those eroded by the action of strong tidal currents (Dalrymple et al., 1994). Valleys cut by shelf-edge slumps and mass flows are generally confined to the outer shelf and upper slope, although the heads of some submarine canyons may extend a considerable distance landward. Examples are the Scripps and Monterey Canyons in California (Shepard, 1963) and the “No Ground” Channel incised into the Ganges–Brahmaputra Delta (Kuehl et al., 1997). These valleys generally become both deeper and wider in a seaward direction.

Valleys formed purely by tidal erosion processes are not well documented in the literature, presumably because the initial valley is usually inferred to have formed by fluvial or glacial processes during low sea level stands, followed by further erosion by tidal currents under transgressive, high-stand conditions. For example, in his review of the seabed morphology of the tidally dominated shelf around Great Britain, Pantin (1991) attributed tidal current scour to the origin of only a few shelf valleys, such as St. Catherine Deep in the English Channel. Similarly, most submarine valleys on the macrotidal Korean shelf are heterogeneous, with tidal current scour overprinting features that were at least partially formed by glacial or fluvial processes during the Quaternary glaciations (Chough et al., 2000, 2002). Tidally scoured sections of such shelf valleys generally exhibit local depressions with closed bathymetric contours (see also Harris et al., 1995).

In the case of many continental shelves, significant portions of the valleys formed during low sea level were infilled with transgressive sediment as sea level rose (e.g., Dalrymple et al., 1994). On the northeast Australian continental shelf, a combination of factors appears to have conspired to limit the overall effect of low sea level fluvial erosion. These factors include (1) the mostly arid climate (and thus, low river discharge) that has persisted in Australia throughout the Quaternary; (2) the continent’s relatively low relief and, thus, low river energy (e.g., Woolfe et al., 1998); and (3) although alpine glaciers formed in southeast Australia and Tasmania during the Pleistocene ice ages (Williams, 1984), they did not extend down to sea level and glaciers have not formed in NE Australia at any time during the Quaternary. Consequently, shelf valleys formed by tidal current scour are more easily recognised on the Australian shelf (because we can discount glacial processes) and a number are found where tidal ranges are meso- to macro-tidal (2–4 m and >4 m, respectively). Examples are the tidally scoured deeps formed between offshore islands and the coast within Banks Strait off northeastern Tasmania and Van Dieman’s Gulf in the Northern Territory (Harris, 1994a).

In the Torres Strait region off northeastern Australia, the occurrence of tidally scoured valleys was described by Harris (1994b, 2001). In particular, the erosion and formation of the deeply incised section of Missionary Passage (up to 60 m deep locally; Fig. 1A) was attributed to modern tidal current scour (Harris, 2001). Further to the east, along the southern part of the Gulf of Papua, Harris et al. (1996) describe an “incised valley zone” that exhibits a complex, offshore–onshore trending seafloor topography on the middle to outer shelf between 50 m and 120 m water depth (Fig. 1B). The data available at that time indicated the presence of a well-developed shelf valley southeast of Bramble Cay (Fig. 1A), along the northern margin of the
Great Barrier Reef (GBR), forming a system extending “over a 100 km east–west distance between the 60 m and 120 m isobaths” (Harris et al., 1996, p. 802). In that study, the shelf valleys were attributed largely to low sea level fluvial incision and the deposition of regressive, fluvial–deltaic complexes during the late Quaternary. Tidal current scour was thought to have played a secondary role, by overdeepening some sections of the shelf valleys and reworking older deposits.
Here we present new detailed multibeam sonar data to show that one shelf valley located along the northern edge of the GBR (southern Gulf of Papua) forms a complex network, extending at least 93 km across the shelf that contains isolated depressions that are as much as 220 m deep locally (Fig. 1A and B). Our new data indicate that large sections of the valleys were eroded during the late Quaternary by tidal currents and in many cases, appear never to have contained significant river flows. The existence of these valleys raises important questions regarding the creation of transgressive estuarine embayments in such carbonate provinces, as well as the interaction and coexistence of the large Papua New Guinea rivers with the northern Great Barrier Reef throughout the late Quaternary. The question we pose is: what factors have controlled the for-
mation of over-deepened (>200 m deep) shelf valleys in the northern Great Barrier Reef?

1.1. Study area: the Gulf of Papua and northern Great Barrier Reef

The Gulf of Papua continental shelf forms a low-gradient platform typically 50–90 m deep and can be divided into four geomorphic zones: (1) a low-relief, inner-shelf, Holocene deltaic zone; (2) a high-relief, mid- to outer-shelf incised valley zone; (3) a high-relief, southern reef zone; and (4) a moderate to low-relief mid- to outer shelf zone in the east and northeast (Harris et al., 1996). The deltaic zone is an extensive, flat, shallow surface in 5–30 m water depth (Fig. 1A). It is bordered by a relatively steep prodelta region in 20–50 m of water that extends along the coast between the tide-dominated Fly and wave-dominated Purari River mouths (Fig. 1A; Harris et al., 1993). Seismic profiles and radiometrically dated core samples suggest that the Fly Delta is prograding seawards at an average rate of about 6 m/a (Harris et al., 1993). Progradation is indicated also by the occurrence of beach ridges aligned parallel to the coastline (Baker, 1999) and by seismic data that show prodelta muds downlapping progradationally onto the modern shelf carbonates that mark the maximum flooding surface (Harris et al., 1993, 1996; Walsh and Nittrouer, 2003). Collectively, the Gulf rivers deliver approximately 350 million tonnes/year of sediment and discharge approximately 13,000 m³/s of water into the coastal environment (Harris et al., 1996). The Gulf coastline is dominated by mangrove-forested deltaic islands having an onshore–offshore orientation (Fig. 1A) that reflects the influence of tidal processes.

The high-relief, mid- to outer-shelf incised valley zone has a complex, offshore–onshore-trending sea-floor topography on the middle to outer shelf between 50 m and 100 m water depth. Two separate, large shelf-valleys are recognised in this paper; the northern valley is called the “Bramble Valley,” named for Bramble Cay located nearby (Fig. 1B). The southern valley is called the “Darnley Valley” in this paper (named for Darnley Island, located nearby; Fig. 1B). Available bathymetric data suggest that the Darnley Valley extends east–west for about 93 km across the northern limit of the Great Barrier Reef before turning south-westwards where it extends at least a further 20 km into the Great North East Channel (Fig. 1A–C). Details of the morphology, seismic character and formative processes of these two valleys, based on newly collected data as part of this study, are presented and discussed further below.

The high-relief, southern reef zone is a complex of barrier and patch reefs in the southern part of the study area, south of 9°30′. The bathymetry is rugged near steep-sided coral reefs which locally may have vertical sides. Between the reefs, depths are mostly in the range of 30–70 m, with some broad shallows less than 20 m and local depressions up to 100 m deep. The available bathymetry data compiled for this study shows a branch of the Darnley Valley extends southwards into the reef complex east of Darnley Island (Fig. 1B). Water depths increase rapidly to the east of the barrier reef, which is located on the shelf margin of the Coral Sea basin (Fig. 1A) in water 120–140 m deep.

The moderate- to low-relief, mid- to outer-shelf zone lies north of the incised valleys and offshore from the deltaic zone. Closely spaced, 20–50-m isobaths, trending parallel to the coast, delimit the steep prograding edge of the Holocene deltaic sediments and contrast with the onshore–offshore trending ridges and swales in 50–80-m depth. These ridges are flat-topped and have been described as “mesa”-like in profile (Harris et al., 1993). Based on their morphology, seismic character and core samples, including one radiocarbon date of 33,850 years BP taken from deltaic-marine sediments (massively bedded gray mud with scattered shell debris throughout) on the top of one of these banks, they are interpreted to be relict Pleistocene deltaic deposits (Fig. 1A). Generally, this zone forms a low-relief plain, gently dipping towards the shelf break which is in about 140 m of water.

2. Methods

Bathymetry, seabed sediment samples, seismic, water column and seabed video data were collected using the Australian National Research Facility, R/V Franklin during a cruise carried out in January–February, 2002 (Geoscience Australia Survey 234, National Facility Cruise 01/02; see Harris et al., 2002). We used a Reson model 8101, 240 kHz swath system for multibeam sonar mapping together with a Datasonics 3–7 kHz Chirp Sub-bottom profiler (model
no. DSP 661/66) and model TTV170S tow fish. Survey data were collected along evenly spaced track lines, over a total track length of around 1400 km spread between two survey areas on the middle and outer shelf (Fig. 1). Navigation was by differential global positioning system (DGPS).

Sampling stations occupied during the cruise included the collection of water column profile data using a Seabird SBE911 CTD, calibrated by surface and bottom water samples. Seabed sediment samples were collected using a Smith Macintyre grab and a 1-tonne gravity corer, also rigged to work as a piston corer. An underwater video camera was also deployed at each station to document the substrate character and benthic biota.

Surface sediment grab samples were analysed for percentage gravel, sand and mud content by the sieve method, using nested 2-mm and 63-μm analytical sieves. Carbonate content was determined on the dried gravel sand and mud fractions separately using a carbonate bomb (Muller and Gastner, 1971).

3. Results

3.1. Acoustic survey data

3.1.1. Survey Area A (middle shelf)

The survey in the middle-shelf area confirmed the presence of the Darnley Valley submarine valley sys-
tem, trending east–west across the shelf (Figs. 1A–C, 2A and B), as described by Harris et al. (1996). Multibeam survey results collected in this study show that the Darnley Valley comprises two separate limbs, which branch around an unnamed rocky pinnacle reef, located in the west-central part of survey area A (Fig. 2A). The Darnley Valley is as deep as 130 m below sea level south of the pinnacle reef, and shoal reefs were found in the southernmost section of the survey area, reaching to within 9 m of the sea surface. Smaller, low-relief (± 10 m) gullies drain into the Darnley Valley from shallow platforms located along the valley margins (Fig. 2A).

The seismic survey data collected demonstrates that the floor of the Darnley Valley is commonly featureless and acoustically opaque. The two limbs of the Darnley Valley separate three elevated platforms (P1, P2 and P3, Fig. 2A) each having its own distinct assemblage of acoustic features (Fig. 3A). The southernmost platform (P1) is dominated by rocky (coral) reefs that locally rise up towards the sea surface (Fig. 3A). The largest of these reefs (having the greatest bathymetric relief) is located adjacent to the southern walls of the Darnley Valley. Platform P1 also exhibits localised, infilled channels, erosional notches and incisions (Fig. 3A). The seabed is acoustically

![Seismic section](image)

Fig. 3. Chirper-seismic sections (A–D). The locations of the sections, including start/stop points of section parts, are shown in Fig. 2A and B. Seismic sections show (A) a profile of sediment onlapping onto the southern side of platform P2 (inset A1), rocky reefs adjacent to the unnamed reef (Fig. 2A), incised valley floor with sediment wedges (inset A2) and incised surface of Platform P1; (B) a profile starting over the smooth, sub-horizontally bedded sediment body of Platform P3, exhibiting lateral accretion surfaces and possible slumping on its southern margin (Inset B1), and an undulating, irregular surface of Platform P2, containing rocky-reef outcrops (Inset B2) and local incisions; (C) high-relief, rocky-reef surface adjacent to East Cay, with small sediment mounds in local depressions (Inset C1), incised valley floor with localized sediment mounds (Inset C2), and reef-studded surface of Platform 4; and (D) low-relief valley floor in ~140 m depth with sediment-filled depressions (Inset D1), smooth, subhorizontally bedded sediment body (Inset D2), which crop out on its southern margin, and reef-studded surface of Platform 5.
highly reflective and there is no evidence of unconsolidated sediment deposits associated with platform P1.

The central platform (P2) includes a large (>2 km across), unnamed patch reef on its western margin (Fig. 2A). The elevated, middle part of platform P2 exhibits widespread erosional notches and incisions (Fig. 3A and B), with some rocky reefs along the eastern part of the surveyed area. Subsurface reflectors, in the form of lateral accretion surfaces, occur on both sides of platform P2 and suggest sediment deposition associated with the lateral migration of former river channels or deltaic distributary channels. These lateral accretion surfaces are commonly of low relief, <10 m in overall amplitude. On the southern flank of platform P2, foresets dip gently towards the south (Fig. 3, Inset A1). To the south of the unnamed pinnacle reef (Fig. 2A), the sediment reaches a maximum thickness of around 20 m above acoustic basement. A dune field occurs at a depth of between 43 and 70 m on the southern flank of platform P2 (Fig. 2A). These large-scale, submarine dunes (terminology of Ashley, 1990) rise about 4–6 m above the level of surrounding seabed and appear to have their steeper faces oriented towards the west. They tend to have sharp crests and no internal stratification was visible in our seismic records.

The northern platform (P3) exhibits gullies, notches and incisions, but the most prominent feature of the northern platform is the widespread occurrence of subsurface reflectors in the Chirp seismic data. These are most common in the west and comprise lateral accretion surfaces, gently dipping towards the south on the southern flank of the platform (Fig. 3A).

3.1.2. Survey Area B (outer shelf)

On the outer shelf, our survey discovered a seaward extension of the Darnley submarine valley complex, which attains a maximum depth of 220 m in the area we surveyed (Fig. 2B). This is the deepest shelf valley yet found on the NE Australian shelf. The deepest sections of the Darnley Valley floor form a series of isolated depressions having closed contours (Fig. 2B). The valley is flanked on its southern and eastern margins by rough, rocky-reef seabed that is acoustically opaque,
apart from isolated sediment lenses up to about 10 m in thickness (Fig. 3C and D).

On the northern side of East Cay is another shelf valley, called the “Bramble Valley” in this paper. Available bathymetric data suggests that the Bramble Valley extends westwards to the north of Bramble Cay and as far landwards as the prograding edge of the Fly River Delta. In the seaward part of the Bramble Valley mapped in our study (Fig. 2B) seismic sections reveal only isolated sediment lenses, <5 m in thickness (Fig. 3D). The Bramble Valley attains a maximum depth of around 120 m north of East Cay (Fig. 2B) and seawards of this it shoals to <100 m and becomes indistinct, where it merges with a broad shelf area, mantled with large-scale, submarine dunes (terminology of Ashley, 1990). The dunes rise about 4–6 m above the level of surrounding seabed and appear to have their steep faces oriented towards the southeast. They tend to have well-rounded crests and no internal stratification was visible in our chirp seismic records.

The major geomorphic features of the outer shelf are submerged platform reefs flanking the Darnley Valley (P4) and extending eastwards from East Cay (P5; Fig. 2B). The largest platform (P5) is cut by two channels and exhibits a sharp eastern face, aligned north–south over a distance of about 15 km. The surface of both platforms P4 and P5 is characterised by a strong acoustic reflector, suggesting a hard, rocky seabed (Fig. 3C and D).

A hypsometric analysis of the bathymetry data for the two survey areas (Fig. 2A and B) indicates that the platforms (P1–P5) are consistently located at a depth of around 45–55 m below sea level (Fig. 4). Peaks in the hypsometric curves, corresponding with the broad platform surfaces, can be correlated between the two survey areas. Other peaks correspond with the relatively flat and broad valley floors at around 85 m depth in the mid-shelf area (Figs. 2A and 4) and with broad outer shelf areas where dune fields occur at a depth of around 95 m (Figs. 2B and 4).
3.2. Sediment sample and video-observation data

Regional surface sediment distribution maps were published by Harris et al. (1996). The information collected in our study includes underwater video observations of the seabed, which provides details of the surface sediments found on the deep valley floors and some insight into the modern sedimentary processes in this setting.

Darnley Valley floor sediments from the middle shelf (Area A) are relatively muddy having a mean mud content of 20.7% (Stations 32–36, 42–45), by comparison with sediments deposited on the elevated platforms where samples contain an average of 9.2% mud (Fig. 5A). This higher mud content is reflected in the underwater video observations (Table 1), in which the valley floor is generally observed to be muddy, flat and featureless with sparse biota (i.e., little if any biota was observed...
Fig. 5. Maps showing distribution of surficial sediment mud content (percentage dry weight) for (A) the mid-shelf and (B) outer shelf study areas. The station numbers shown correspond with information listed in Table 1. See Fig. 1 for the locations of the maps.
at stations in greater than 80 m water depth; Table 1). In contrast, the platforms contain a greater diversity of substrate types, including coral bommies, limestone rubble and sandy sediments with ripple marks. Carbonate content did not vary between the valley floor and platform environments; valley floor

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For locations of stations, see Fig. 5A (middle shelf stations) and B (outer shelf stations).
stations \(n=8\) contain 62.1% carbonate mud and have a 59.6% total carbonate content, which is similar to platform stations \(n=13\) which contain 64.2% carbonate mud and have a 61.2% total carbonate content.

Outer shelf (Area B) sediments are generally more coarse (only 2 out of 20 stations contained more than 20% mud) and generally higher in carbonate mud content than the middle shelf sediments (Fig. 5A and B). Outer shelf sediment samples taken from the Darnley Valley floor (54, 58, 72–75; Fig. 5B) have a mean gravel content of 22.1%, which is higher than all other areas sampled in this study. For example, surface sediments at Station 75 in 220 m water depth comprised gravelly (25% gravel) calcareous (81% carbonate) coarse olive sand (5Y 5/3) with abundant granule-pebble shell hash. The sample included a live sponge, hydroid, crab, mysid shrimp and polychaete worms (Table 1). Underwater video at this station showed the seafloor was relatively flat with rare burrows and pits ~5 cm in diameter, and sparse biota, apart from some small rocky outcrops where soft corals, hydroids and sponges were seen (Table 1).

![Fig. 6. Map showing the location of core samples taken on the middle shelf, and illustrating the occurrence of the Holocene high-stand facies and transgressive fluviodeltaic facies. Inset: core X-radiograph (positive) showing laminated sediments comprising the transgressive-aged sediments located on the middle shelf in core from station 50.](image-url)
The other main difference between outer shelf and middle shelf surface sediments is that the mean carbonate mud content is 82.6 ± 3.9% \((n = 22)\) on the outer shelf, compared with 63.4 ± 13.8% \((n = 21)\) on the middle shelf. This difference probably reflects the greater distance between the major terrigenous sediment source (i.e., The Fly River) between the outer shelf area, compared with the middle shelf area.

3.3. Sediment cores and radiocarbon dates

Sediment cores from the middle shelf contained a 0.5–1-m-thick bed of massive, Holocene, carbonate, poorly sorted, muddy gravelly sand sediment which overlies a fine-grained, terrigenous, laminated to finely bedded fluvial–deltaic facies. Laminations and thin beds (1–5 cm thick) of fine sand occur within the terrigenous mud and are clearly observed in X-ray photographs (Fig. 6). Radiocarbon dates from peat layers extracted from within the fine-grained, laminated to bedded, terrigenous sediment facies (Table 2) are from around 8000 to about 19,000 years old, which indicates they were deposited mostly during the post-glacial sea level transgression of the Gulf of Papua shelf. The corrected peat dates are consistent with the published sea

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Laboratory reference numbers refer to the University of Sydney (SUA) and Rafter Radiocarbon Laboratory (NZA), New Zealand. Radiocarbon ages are uncorrected in years before present (BP). The uncorrected radiocarbon ages were converted to upper and lower estimates of calendar ages using the INTCAL-98 calibration curve (Stuiver et al., 1998; see Fig. 7). The locations of cores 234/21PC05 234/22PC06 are shown in Fig. 1C (labelled with underlined station numbers only, i.e., 21 and 22, respectively) and locations of cores 234/41GC02, 234/43GC04 and 234/49GC10 are shown in Fig. 6 (labelled with underlined station numbers only, i.e., 41, 43 and 49, respectively).
level curves of other workers (e.g., Edwards et al., 1993; Bard et al., 1996; Fig. 7).

4. Discussion

4.1. Origins of shelf valleys

The Darnley and Bramble Valleys mapped in this study appear to have been formed by at least two different processes operating over glacial–interglacial timescales. The Bramble Valley is less than 120 m in depth over its entire length. Lateral accretion surfaces are observed in seismic sections along its walls, which are documented in sediment cores as transgressive-aged, terrigenous mud deposits (Harris et al., 1996). These transgressive-aged deposits are similar in composition and primary sedimentary structures to modern deltaic deposits that have been described from the nearby Fly River delta (Dalrymple et al., 2003), and we infer a similar (deltaic) depositional environment for this facies. Mangrove peat beds are commonly associated with deltaic islands and intertidal mud flats in the modern Fly Delta (e.g., Baker et al., 1995; Baker, 1999; Dalrymple et al., 2003). We conclude that the Bramble Valley was probably one of the main channels (if not the main channel) for the Fly River during the last glacial maximum, and that it was formed by fluvial erosion during Quaternary glacial maxima and modified by fluvial–deltaic sedimentation during the post-glacial transgression, between 18,000 and 6500 years BP.

The Darnley Valley, located further to the south, has a more complex morphology and was probably formed by several different processes operating over different temporal and spatial scales. Lateral accretion surfaces are observed in seismic sections which are also documented in sediment cores as transgressive-aged, terrigenous mud deposits. Hence, the Darnley Valley was influenced by fluvial–deltaic depositional processes during the post-glacial transgression, between 18,000 and 6500 years BP.

The Darnley Valley was influenced by fluvial–deltaic depositional processes during the post-glacial sea level rise. This is not surprising, given that the modern Gulf of Papua coast is comprised entirely of mangrove-forested, deltaic islands that migrate laterally (Harris et al., 1993, 2004; Walsh and Nittouer, 2003). However, lateral channel accretion deposits are found along the mar-
gins only of the northern limb of the Darnley Valley and in patches along the northern wall of the southern limb. None were found along its southern margin on the middle shelf (Fig. 2A) or at any location on the outer shelf (Fig. 2B).

The Darnley Valley is over-deepened locally, to depths of over 200 m. Erosion of the valley floor to this depth cannot be explained by fluvial erosion during late Quaternary, glacial, low sea level periods even taking into account an inferred subsidence rate of about 10 cm per 1000 years (Pigram et al., 1989), because sea level did not drop more than 120–130 m below its present position. Sedimentary strata underlying the Darnley Valley are thought to be comprised of Cenozoic, interbedded carbonates and fluviodeltaic deposits (Pigram et al., 1989) and there is no seismic profiling evidence for a major basement fault to explain the position of the valley.

Isolated depressions 150–220 m deep with closed bathymetric contours at both ends, on the floor of the Darnley Valley demand an explanation other than fluvial erosion during glacial maxima. Given their depth and the closed contours of their morphology, it is possible that depressions along the length of the Darnley Valley were the sites of lakes during the last ice age when Torres Strait formed a land-bridge between Australia and Papua New Guinea. Given that the valleys are incised into limestone, karst processes may have played a role in forming the depressions. However, there is no indication of former lake deposits in our cores from the Darnley Valley floor, nor were any thick, unconsolidated sediment deposits observed anywhere on the floor of the Darnley Valley in our seismic records. Karst processes may have played a role in creating localised depressions in the study area, perhaps as much as 10–20 m in relief. However, it seems unlikely that the elongate orientation of the depressions (that are aligned with the axis of the valley) or the shear vertical scale of relief observed for the Darnley Valley could be explained by Karst processes alone. We conclude that processes other than (or in addition to) Karst must have formed the deepest sections of the Darnley Valley.

To account for the absence of lacustrine sediment deposits within isolated depressions of the Darnley Valley, we infer that either (1) there were no lakes here during the ice ages, and hence, no lake deposits exist; (2) there are lake deposits but they are too thin to be resolved by our Chirp sub-bottom profiler; or (3) there were lake deposits but the small volumes of sediment deposited were exhumed by tidal currents during the post-glacial sea level rise (and flooding of the shelf). In the latter case, we might expect to find strong tidal currents flowing today within the scoured sections of the valleys. The available current and oceanographic data, however, indicate that this is not so.

Recent tidal and wind-driven current modelling work carried out for the region by Hemer et al. (2004) indicates that tidal and wind-driven currents over the mid- to outer shelf valleys are relatively weak. Strong tidal currents do occur in central Torres Strait and in the 60 m deep valley (Missionary Passage; Fig. 1) located north of the Warrior Reefs on the inner shelf (Harris, 2001), but tidal flows are generally weaker in the eastern patch reef complex. Strong tidal flows must occur locally to explain the sharp-crested, active dunes on Platform P2 (Fig. 2A); however, the large area of dunes in deep water in Area B having rounded crests (Fig. 2B) that we assume to be moribund coincides with an area where modeling predicts weaker currents. Low current energy is also consistent with the accumulation of muddy sediments on the Darnley Valley floor on the middle shelf (Fig. 5A). Oceanographic observations indicate that the Darnley Valley provides a conduit onto the shelf for cool and saline, upwelled Coral Sea water (Harris et al., 2004). Temperature and salinity depth profiles taken within the valley during the waning spring tide phase, suggest that the water column is stratified above 50 m depth, although any density-driven circulation is likely to be sluggish (speeds of <0.1 m s⁻¹). It appears, therefore, that the modern current regime could not have created the deep valleys observed on the mid- to outer shelf. The question is, therefore, how (and when) were the valleys formed?

4.2. Tidal current modelling of low sea level scenarios

To answer this question, we have carried out a simple tidal modelling exercise. A brief description of the tidal model follows; details are documented elsewhere (Harris et al., 2000; Porter-Smith et al., 2004). The tidal model has a resolution of 0.067° in both latitude and longitude, equal to about 7.4 km. The bathymetry input was not varied to account for sediment deposition, reef growth or erosion, which are
considered small within the area of interest (incised valley zone) in comparison with the model resolution. The model uses major eight constituents M2, S2, N2, K2, K1, O1, Q1, P1 and was run for eight different sea levels at 10-m increments below the present sea level. The solution was obtained using time stepping on an Arakawa C grid by applying periodic forcing and time stepping from homogenous initial conditions. The solution was achieved in 10,000 time steps using a step length of 15 s. This corresponds to running the model for roughly 2 days. Along the open boundaries around the edges of the model a global ocean tide model by Andersen et al. (1995; version AG95.1) was used to provide boundary elevations. The model forcing was not varied for the different sea level increments, which is a potential source of error, but this must be accepted since we do not have any data to avoid making the assumption that the tidal forcing parameters do not vary with changing sea level.

The results (Fig. 8) for the modern sea level are consistent with available observational data; bottom stress due to maximum spring tidal currents is generally low apart from a few localized areas around the central Darnley Valley (where active dunes also occur; see above), near Missionary Passage and among the distributary channels of the Fly Delta. With sea level at −10 m, the model suggests that bottom stress maxima occur over the eastern Missionary Passage area and in small patches around Darnley Island and other locations north of the island. With sea level at −20 m, Torres Strait is exposed and the Australian mainland is joined to Papua New Guinea; the model suggests that bottom stress maxima increase in overall intensity and occur in the Great North East Channel, around the patch reefs adjacent to Darnley Island and around patch reefs on the outer shelf flanking the Darnley Valley. With sea level at −30 m, the model suggests that intense bottom stress maxima occur; tides are apparently amplified within a broad embayment extending eastwards from Missionary Passage. Bottom stress “hot spots” are also centred over the Darnley Valley and part of the Bramble Valley. The pattern is virtually the same for sea level at −40 m, albeit shifted slightly eastwards. With sea level at −50 m, the Missionary Valley is mostly exposed and the model suggests that three bottom stress “hot spots” occur, centred over the Darnley Valley the Bramble Valley and an area north of the Bramble Valley. As sea level is lowered further too −60 and −70 m, the bottom stress “hot spots” become smaller in size as more shelf area becomes emergent. Bottom stress “hot spots” are predicted to occur in different places along the Darnley Valley at all depths between 30 and 60 m (see Fig. 8).

In summary, the model (Fig. 8) predicts that maximum tidal bottom current stress reached their highest values over the site of the deepest shelf valleys when sea level was between 30 and 50 m below its present position. At these depths, the geomorphology of the shelf manifests itself as a chain of elongate islands (the modern barrier reef) separating the open sea from a shallow, protected lagoon. Currents are accelerated as they are forced to flow through the constricted channels between the shelf-edge islands, and in particular as they flow around the northern promontory of the island chain. The strongest tidal flows are predicted to occur at the northern end of the shelf edge barrier (Fig. 8), and although the 7.4-km resolution of the model is too coarse to resolve the details of flow over the complex bathymetry in the area, this general area coincides with the location of the deepest (>200 m deep) segment of the Darnley Valley south of East Cay.

The flat-top surfaces of submerged reef platforms adjacent to the valleys (Fig. 2A and B) also occur in this 40–50-m depth range, suggesting that these relict reefs (“give-up reefs” using the terminology of Neumann and Macintyre, 1985) developed at times when sea level was at about 40 m below its present position. These submerged reefs occur at similar depths to those reported from other locations in the GBR (Harris and Davies, 1989). When sea level drops below −40 m, these reefs are emergent and hydraulic tidal flow is further enhanced.

The overall shape of the Darnley Valley itself points to processes unrelated to erosion by the Fly River. It has tributary branches extending southwards into the northern Great Barrier Reef patch reef province, and its western end turns southwestwards, into the Great North East Channel (and not northwest towards the Fly River catchment). These features are more easily explained as being created by tidal water exchange between the Coral Sea and the protected lagoon that is formed when sea level drops below around 30 m (Figs. 1B and 8).

When considering the integrated effect of the changes in tidal flow associated with different sea
Fig. 8. Plot of peak (spring) tidal bed stress (N m$^{-2}$) derived from a tidal model, with outputs derived for sea levels at 0, 10, 20, 30, 40, 50, 60 and 70 m below present position. The locations of modern land (in black) reefs (dark gray), and the 50 m isobath outlines of the Missionary, Darnley and Bramble Valleys are shown. Locations of Missionary passage (MP), the Great North East Channel (GNEC), Darnley Island (DI), Bramble Cay (BC) and East Cay (EC) are also shown.
level scenarios, it is important to keep in mind that the duration of sea level at each point has not been equal over the last glacial cycle (past 120,000 years; Fig. 9A and B). The eustatic sea level curve (e.g., Chappell and Shackleton, 1986; Fig. 9A) indicates that over the past 120,000 years, sea level has been between 30 and 50 m below its present position for about 38% of the time. Prolonged periods (>10,000 years duration) of sea level within this depth range occurred during isotope stages 3, 4, 5a and 5c (Fig. 9A). Isotope stage 3, in particular, was a time span of around 22,000 years during which sea level was positioned at between 30 and 50 m below present. It is not just the depth where maximum tidal bed stress occurs that is important, but also the duration of sea level within the 30–50-m depth range (equal to 38% of the last 120 ky; Fig. 9B) that must be considered in considering the development of the shelf’s geomorphology. It is logical that, all things being equal, current erosion features would form at depths corresponding with the long-lived and strong tidal flow conditions related to sea level at 30–50 m below present. Although it is difficult to accurately determine the age of any geomorphic feature formed by erosion, we conclude that the over-deepened Darnley Valley is a relict feature, whose origin is related mainly to tidal current scour during the late Pleistocene when sea level was ~30–50 m below its present position.

An important consequence of these valley-erosion processes is to halt the southward advance of terrigenous sediment, supplied to the Gulf of Papua from the island of New Guinea, into the Great Barrier Reef province. During interglacial, high sea level stands, such as at present, fluvial deltaic deposition is focused along the coast with the prograding delta extending offshore into waters less than around 40 m deep (Harris et al., 1993). The Darnley Valley tends to trap only small amounts of fine-grained terrigenous sediment (Fig. 5A and B). During intermediate sea level positions (isotope stages 3, 4, 5a and 5c; Fig. 9) strong tidal flows scour the valley clear of unconsolidated sediment. The integrated result, over several glacial/interglacial sea level cycles, is that the valley system is maintained as it is seen today.

4.3. Valley formation on tropical carbonate shelves by tidal scour and reef growth

The formation of shelf valleys by tidal current scour and sea level change in the northern Great Barrier Reef implies a conceptual model for understanding the evolution of tidally incised shelf valley systems (Fig. 10), which can be contrasted with the conventional model of fluvially incised valley formation. For both types, the changes caused by a rise or fall of relative sea level are of fundamental importance. However, whereas a lowering of sea level results in fluvial erosion, entrenchment and the formation of fluvially incised valleys (a sequence boundary; e.g., Vail et al., 1977; Van Waggoner et al., 1990), the formation of a tidally incised valley

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Fig. 9. (A) Global eustatic sea level curve for the last 150,000 years, modified from Chappell and Shackleton (1986) to illustrate times of sea level positioned at between 30 and 50 m below present (grey-shaded areas). Isotope stages are after Martinson et al. (1987). (B) Histogram showing percentage of time that sea level has been within 10-m depth bands (i.e., 0–10 m, 10–20 m, etc.) over that past 120,000 years (isotope stages 1 to 5d, inclusive), based on the curve shown in “A”. The graphs show that sea level was within the 30–50-m depth range for approximately 38% of the time (46,400 years) over the past 120,000 years. For comparison, sea level has been within the 20–60-m depth range for approximately 60% of the time (74,500 years) and in the 0–10-m range for only 12.8% of the time (15,500 years).
relies on the occurrence of a “rimmed” outer shelf to establish a hydraulic pressure gradient between the shelf-lagoon and the adjacent ocean basin (Fig. 10). A key factor is the relative tidal range, which must be large enough to generate the strong tidal flows necessary to erode the seabed and form the shelf valleys. The tidal flows attain a maximum value when the largest hydraulic pressure gradient is forced through the smallest channel cross section, or as in the case of the Darnley Valley, around the end of a promontory (Fig. 10).

The generalised stratigraphic succession produced by the transgression of tidally incised shelf valleys will also differ from the conventional, fluvially incised valley-fill model. The facies succession of an infilled estuary, in relation to a rise and stabilisation of relative sea level, consists of an erosional unconformity overlain by alluvial channel deposits (lowstand systems tract, LST) followed by estuarine/marine units (transgressive systems tract, TST), which vary in character depending upon sediment supply and the relative influence of tides and waves (Daly et al., 1994). High-stand systems tracts (HST) marine sediments drape over the TST deposits, completing the succession.

The facies succession within tidally incised shelf valleys mapped in the present study includes an erosional unconformity that is not necessarily over-

Fig. 10. Conceptual model showing the evolution of tidally incised shelf valleys and inferred facies succession. (A) “Intermediate” sea level conditions dominate the late Quaternary and give rise to valleys that are tidally incised into broad platform reefs on rimmed, tropical carbonate shelves. The occurrence of a “rimmed” outer shelf establishes a tidally varying hydraulic pressure gradient between the shelf-lagoon and the adjacent ocean basin, which reaches a maximum tidal energy under certain sea level conditions. Tidally incised channels may be further increased in relief by framework coral growth along the valley margins, akin to levy banks, through the late Quaternary to produce steep-sided (locally vertical) valley walls. Tidal erosion liberates shelf sediment for export to the adjacent slope and forms a regional erosional unconformity. (B) During glacial, low sea level conditions, the shelf valleys may be transformed into lakes perched on the outer shelf, trapping sediments and limiting sediment export to the adjacent slope. Post-glacial sea level transgression of the shelf results in erosion and localized exhumation of the valleys. (C) High-stand valleys (e.g., Fig. 1) contain weak currents and may be locally depositional, containing muddy calcareous marine sediments. Elsewhere, deposits of relict carbonate gravels dominate valley floor deposits.
lain by any unconsolidated deposits. LST deposits may contain lacustrine facies (NB the valleys in our study were scoured clear of any such deposits). The sequence boundary may be overlain by thin beds of coarse-grained, transgressive marine sediments, grading upward into lower energy, muddy gravelly sands (HST marine sediments; Fig. 10). A likely scenario is that, as infilling of the lagoon leads to reduced tidal flows in the valleys (due to the diminishing size of the tidal prism), the preservation potential of LST lacustrine and TST marine deposits is enhanced.

A common feature of the channels in the northern Great Barrier Reef is the growth of coral reefs, like river levy banks, on the margins of channels. Current control over reef growth and reef morphology is well established in the literature. For example, the modern barrier reef in the study area was described by Veron (1978) who noted that some shelf-edge, barrier reefs appear to have a “deltaic” shape in plan view (this term was first used to describe a specific reef type by Maxwell, 1968). Strong tidal flows up to 3.8 m/s characterize the narrow, inter-reef channels, which are about 33 m in water depth. Veron (1978) explained the deltaic morphology as a reef-growth response to the strong tidal flows characteristic of the Torres Strait region. The elongate reefs in central Torres Strait have the appearance of tidal current sand banks in plan view, as first noted by Off (1963) and later studied by Jones (1995) using seismic profiling.

Reefs growing preferentially along the margins of tidally scoured channels act as a positive feedback, by further constricting the channel width and accelerating the tidal flow. The vertical scour and over-deepening of channels by tidal currents reaches a maximum in the most narrow part of the channel, at the point of greatest flow constriction, and tidal energy drops away along the channel axis in both a landward and seaward direction, which explains the closed bathymetric contours of tidally scoured channels. Missionary Passage at the northern end of the Warrior Reefs (Fig. 1) is a modern example of a tidally scoured channel that exhibits these morphological features. Tectonic subsidence of the Gulf of Papua foreland basin at rates of around 10 cm per 1000 years (Pigram et al., 1989) may also be a factor for the evolution of channels.

Our model of tidally incised valley formation may be applied to other rimmed shelves in Australia and elsewhere. In particular, the modern valleys adjacent to the Sahul Shoals in the Timor Sea (e.g., the Malita Shelf valley) have a similar geomorphology, exhibiting closed isobaths and a significant basin (Bonaparte Depression) located landward of the valley complex (Lavering, 1993; Fig. 11). These incised channels have closed bathymetric contours, contain silty clays and molluscan debris (Lavering, 1993) and currents measured in the channels are mainly weak and variable (Marshall et al., 1994); it may be concluded that they were not created by modern processes. Further tidal current modelling, under different sea level scenarios, is needed to determine the depth range at which tidal currents are at a maximum, when the emergent Sahul banks produced accelerated tidal flows through interbank, incised channels. Other arid, tropical carbonate shelves may exhibit similar, outer-shelf incised valley systems, both in the modern world and in the rock record.

4.4. GBR transgressive sediment export to slope explained?

In a study of sediment mass accumulation rates on the slope adjacent to the Great Barrier Reef, Page et
Page et al. (2003) have noted that peaks in sediment accumulation rate do not conform to the prediction of the conventional model, which calls for maximum sediment export during sea level low-stands. Over the last glacial cycle, the conventional model predicts that maximum export to the slope would have occurred around 18 ky BP, but instead Page et al. (2003) measured peak export to occur from between 12 and 7 ky BP, during the rising phase of sea level. Page et al. (2003) suggest that the reason for this low sediment discharge during the last glacial maximum was because sediment is deposited on the low-gradient shelf behind the rimmed profile. Flooding of the shelf during sea level rise liberates the sediment stored behind this rim resulting in an increased sediment supply to the adjacent slope.

Our model for tidal incision of rimmed shelves provides a mechanism to explain how the sediment is mobilized during sea level rise. Our model predicts a phase of strong, tidally induced, bed stress on the outer shelf when sea level is between 30 and 50 m below its present position. Available sea level curves indicate this depth range corresponds to a time of from between 11 and 9 ky BP (Fig. 7), which is within the time range of 12–7 ky BP specified by Page et al. (2003) for maximum sediment export from shelf to slope. The ebb-orientation of the large field of moribund dunes on the outer Gulf of Papua shelf (Fig. 2B) also conforms with the concept of sediment export from the shelf caused by a pre-Holocene phase of enhanced tidal current activity.

5. Conclusions

Shelf valleys at the northern end of the Great Barrier Reef may be divided into types having two different origins. The Bramble Valley in the north is clearly a relict fluvial valley, exhibiting lateral accretion surfaces observed in seismic profiles and incised margins that intersect and truncate underlying strata. The over-deepened Darnley Valley, located among reefs in the northernmost GBR, however, appears to have formed by a combination of reef growth and tidal current scour. During sea level transgression of the shelf, the Bramble Valley was an estuary where fluvial deltaic and marine sediments were deposited, as documented by cores and seismic data. The Darnley Valley, however, would have formed an estuarine embayment, whose origin is not reliant upon fluvial erosion processes, and where cores and seismic data indicate minimal terrigenous deposition occurred.

The tidally incised Darnley Valley is up to 220 m deep locally and extends for 93 km across the continental shelf. Depressions on the valley floor exhibit closed bathymetric contours at both ends and are floored with well-sorted carbonate gravelly sand containing a large relict fraction and up to 20% mud, locally. The deepest segments of the Darnley Valley were probably the sites of lakes during the last ice age, when Torres Strait formed an emergent landbridge between Australia and Papua New Guinea. Current modeling and observations suggest that modern tidal flows are weak and insufficient to have eroded the valley. Numerical modelling further predicts that the strongest tidal currents occur over the deepest, outer-shelf segment of the valleys when sea level is about 30–50 m below its present position. This depth range corresponds to a brief period of around 9–7 ky BP during the post-glacial sea level rise, but more importantly also to several prolonged phases of sea level during oxygen isotope stages 3, 4, 5a and 5c (Fig. 9). These results are consistent with a Pleistocene age and relict origin of the over-deepened portions of the valley floor. Tidal erosion and mobilisation of sediments could explain the peak in export of shelf sediments to the adjacent slope during the post-glacial sea level rise as reported by Page et al. (2003).

We propose a conceptual model to explain the evolution of shelf valleys that are tidally incised into broad platform reefs on rimmed, tropical carbonate shelves. The occurrence of a rim on the outer shelf establishes a tidally varying hydraulic pressure gradient between the shelf-lagoon and the adjacent ocean basin, which reaches a maximum under certain sea level conditions (Fig. 10). Tidally incised channels may be further increased in relief by framework coral growth along the valley margins, akin to levy banks, through the late Quaternary to produce steep-sided (locally vertical) valley walls. This model may explain the evolution of valleys incised into the Sahul shelf of northern Australia as well as other rimmed carbonate shelves.
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References


