North Johnstone and Lake Eacham Landcare (UJLE LC)
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11 September

Dear Sir

RE: Comments on your issues paper: Industries in the Great Barrier Reef Catchment and Measures to Address Declining Water Quality

We would like to take the opportunity of commenting on the questions that you pose in your Issues Paper. We are not qualified to answer all your questions but we are qualified to answer some. In this reply I will not repeat the questions just refer to them by number.

Q1: The Eacham group feels that John Brodie's "End of River Targets" report of 2001 dominates your approach. Papers such as those by Piers Larcombe (attached) quietly refute much of Brodie's suggestions regarding the amount of sediment coming down streams and the potential damage.

Q2: Agriculture provides multi-factors, which could contribute to deterioration to water quality entering the GBR. Examples of sustainable agriculture including erosion control, accurate water scheduling, accurate application of irrigation water and determining when plants require fertiliser and applying it appropriately can all be found in the agricultural industries on the Atherton Tableland.

Q3: Whilst the UJLE LC group believes that the impact of current land-based activities on the GBR are small; if it is perceived that deterioration is serious then it would have serious implications on economic and social values in the region.

Q4: The Commission should undertake detailed investigations of a few regions. We are scheduled to meet with representatives this week.

Q5: We are concerned with simple statistics. Only half the Queensland cattle industry has catchments that drain into the reef, and the same would apply to horticulture. It is true that most of Queensland's sugarcane is grown in GBR catchments. Care must be taken with allocation of productivity to various regions.

Q11: Growth projections for the Tableland dairy industry are reasonable and steady over the next 10 to 20 years. The Tableland dairy factory has recently expanded its cheese operation

Q14: Variables used to predict the future for the dairy industry include total cow numbers supplying a factory, typical herd size and stocking rates. A most important factor is the $cost per litre of milk. Also of importance are employment and the stability of the number of farmers in the district.

Q15: The main industry in the UJLE LC area is dairy. Factors that can affect the quality of runoff water include: irrigation demand and use efficiency, effluent management, fertiliser management, erosion control, creek-bank vegetation, pasture management and chemical usage. These issues have all been tackled in recent years through a water use efficiency project, fertiliser scheduling, erosion control study and a major campaign into effluent containment and reuse.

Q16: There is a widespread interest in more precise scheduling of water and nutrients. Co-operative efforts to re-vegetate stream banks have been facilitated by money being available from NHT. However, the major incentives to growers are the savings in energy costs and fertiliser costs (i.e. a reduction in $cost/litre milk) but the saving of water is also important. This is especially so in the Barron Catchment where a Water Allocation Plan is pending that may fairly drastically reduce the volume of irrigation water allocated to each farmer.

Q17: Queensland Dairy Farmers association has developed a code of practice for dairy farmers. The Primary Green concept proposed by the Natural Resource Management Board (Wet Tropics) to accredit farmers in reef safe practice has merit and is worthy of serious consideration.

Q18: Your preamble to question 18 reflects a philosophy of “one in all in” because of the difficulty of identifying polluters. This is unfair. Those causing pollution need to be targeted, hence the need for accurate and timely measurement. Models used in prediction, such as those used in Brodie’s report must be rigorously ground truthed.

Money spent on ground in the catchment is important. There is a worry with the current trends towards the use of end of river targets because these act as integrators of whole of catchment without determining the sources of pollution even when they are accurately measured, and this could lead to targeting of the wrong things for correction and money wasted.

We suggest the following:

- Fair price for agricultural produce and farmers can afford to do on farm “non-productive” work such as caring for streams reducing pollution etc
- Extension Officers need to be funded to supply one on one farm service to assist growers develop more sustainable practices, this is especially so where the more sustainable practice is complicated and only provides marginal or no benefit to the farmers $cost/litre of milk. E.g. The present water use efficiency project being extended by UJLE LC has reduced a typical irrigation requirement from 10 Ml/ha to 7.5 Ml/ha through one on one extension. This amounts to 70 Ml/ha/yr for a typical irrigated dairy farm. At typical pumping cost of $42 per Ml this amounts to almost $3,000 per year saving in costs per farmer. Sixteen farms have enjoyed this benefit for an extension cost of only $15,000.

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NOTE

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Increased sediment supply to the Great Barrier Reef will not increase sediment accumulation at most coral reefs

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Abstract The rate of terrigenous sediment supply to the central Great Barrier Reef (GBR) coastline has probably increased in the last 200 years due to human impact on the catchments of central Queensland. This has led some researchers and environmental managers to conclude that corals within the GBR are under threat from increased turbidity and sedimentation. Using geological data and information on sedimentary processes, we show that turbidity levels and sediment accumulation rates at most coral reefs will not be increased, because these factors are not currently limited by sediment supply.

Key words Coral reefs · human impacts sedimentation · turbidity · Great Barrier Reef

Introduction

The Great Barrier Reef (GBR) shelf hosts the largest coral reef ecosystem on Earth, and a clear understanding of human impacts upon it is important for effective management. The potential impacts of catchment-based human activity on sediments on the coastal zone and coral reefs of the Great Barrier Reef (GBR) coastline are mainly twofold: (1) increased sediment supply, and (2) increased turbidity and/or sediment accumulation. There is a clear case for increased sediment supply to the coastline over the last 200 y (eg. Belperio 1983, 1988; Moss et al. 1993; Neil and Yu 1996; Wasson 1997; see also Bird et al. 1995). While the scale of any such increase remains poorly constrained, we do not contest that an increase has occurred.

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The second, and perhaps somewhat contentious issue, is that raised sediment flux to the coast is causing impacts upon coral reefs of the GBR through increasing turbidity and sedimentation. While such a case has not, to our knowledge, been presented in the formal scientific literature, it has become firmly embedded as an environmental management issue and as a focus of public debate (see Zann 1995; Brodie 1996 p.33; Wasson 1997; see also Bell and Gabric 1990, 1991 and Larcombe et al. 1996 for related issues). We evaluate these concerns, using a geological context and an assessment of current understanding of sedimentary processes on the central section of the GBR shelf. While our arguments refer mostly to the post-glacial time period (< 18 ky BP) and the Holocene highstand (about < 5.5 ky BP), similar arguments may apply (to varying extents) to any natural changes in sediment supply during the last and previous interglacials.

The interplay between coral reefs and terrigenous sediment along the inner-shelf of the GBR shelf can be discussed in terms of two principle components, sediment accumulation and suspended sediment (the latter being the main regional contributor towards turbidity). *Sediment accumulation* describes the increase in thickness of a sediment body, caused by addition of material at its upper surface. In this context, accumulation is a regional geological phenomenon, and has probably played a significant role in controlling the distribution of coral reefs within the GBR at various stages of sea level (Woolfe and Larcombe 1998; Larcombe and Woolfe 1999), primarily because accumulating sediments blanket substrates otherwise suitable for colonisation by corals. In contrast, *turbidity* is a transient oceanographic phenomenon, that is temporally and spatially variable because it is largely related to physical forces acting on the sea bed. The role of turbidity in influencing the distribution of corals is thus also spatially variable, related to regional variations in turbidity

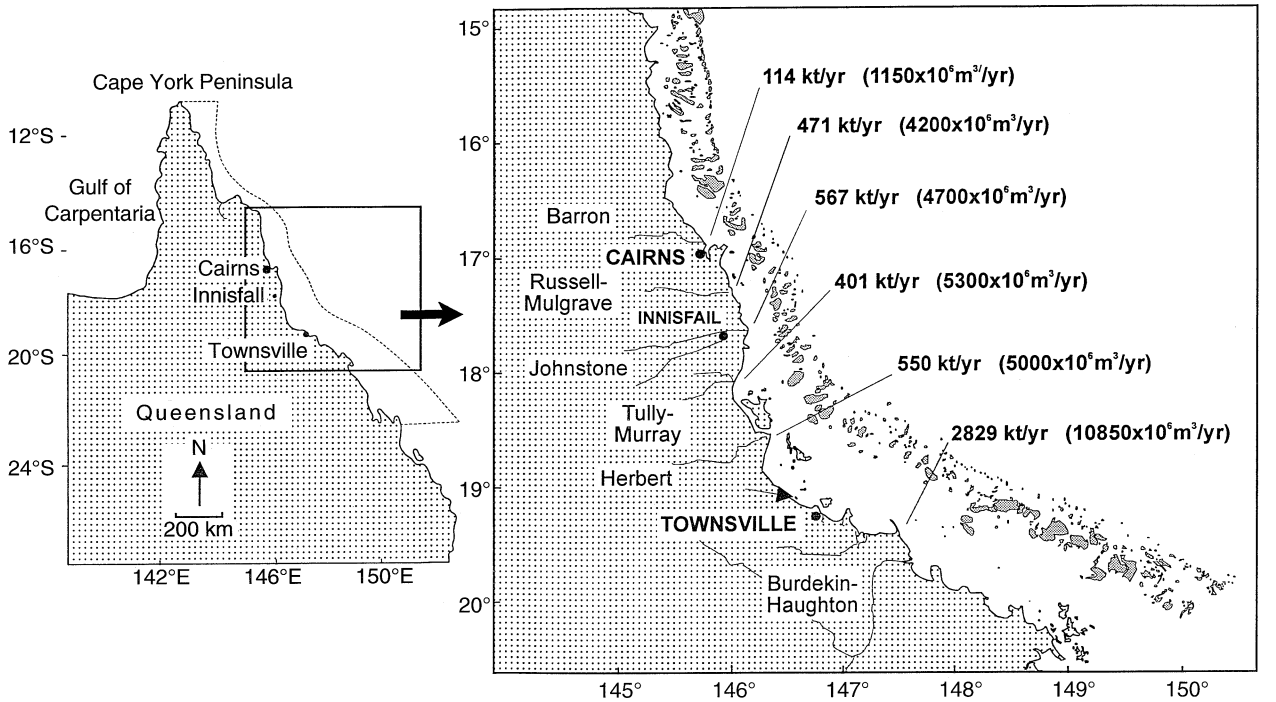

Fig. 1 Location map showing the main rivers adjacent to the central Great Barrier Reef coastline, and their estimated annual discharges of sediment (and water) (from Moss et al. 1993)

regimes, and, also on a regional scale, is probably partly controlled by the location of accumulations of muddy sediments. It is also necessary to distinguish between changes in the turbidity of rivers entering the GBR lagoon and changes in turbidity in the lagoon itself. Few coral reefs occur near river mouths, because of the high turbidity, rates of sediment accumulation, and low availability of suitable substrates generally associated with such environments (Hopley 1995).

The widely perceived impact of increased sedimentation at reef sites on the GBR is well illustrated by Furnas and Brodie (1996) who wrote: '*While many parts of many coastal reefs appear to be in a relatively 'normal' state . . . . shallow flat communities with significant branching coral reef assemblages have largely disappeared from most (though not all!) nearshore reefs over the last* 50–100 *years*'. They went on to state that: '*In most cases, the degraded reef flat structure has been infilled with sediments. It may be hypothesised that these changes reflect increased sediment and nutrient loads in the coastal zone.*'

However, little supporting evidence exists for increased rates of sediment accumulation or elevated nutrient loads at reef sites. Further, detailed treatments of the supply of sediments (see Fig. 1), freshwater, and nutrients to the GBR lagoon (e.g. Wasson 1997) have not yet led to the establishment of links between increased sediment and/or nutrient supply, changed environmental conditions within the GBR lagoon, and impacts upon coral reefs. To our knowledge, there have been no refereed journal publications which link impacts on GBR reefs with raised turbidity and/or rates of sediment accumulation. Despite this, major reports related to environmental management (e.g. Zann 1995) and a number of articles in popular science journals and newspapers (e.g. New Scientist 1995) promulgate such ideas. In our view, such propositions remain unproven and require explanation. The arguments made in this paper consider only the characteristics of sediment accumulation and turbidity, as necessary first steps for improved appraisals of the potential for impacts from sediment-related factors. Thus, we do not address the potential impacts of changes in supply of sediment-bound contaminants to reefs in the lagoon, or of changed nutrient regimes within it.

Holocene sediment accumulations and sediment availability on the shelf

Along the central GBR coast, sediment transport is predominantly northwards and can be inferred from coastal geomorphology (Hopley 1971; Belperio 1983; Woolfe et al. 1998), current-meter data (e.g. Belperio 1978), Larcombe et al. 1994; Lou and Ridd 1997; Woolfe and Larcombe 1998, and textural and mineralogical data (Beach Protection Authority 1984). This transport direction has been established throughout the mid- and late Holocene, evidenced by the clear pattern of sites of clastic sedimentation along the central GBR coastline. The main terrigenous deposits include relatively minor volumes in chenier ridges and

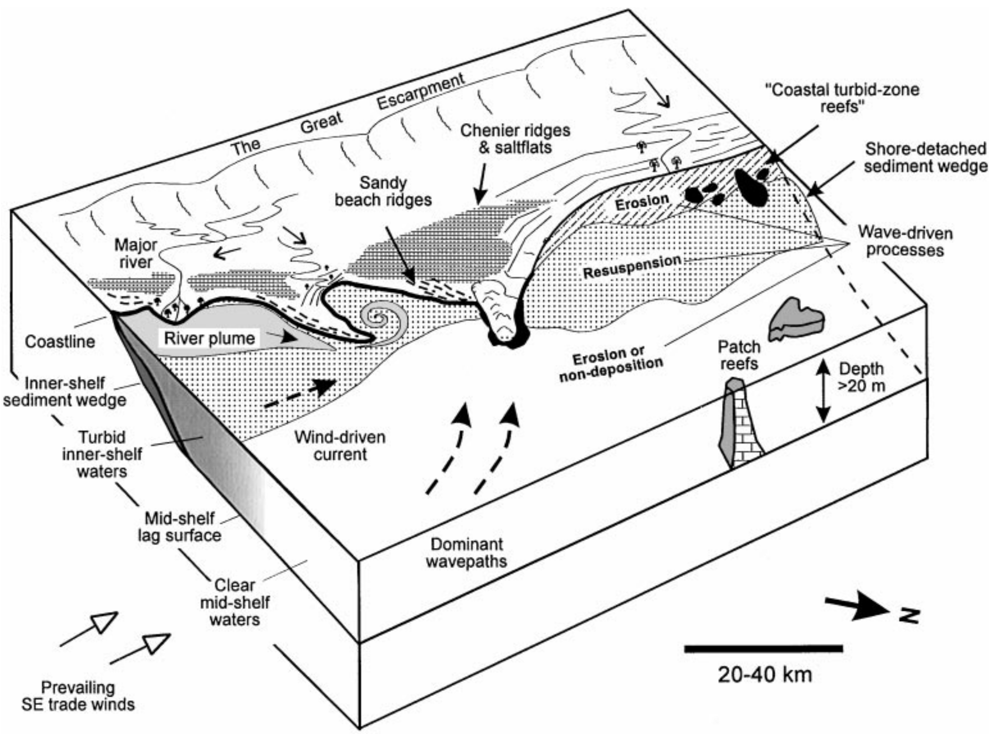

Fig. 2 Schematic view of the central GBR coastline and inner-shelf showing main sedimentary environments and mechanisms of sediment resuspension and transport. Suspended sediment concentrations maintained along the inner shelf by wave resuspension during trade-wind periods greatly exceed those present in river plumes (modified after Woolfe and Larcombe 1998)

inter-chenier plains (the latter largely comprising saltflats) and substantially greater volumes stored in large bodies of muddy intertidal and subtidal deposits. These nearshore deposits form an inner-shelf sediment wedge generally less than 5 m thick, that typically extends out to the 20 m isobath (Maxwell 1968; Belperio 1983). These marine wedges are most prominent in northward-facing embayments, which are relatively protected from the wind and swell waves induced by the prevailing SE trade winds (Belperio 1988; Woolfe et al. 1998). In such environments, the sediment wedges are shore-attached (e.g. Carter et al. 1993). In settings more open to the swell waves, the wedge is commonly shore-detached, separated from the coastline by a narrow band of erosion or non-deposition (e.g. Johnson and Searle 1984; Woolfe and Larcombe 1998). Seaward of the terrigenous wedge and within the main reef tract, the shelf is largely devoid of Holocene terrigenous sediment (Scoffin and Tudhope 1985; Harris et al. 1990). Living coral reefs are absent on the sediment wedge itself, however corals do occur in places immediately seaward of the wedge (especially as fringing reefs on islands) and locally landward of the wedge where the wedge is shore-detached (Woolfe and Larcombe 1998; Larcombe and Woolfe 1999, and Fig. 2).

In most places on the inner shelf, the thickness of the sediment wedge means that there is ample (muddy) sediment immediately available for resuspension. Sediment availability does not limit the concentration of suspended sediment (and largely, turbidity) in the water column, rather the controls are hydrodynamic in nature (e.g. Larcombe et al. 1995; Woolfe and Larcombe 1998; Larcombe and Woolfe 1999). Sediment availability probably only becomes important towards the boundary with the middle shelf, and in areas remote from riverine inputs, where surficial sediments become thin and patchy and will therefore in some circumstances limit turbidity. Consequently, in areas removed from a pro-delta, an increased rate of sediment supply to the coastline would have no detectable effects upon sediment availability, and hence turbidity, sediment transport and sediment accumulation.

Sedimentary processes on the central GBR shelf

Waves, tides and wind-driven currents

The main energy source for sediment transport is the SE trade wind, which blows persistently along the main portion of the GBR lagoon in the 'dry season' (about April–Nov.). In contrast, the shorter 'wet season' has lighter and more variable winds, except when episodic cyclones occur. The SE winds produce swell waves on the inner shelf (period > 6 s) which are the primary agent of resuspension of bed sediments (e.g. Larcombe et al. 1995). On reaching the shoreline, these waves drive a longshore drift of sandy material to the north, and the wind forces a wind-driven northwards-flowing current. Locally, tidal action may be important in influencing turbidity, (e.g. Kleypas and Hopley 1992). Cyclones, although of high magnitude, are infrequent (Puotinen et al. 1997) and have complex wind and wave fields. Except for some localised areas where rates of coastal progradation have been high throughout the mid- and late-Holocene (e.g. the southern margin of north-facing coastal embayments), cyclones appear to have relatively little long-term sedimentary and geomorphic expression along the coast (Woolfe et al. 1998). Along much of the mainland coastline, waves and wind-driven currents associated with the SE trades appear to have reworked deposits of even the most intense cyclones.

Turbid river plumes

River flood plumes are a relatively local and short-term influence on turbidity on the inner shelf (Wolanski 1994; Taylor 1996). Away from the river mouths, river plumes on the inner shelf of the GBR have sediment concentrations of a few mg/l and may only be one or two metres thick (e.g. Taylor 1996). With northerly or offshore winds, these plumes may extend tens of kilometres offshore and may directly impinge on mid and outer-shelf reefs (Brodie 1996; Brodie and Furnas 1996) before being dispersed laterally and vertically. Despite being visually spectacular (especially by being distinguishable in colour from ambient lagoon water) the sediment load carried by such plumes is minimal. As an example, recent data from a major plume of the Barron River, Cairns (350 km north of Townsville) indicates a plume confined to the upper 2 m of the water column and containing suspended sediment concentrations (SSCs) of only 3–10 mg/l (Taylor 1996). In the event that such a plume was large, extending for 45 km along the coast and for 10 km out from the coastline, then it would contain less than 9000 tonnes of suspended sediment.

In contrast, SSCs in Cleveland Bay, off Townsville, are controlled by swell waves which stir bed sediments and may produce depth-averaged SSCs of 50 mg/l or more (Larcombe et al. 1995). With an area of 200 km^2 and an average depth of 5 m, the total mass of sediment resuspended in the bay is about 50 000 tonnes. Depth-averaged SSCs are probably twice as much during some swell wave events. Thus, the mass of sediment along the central GBR coastline held in suspension by swell waves (which affect the coast for much of the year) is likely to be several orders of magnitude greater than the suspended load introduced by even the largest individual turbid plumes. Consequently, we infer that, in terms of direct sedimentation, turbid plumes are not a significant threat to mid and outer-shelf sites.

Fundamental hydrodynamic controls upon sedimentation

The main factors which control the generation and distribution of turbidity (caused by sediment particles) on the shelf are illustrated in Fig. 3, and described briefly below.

Resuspension by waves

- the maximum shear stress at the bed is related to the maximum orbital velocity attained by water particles near the bed under waves ($U_{b\max}$), which, for any depth, is related strongly to wave period. For the central GBR, swell waves (here defined as those with wave periods > 6 s) are the major influence over most of the inner shelf (Larcombe et al. 1995).

Resuspension and transport by unidirectional current

- the shear stress generated at the bed is less for unidirectional currents than under waves for an equivalent fluid speed, so their ability to resuspend particles is less. On the inner GBR shelf, such currents will commonly augment sediment resuspension by waves, and will transport material already in suspension. However on their own, unidirectional currents (apart from strong cyclone-induced flows) will generally create relatively little turbidity and transport little sediment (Larcombe et al. 1995). In most areas of the shelf, tidal currents on the shelf are unidirectional for periods of a few hours. Wind-driven currents may persist for periods of many days.

Particle settling

- some fine-grained sediment is transported to the coast in riverine waters, maintained in suspension by turbulence. Where these flows meet saline water, they are relatively buoyant, and a surface freshwater turbid plume may extend into the inner-shelf above the saline seawater. Where fresh and saline waters mix, particles may cluster together, forming flocs, with greater settling velocities than the individual particles. This mechanism is locally and seasonally important, in estuaries and within embayments into which large rivers discharge.

Vertical mixing (turbulent diffusion)

- sediment particles in the water column are mixed vertically by turbulence and by vortices of various scales, leading to diffusion of sediment within the water column (see e.g. Dyer 1986).

A full treatment of sediment transport issues may be found elsewhere (Middleton and Southard 1984; Dyer 1986; Wright 1995; Allen 1997). In the context of the GBR, it should be noted that where sediment is already available for resuspension, the addition of extra sediment to the shelf system does not alter the concentration

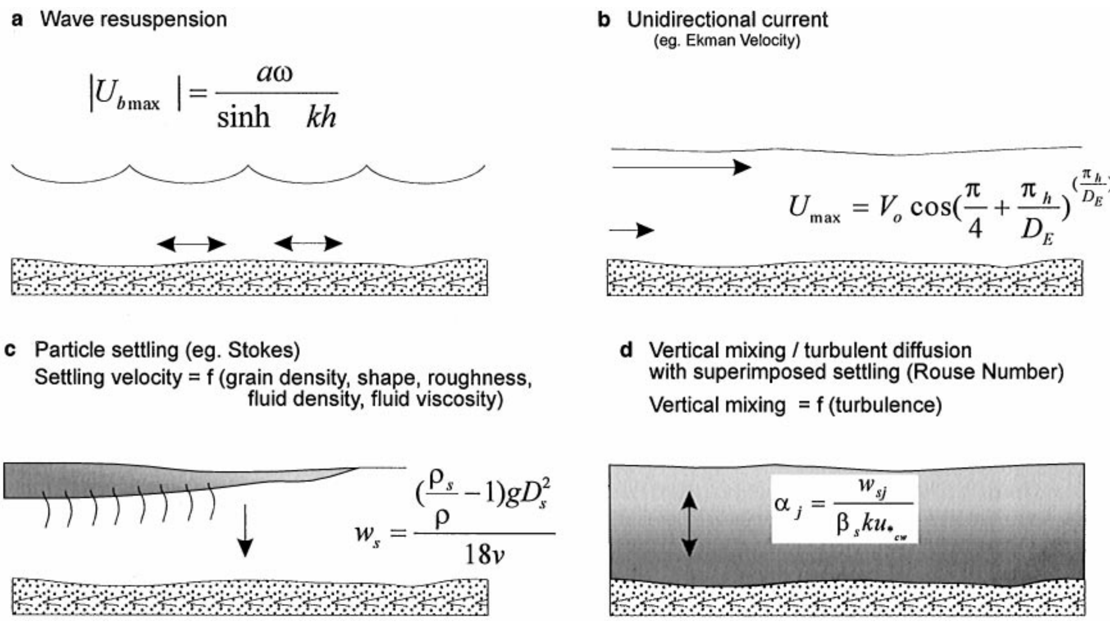

Fig. 3a–d The main factors influencing turbidity. **a** Resuspension of bed material by waves can be represented by the maximum orbital velocity at the bed ($U_{b\max}$), where a is the wave amplitude at the surface, ω the wave frequency (in radians), k the wave number and h is the depth (Wright 1995). **b** Resuspension and transport of suspended material may be strongly influenced by unidirectional currents. For wind-driven currents, a general rule-of-thumb is that the speed of the surface wind-driven current is approximately 3% of the wind speed measured 10 m above the sea surface. In moderately deep water (e.g. seaward of the GBR inner shelf) the decrease in velocity with depth h is given by the Ekman equation, where V_o is the surface current velocity and D_E is the Ekman depth (Allen 1997). **c** Stokes Law describes the rate of settling for fine-grained particles in non-turbulent waters, providing a first estimate of settling from turbid flows, but probably overestimating actual settling rates in nature because of turbulence. Downward settling velocity (w_s) of particles (e.g. from a turbid plume) is estimated using the densities of the sediment particle and the water respectively ρ_s and ρ, the particle diameter (equivalent settling diameter) D, acceleration due to gravity g and fluid viscosity v. For comparison and for coarser particles, see the empirical equations of Gibbs et al. (1971) and Hallermeier (1981). **d** The ratio of the rate of downward settling of particles to that of upward migration through eddy diffusion is given by a Rouse Number (α_j) where, w_{sj} is the downward setting velocity of a particle of size j (see Stokes equation), β_s is a constant (close to unity in unstratified flows), k is the Von Karman constant (0.4) and u^*_{cw} is the current-wave shear velocity (Dyer 1986; Wright 1995)

of sediment in the water column. The controlling parameters are those related to the physics of sediment transport. Locally, and on short time scales, a small degree of sediment transport may remove finer sediment components to leave a layer of coarser, immobile material, which then protects finer sediment beneath from further erosion. This 'armouring' of the sea bed may reduce sediment availability and thus turbidity. The period over which armouring is likely to be important will relate partly to the nature and rate of bioturbation. On much of the inner shelf the upper layers of the sediment body are homogenous to depths of 20–30 cm (Belperio 1978; Gagan et al. 1988; Carter et al. 1993), which indicates that the effects of bioturbation exceeds the potential rate of armouring.

Trapping and bypassing along the coastal sediment transport path

On the central GBR, the main point source of terrigenous sediment is the Burdekin River (Belperio 1983, 1988; Moss et al. 1993) and a series of embayments northwards along the coast contain sediments derived largely from this river. Modern and Holocene sedimentation rates decrease northwards in successive embayments. With the exception of true deltaic areas, sediment supply to and accumulation in the inner-shelf wedge is controlled by transport parallel to the coast (Belperio 1983; Woolfe et al. 1998) and is therefore ultimately controlled by winds, waves, and tides. Given this pattern of along-shelf sediment dispersal, an important concept is the 'trapping efficiency' of coastal embayments. As used here, an embayment with a trapping efficiency of 10% would trap 10% of sediment introduced into the bay itself (in the long-term) and allow transfer of the remaining 90% downdrift along the coast. Woolfe and Larcombe (1998) have compared sediment accumulation rates for the Holocene (based on core data from Cleveland Bay, near Townsville; Belperio 1978, 1983; Carter et al. 1993; Larcombe and Carter 1998) with accumulation rates inferred by modern measures of sedimentation (time-series oceanographic, turbidity and sediment trap data; Larcombe et al. 1994; 1995; Lou and Ridd 1997). They inferred that Cleveland Bay has a trapping efficiency of only 0.2%, so that the modern bay acts as a zone of sediment transfer far more than a zone of accumulation.

Higher trapping efficiencies might be expected during the mid-Holocene, which would reduce through time as embayments became progressively filled and increased quantities of sediment were transported northward along the coastal transport path. When coastal progradation had progressed to the extent that the effective delta front and pro-delta extended outside the embayment into which the (Burdekin) river disgorged, the coast would have become straightened (in hydrodynamic terms), reducing trapping and increasing sediment bypassing. Marked increases in rates of along-shelf transport, and associated decreases in rates of sediment accumulation in proximal embayments would have resulted. Finally, apart from the potential for slightly reduced wave energies on the late Holocene inner shelf, as the elevation of coral reef flats met sea level (Hopley 1984), there is no evidence to indicate that the major oceanographic forcing factors upon sedimentary conditions have changed significantly since the mid-Holocene.

Progradation of the inner-shelf sedimentary wedge

The regional coastal sediment wedge has in many places prograded seawards a short distance (< 6 km) since the mid-Holocene sea-level highstand, at rates of up to about 1 m/y (e.g. Belperio 1983; Carter et al. 1993). The mean rates of vertical accumulation (over the last 6000 y) range from 0.03–0.2 mm/y on the mid-shelf off Townsville (recalculated from core and seismic data of Ohlenbusch 1991 by Woolfe and Larcombe 1998) to a maxima of 0.5–8.0 mm/y in intertidal zones of Upstart Bay and Bowling Green Bay (Belperio 1983). Rates of sediment accumulation can also be inferred from estimates of sediment supply to the coast. Estimates of the modern (post-European settlement) annual supply of sediment to the GBR shelf from the mainland are about 13–28 Mt (Belperio 1983; Moss et al. 1993; Neil and Yu 1996). Assuming that the sediment grains have an average density of 2.7, and that they are deposited evenly over the area of the modern inner-shelf sediment wedge (about 10 000 km^2) at a porosity of 30%, the sea bed would be predicted to be accumulating vertically at a mean rate of 0.7–1.5 mm/y. With the regional sea-bed slope of about 1 : 1000, this would correspond to rates of seawards progradation of 0.7–1.5 m/y.

Regionally, and in the long term, seaward progradation of the sediment wedge (Harris et al. 1990) may ultimately pose a threat to adjacent inner-shelf reefs because turbidities would increase as the sediment wedge approaches. In some cases, reef burial might eventuate. Given a relatively stable sea level, and continuation of long-term rates of coastal progradation, the continental islands around 5 km beyond the outer edge of the modern inner shelf sediment wedge, might be impacted by significantly increased turbidities (related to the seawards advance of the inner-shelf sediment wedge) on a time period of 5000 y. However, over the next 10–50 y, average water depths on the coastal wedge would likely decrease by only 7–75 mm. Given a predicted rise in global mean sea level by 2050 of 75–450 mm (Watson et al. 1998) actual water depths are likely to increase at most sites, and, as a consequence, turbidity may be reduced.

Even allowing for the possibility that the estimates of modern rates of sediment supply to the shelf are too low, we conclude that the time scales involved in producing regional changes in sedimentation and turbidity are far greater than can reasonably be addressed by environmental management. Human impacts will be largely undetectable in the regional turbidity record. Future field studies might focus on sedimentation at the seaward feather edge of the inner-shelf terrigenous sediment edge, where sediment availability is presently a limiting factor in turbidity and sedimentation, and to those coral reefs immediately adjacent to identified point sources of sediment input.

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SEDIMENT DISPERSAL ALONG THE INNER SHELF OF THE CENTRAL GREAT BARRIER REEF

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ABSTRACT

The Great Barrier Reef (GBR) is the worlds largest and most complex system of coral reefs, located on a continental shelf into which the Holocene input of sediment has been, in global terms, relatively low. Since European settlement, it is possible that there has been an increase in river sediment supplied to the GBR coastline, and understanding the likely fate and impacts of this sediment is important to environmental managers of the GBR region. Further, the GBR shelf represents a continental shelf where carbonate and land-derived sediments are mixed, and also a shelf which is impacted by cyclones. This contribution briefly reviews the nature and processes of sediment movement pertinent to the Great Barrier Reef (GBR) coastline.

<u>Footnote</u>

Ken Woolfe died tragically December 1st, 1999. His passion and enthusiasm for earth science will be missed.

INTRODUCTION

The Great Barrier Reef (GBR) shelf (Fig. 1) is a mixed siliclastic-carbonate province (Belperio, 1983) famous for its colourful coral reefs, clear waters and abundant marine life. The shelf is typically 80-120 km wide in the central section of the GBR, and has an average depth of c. 40 m. Recently it has become widely accepted (see Zann & Sutton, 1995) that the amount of sediment reaching the Great Barrier Reef coastline has increased over the last 200 years as a direct result of agricultural and urban development associated with settlement of Europeans. This post-European increase in sediment supply down rivers has the status of 'common knowledge' and is logical in many respects, particularly when considering catchment modifications such as those associated with grazing, deforestation and tilling of grassland and savanna. We should note, however, that at present, the increase is heavily inferred than proven fact, and the magnitude of any increase is certainly unquantified (see Larcombe et al., 1996, Larcombe & Woolfe, 1999, for discussion).

The fate of river sediments once in the marine environment is of concern to environmental managers, for reasons including:

- Suspended sediment increases turbidity, reducing water clarity and thus tourist enjoyment of the marine life.
- Increased turbidity may reduce light levels on the seabed and hence inhibit coral growth.
- Enhanced sedimentation may occur over time periods of hours to years, resulting in the physical burial and perhaps the subsequent death of corals or other benthic organisms.
- Agricultural and industrial contaminants may be introduced to the marine environment and transported via sediment particles.

These concerns have heightened awareness amongst the scientific community of the importance of river sediment accumulation in coastal environments and considerable effort is now being directed towards generating an understanding of the rates of sediment supply, the mechanisms of sediment dispersal, the temporary sediment stores (on a timescale of a centuries to a few thousand years) and the ultimate locations of sediment repositories on the GBR shelf (Larcombe et al. 1996, Wasson 1997, Orpin et al. 1999, Larcombe & Woolfe, 1999). A good qualitative understanding of the physical processes operating on the inner shelf of the GBR has developed, and in this chapter we present a working model for the dispersal of sediment along the central GBR coastline.

PROCESSES CONTROLLING SEDIMENT SUPPLY TO THE GBR COAST

The Queensland Department of Primary Industries maintains, or has previously maintained, flow gauging stations on many of the catchments bordering the GBR lagoon (e.g. Moss et al, 1993, Horn 1995). Based on all available gauging records, catchment areas, land use and rainfall patterns, estimates of the rate of supply of terrigenous sediment to the coastal zone have been prepared. While estimates of total sediment load vary greatly, from 13 Mty^{-1} (Moss et al., 1993) to 28 Mty^{-1} (Belperio 1983), it is clear that sediment supply is largely controlled by short-duration, high-volume flows associated with individual meteorological events (e.g. tropical cyclones, rain depressions, convergences).

It is widely asserted that the terrigenous sediment flux to the Great Barrier Reef has increased as a result of human impacts on catchments, particularly in the last 200 years (Belperio 1983, Belperio and Searle 1988, Moss et al. 1993, Neil and Yu 1995). However, most of the rivers entering the Great Barrier Reef lagoon are 'flashy' (i.e. have extremely large, high flow/low flow ratios) and at high flow stages, the river is able to transport cobbles and larger clasts, which in practice makes *in-situ* measurements of sediment transport difficult. Further, the rivers overtop their banks, inundating the floodplain for many kilometres on either side of the main channel, making the gauging of flows and sediment fluxes even more problematic. In addition, the hydrology and vegetation dynamics of many catchments are not well known. Quantification of the sediment increase associated with land use change is thus extremely difficult (e.g. Belperio 1983, Horn 1995, Mitchell et al., 1996). Current estimates of the rates of terrigenous sediment supply to the central GBR shelf derive from:

1) estimation of the volume of Holocene sediment on the shelf, to give a long-term average of sediment accumulation rate (Belperio, 1983; Harris et al., 1990; Carter et al., 1993, Woolfe & Larcombe, 1998);
2) extrapolation of measurements of sediment transport in rivers and estuaries to annual or longer timescales (e.g. Belperio, 1979; 1983; Belperio & Searle, 1988), or;
3) modelling sediment yields from soil erosion and runoff in the river catchments (Moss et al., 1993; Neil & Yu, 1995).

Most terrigenous Holocene deposits are confined to the inner-shelf and well documented, so that back-calculating long-term sediment input from them is fairly reliable but is a long-term average (few thousand years), and provides background data only for studies of recent sediment supply and accumulation (Table 1). Due to the nature of many rivers of the central GBR coastline, whose characteristics include relatively low mean annual runoff, great interannual variability of discharge, heterogenous vegetation patterns in their catchments (including altered catchments), and unusual channel morphologies, the latter two methods can result in considerable uncertainty in the calculated rate of sediment supply.

Using their catchment model, based on catchment-scale data, Neil and Yu (1995) indicate that since European settlement, sediment fluxes to the coast from individual catchments have increased between 1 and 30 times (depending on land use changes), and the total increase in sediment flux to the Great Barrier Reef coastline since European settlement is c. 2-4 times. Methods of addressing sediment delivery to the coast are being refined progressively, and although its magnitude is undocumented, the occurrence of an increase is unchallenged.

Thousands of dams have been constructed in the GBR hinterland. These range in scale from small ($<10^6$, i.e. 1 Ml) farm dams to large ($> 10^6$ Ml) domestic and agricultural supply dams. As a consequence it is likely that over a few decades to a century or so, there will be a decreased supply of coarse-grained sediment to the coast, due to the stabilisation of bars in rivers below the dams and because some sediment will be trapped in the dams. Long-term fluxes of fine-grained suspended sediment may be relatively less affected, because the bulk of this material is supplied to the coast during large-scale runoff events, where dams will be overtopped, and because altered catchments may yield increased amounts of fine-grained sediment. The detailed effects upon coastal sedimentation and inner-shelf coral reefs of dam construction remain unknown.

MECHANISMS OF SEDIMENT DISPERSAL

In terms of the dispersal of sediment along the coast and inner shelf, two types of sediment need to be distinguished:

- Suspended Sediment. Some fine-grained sediment is transported by being suspended in the water, maintained above the bed by turbulence. The weight of suspended material in the water column will decrease with lower flow speeds and smaller waves, but will rarely approach zero.

- Bedload Sediment. Coarser material is moved along or closely associated with the bed. Sediment movement requires a threshold shear stress to be exceeded, so that at low flow speeds, no sediment may be moved at all.

For most practical purposes, suspended load can be considered to consist of ‘muddy’ material (fine silt and clay) which travels approximately at the speed of the water, whereas bedload sediment consists largely of coarse silt, sand and gravel, which travels significantly slower than the water column above. Suspended load is more significant in the transport of contaminants because finer particles have larger specific surface areas (surface area per unit mass) and hence a greater ability to transport surface-attached chemical species.

Sedimentary material found in suspension within the GBR lagoon will have been derived directly from the rivers and/or from existing (reworked and resuspended) shelf sediments. Some suspended sediment is supplied within muddy plumes of rivers, which discharge into the GBR lagoon. Because they are freshwater, these plumes tend to be buoyant and are thus generally confined to the upper few metres of the water column. As such, they have relatively low suspended sediment concentrations (SSCs < 100 mg/l) and overlie marine waters which, during calm conditions, will have still lower SSCs. Another 'source' of suspended sediment is the sea bed itself, where fine sediments may be resuspended upwards from the bed into the water column. Waves, often concurrent with tidal or wind-driven currents, are generally the dominant mechanism in causing resuspension. Muddy waters produced by this mechanism will tend to decrease in SSC upwards away from the bed, and may reach SSCs much greater than those found in river plumes (up to 300 mg/l or more) (Larcombe et al., 1995).

Regardless of its mechanism of generation, the rate at which suspended sediment will be moved is the product of flow depth, with depth-averaged SSC and speed. Generally, the greater thickness and sediment concentration of resuspension plumes result in a higher rate of sediment transport than surface flood plumes. Furthermore, resuspension of sediment from the bed is a process which occurs throughout the year (c. 10^3 h) over large areas of the inner shelf (c. 10^4 km^2) and to depths of c. 10 m, whereas flood plumes are generally small (over c. 10^3 km^2), exist for only brief periods (c. 10^2 h) and are relatively thin (c. 1 m). Thus sediment resuspension is likely to be about three orders of magnitude more important than river plumes in terms of coastal sediment transport.

Bedload transport only occurs once threshold velocities have been exceeded, and even then, the speed of the moving sediment grains is significantly slower than water movement. Transport will occur near the coast in rivers and estuaries under the influence of freshwater flood and tidal currents. It will also occur on the inner shelf as a result of waves alone, or waves in combination with other currents.

There are a number of mechanisms that might control the distribution and dispersal of river sediment reaching the coast. Below, we describe some of the principle mechanisms that influence sediment dispersal in the coastal zone and comment on their potential significance on the GBR shelf.

- Oceanographic Currents

Major oceanic currents are largely prevented from entering the GBR lagoon (for map see Larcombe, this volume, Fig. 1) by the presence of the barrier reef, but the Northeast Australian current can generate a significant net flow in the lagoon during certain times of year and under certain wind conditions (Wolanksi 1994). However, these currents do no directly impinge on the coast, and they are not considered important in the distribution of sediment.

- Wind-Driven Currents

Wind-driven currents result from friction between the atmosphere (wind) and the water surface, and thus tend to be surface currents. Even in the relatively shallow waters of the GBR shelf, these currents do not necessarily propagate to the bed. Friction between the wind and the water is proportional to the roughness of the water surface, for any given wind speed, the magnitude of the wind-driven current is increased by the presence of surface waves. The GBR lagoon (Larcombe, this volume, Fig. 1) lies within the southeasterly trade wind belt, and for approximately 9 months of the year (March-Nov) persistent southeasterly winds of 10-15 knots occur. This results in a strong northward-flowing wind-driven surface current (Figs. 2 & 3) which has a significant impact on the dispersal of suspended sediment. Wind-driven currents rarely exceed the thresholds for bedload transport, but, in conjunction with waves and tidal currents, may locally play a role in the redistribution of bedload sediment. During the summer months (Dec. - Mar.) winds are generally lighter and may even blow offshore. Exceptions to the light winds of summer months in tropical regions (south of c. 8^{o}S) are cyclones, which are discussed later.

- Wave-Driven Currents

Particles in open water and experiencing non-breaking waves move in an orbital pattern with no net translation (Fig. 3a). However, as these waves shoal, begin to steepen and ultimately break, a net translation of water occurs in the direction of wave propagation. Consequently, waves transport water towards the coastline, where they raise water levels and also generate a return flow away from the coast. When waves break at an angle to the coastline (Fig. 3c, d) they generate a coast-parallel boundary current (see below). Breaking waves are very effective resuspension agents. Observations show that wave-driven currents of this type may be strong enough to cause bedload transport and may also overwhelm tidal currents along the GBR coastline. The normal waves parallel the wind, so wind- and wave-driven currents tend to reinforce each other in the coastal zone.

- Rip Currents

Rip currents occur along coasts where the orientation of wave fronts approaching the coastline is nearly coast-parallel (Fig. 3b). Under these conditions, excess water is unable to escape laterally along the coast and strong offshore-directed rip cells are generated. On an open coast these may be strong enough to transport coarse-grained bedload (gravel) seawards, to beyond the surf zone. Consequently, on open coastlines they may represent a significant process of offshore-directed sediment transport. However, within the GBR lagoon, these currents are minimal because of the general lack of long-period waves with significant amplitude, the low gradient dissipative shelf and shoreface, and the tendency for the wave fields to have a substantial longshore component. Consequently, rip currents do not provide a major mechanism of shore-normal sediment transfer.

- Longshore Drift

The expression "longshore drift" is widely and incorrectly used to describe the transport of sediment and water along a coastline regardless of the mechanism. Longshore drift *per se* occurs when wave fronts arrive at an angle to the coast, when particles (bedload) are transported obliquely up the beach during wave run-up and return seaward (shore-normal) in the backwash. Overall this results in the transport of sand particles in one direction along the coastline (Fig. 3d). Longshore drift is a significant mechanism of bedload transport along open coasts (e.g. the New South Wales coastline). While this process occurs along the GBR coastline, and mainly under the influence of the SE trade winds (causing northward transport), the relatively low-energy wave climate (caused by limited fetch) means that the active sandy beaches are effectively partitioned by headlands (cf. pocket beaches). Consequently, longshore drift is probably only locally significant within the GBR.

- Density Currents

Density-driven currents occur when high density water (cold, hypersaline or turbid water) moves downslope under the influence of gravity. Gravity currents are probably best known from the deep ocean where they are associated with the redistribution of slope sediments giving rise to extensive marine turbidites. However, density flows driven by thermal differentials, salinity contrasts and suspended sediment are common off major river mouths (Mulder and Syvitski, 1995). However, within the GBR, both the shallow nature of the shelf and a relatively high wind regime result in effective vertical mixing of the water column in the coastal zone. This mixing, together with a low-gradient shelf reduces the likely significance of density-driven flows.

- Tidal Currents

Tidal currents are the dominant factor causing movement of sediment within many tidal creeks and estuaries (Wolanski 1994, Larcombe & Ridd 1995, 1996) and are important in transporting fine-grained sediment and coarse materials suspended by waves, in the coastal embayments of the central GBR coast (e.g. Larcombe et al. 1995b). During the dry season, asymmetry of tidal currents within some creeks and estuaries may cause long-term landward movement of suspended and/or bedload sediment into and up the estuaries where it may be stored (Larcombe & Ridd 1995a, b, Furukawa and Wolanski 1997, Furukawa et al. 1997, Bryce et al. 1998). Thus, tides are important as factors contributing to the partitioning of sediment between the shelf and the intertidal/subaerial portions of the coastal sediment wedge. Tidal currents may be strong enough to transport bedload material in some channels between inner-shelf islands (e.g. Whitsunday Islands, 200 km south of Townsville). However, along the open GBR coastline tidal currents are generally not strong enough to cause resuspension. The role of tidal currents in sediment transport along the coast is subordinate to that of wind- and wave-driven currents.

- Eddies

Eddies may occur where currents flow past islands and/or headlands. The presence of large-scale eddies (kilometre-scale radii) combined with flow expansion and reduced wave influence (Fig. 3h) is significant in the sediment-trapping capacity of north-facing bays along the GBR coastline (discussed below).

- Boundary Currents

Boundary currents occur wherever a current impinges on an impermeable or immovable boundary. In the context of this discussion, the coastline represents such a boundary to wind, wave and tidally driven currents, consequently, under some conditions, strong shore-parallel currents are developed.

Moreover, as the prevailing SE winds and associated currents have both longshore and onshore components, a coastal boundary layer is developed, in which suspended particles are moved both shoreward and northwards. This coastal boundary layer corresponds with the landward part of the zone of wave-induced sediment resuspension and is evident along the GBR coastline as a coastally-trapped zone of turbid water (e.g. Figs. 3c, h).

- Rossby Radius

In the absence of other overwhelming processes, buoyant surface plumes such as the plumes resulting from freshwater floods behave like surface jets when they enter the GBR lagoon, and are thus affected by the spinning of the earth. In the southern hemisphere such plumes tend to be deflected to the right, with respect to their direction of movement (the Coriolis Effect) and the radius of this curvature is known as the Rossby radius (Pond & Pickard 1983, Fig. 3f). The Rossby Radius is a function of the cosine of latitude, so that within the tropics, the radius is large. As a result, within the GBR lagoon, both tidal and wind-driven flows tend to overwhelm the Coriolis effect in controlling the direction of flow of river plumes.

THE MINOR ROLE OF CYCLONES IN LONG-TERM COASTAL SEDIMENTATION

Waves are the dominant mechanism of resuspending sediment on the inner shelf of the central GBR (Belperio 1983, Larcombe et al. 1995b; Orpin et al., 1999), and once in suspension, tides and wind-driven currents are dominant in its transport. Belperio (1978) and Larcombe et al. (1995b) have demonstrated that persistent SE winds of only 10-15 kts produce a northward-directed current set that completely overwhelms the southward-directed ebb tide on the inner shelf near Townsville. Thus, wave- and wind-driven currents probably form a major long-term regional control on coastal sedimentation patterns. These patterns are a function of waves transporting sand northwards in the intertidal and shallow subtidal zone, and wind-driven currents carrying resuspended fine-grained sediment northwards in a turbid, coastally trapped boundary layer (cf. Woolfe and Larcombe 1998).

Most major geomorphic features along the GBR coastline, such as northward-directed sandy spits and bars, relatively exposed linear sandy coastlines, and mud-dominated sediment accumulations in north-facing bays, attest to strong northward longshore transport. Data from the mid-shelf off Cape Cleveland and within Cleveland Bay itself (both near Townsville) indicate the dominance of the SE trade winds (dry season) in the production of significant long (>7 s) period waves (Patterson, 1994). While the largest waves are produced by cyclones, these are relatively infrequent episodic events.

The patterns of sediment accumulation together with the orientation of bars and spits along the GBR coast are evidence that the major long-term sedimentary processes are dominated by the trade winds of the dry season.

The apparent subordinate role of cyclones in long-term coastal sediment transport along the GBR coastline is in part counter-intuitive, because cyclones unquestionably create the biggest waves and will produce the most intense sediment reworking (e.g. Gagan et al. 1990). In coastal regions, storm surges and relaxation flows (Fig. 3i, j) may enhance cyclone effects. However, Holocene coastal deposits indicative of cyclonic activity (e.g. cheniers and storm ridges) are almost entirely restricted to the southern sheltered margins of north-facing bays and the prograding regions of the coast which are sheltered by headlands, islands or reefs. This indicates that along the exposed coastlines, waves and wind-driven currents associated with the SE trades are, with time, able to rework most cyclone deposits. On the shelf itself, the sediments resulting from Cyclone Winifred (Gagan et al., 1990) were clearly marked when sampled days after the cyclone, but had been completely reworked by bioturbation a few months later.

COAST-PARALLEL DIVISION OF THE SHELF

The present-day distribution of sediment (and hence the late Holocene 'average') is well established (Maxwell 1968, Orme et al., 1978, Belperio 1983, Johnson & Searle 1984). In general terms, terrigenous sediment is partitioned into a coastal wedge (Belperio, 1978, 1983), whereas the mid-shelf (20 m - 40 m water depth) is essentially starved of terrigenous sediment (Harris et al. 1990, Gagan et al. 1990, Ohlenbusch 1991, Carter et al., 1993). In many places (net) starvation is so extreme that the pre-Holocene land surface is exposed at the sea floor. This also occurs in places on the inner shelf, for example in Cleveland Bay (Carter et al., 1993) and Halifax Bay (Woolfe & Larcombe, 1998). The outer shelf (40 m to 80 m water depth) is also starved of terrigenous sediment. Carbonate-dominated sediment accumulations occur near reefs. Coral debris is dominant in the southern and central sectors, whereas accumulations of the coralline algae *Halimeda* form large bioherms in many northern areas (Maxwell 1968, Roberts & Macintyre 1988; Harris et al. 1990; Woolfe et al., 1998).

This shore-parallel, threefold division of the shelf is evident along the entire Great Barrier Reef shelf and is largely maintained by a combination of coastal boundary currents inhibiting seaward migration of terrigenous sediment. While it may appear that the mid- and outer-shelf are dominated by high rates of carbonate production, cross-shelf differences in the rate of net carbonate production (ie. from corals, algae, foraminifera, molluscs etc) are as yet unquantified. We may view the occurrence of the carbonate province as a result of a relative absence of terrigenous sediment rather than an excessive production of carbonate.

The abundance of terrigenous sediment decreases northwards and the coastal sediment wedge becomes thinner, narrower and more calcareous. Along many open and straight portions of the northern GBR coastline the nearshore wedge is completely absent and fringing reefs pass directly into a carbonate-dominated middle-shelf.

NORTHWARD-FACING EMBAYMENTS - NATURAL SEDIMENT TRAPS

Fine-grained sediment accumulates where wave energies are insufficient to maintain particles in suspension and where flushing is not sufficient to remove resuspended material. Consequently, north-facing bays (e.g. Upstart Bay, Bowling Green Bay, and Cleveland Bay) are prime sites for the accumulation of such sediment. In these embayments, wave energy is reduced because the bays are sheltered from the prevailing SE trade winds. Wind-driven coastal boundary currents tend to be poorly formed or absent. Moreover, eddies associated with the regional northward-directed coastal boundary current introduce turbid water into the generally calmer north-facing bays, where sedimentation occurs.

Sediment transfer zones occur between the natural sediment traps. Along exposed straight reaches of the coast, wave and wind-generated currents drive a strong northward-directed coastal boundary current which transports nearshore sediments northwards. This current prevents the accumulation of permanent muddy deposits but in transporting fine-grained material, it facilitates the production of sandy beach ridges, spits and bars. These sections of the coast represent sediment transfer zones where sediment may be stored temporarily while overall being moved slowly northwards. Muddy sediment, is generally prevented from settling on the beachface due to wave activity. Hence, a shore-detached sediment wedge develops, with the muddier sediment generally confined to the zone below the level of the lowest astronomical tide (eg. Woolfe & Larcombe 1998, 1999).

In these transfer zones the lower beachface may be erosional and the pre-Holocene surface ("Reflector A" of Johnson and Searle 1984) may become exposed as a hard substrate. Where this occurs, colonisation by opportunistic corals is possible, and small reefal accumulations may occur within the turbid coastal boundary layer (Woolfe and Larcombe, 1998, 1999). In places, such colonies may be only short-lived as they may be overwhelmed by solitary dunes migrating northwards along the intertidal and shallow subtidal zone.

CONCLUSIONS

The distribution of terrigenous sediment along the central GBR coastline is largely controlled by the effects of SE trade winds. These winds produce a long-shelf, northward-flowing, wind-driven coastal current which is reinforced by a northward-flowing wave-driven current (Fig. 4). The resultant coastal boundary current transports suspended sediment, while the concentration of suspended sediment within the current is largely controlled by wave energy. Limited bedload is transported northwards under the influence of longshore drift. Some export of suspended sediment to the mid- or outer-shelf is possible when buoyant (low concentration) surface flood plumes spread across the lagoon during calm conditions or when offshore winds prevail. Bottom return currents may occur but, to date, their occurrence is only inferred. The absence of significant deposits of terrigenous mud on the midshelf shows that any such sediment does not remain there. Suspended sediment is carried into mangrove swamps and saltflats by tidal processes where some of it may be trapped. Sediment trapping also occurs where eddies cause the coastal current to carry sediment-laden water into sheltered north-facing bays, where settling and accumulation take place. Cyclones play an important role in the delivery of sediment to the coast but appear to be less important in its evolution over centuries and millenia.

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List of Figures

Table 1. Comparison of long-term accumulation rates of sedimentary environments between the mouth of the Burdekin River and Halifax Bay (arranged in order of distance from source). The flux of terrigenous sediment to the bed is expressed as a multiple of the 'background terrigenous flux' (BTF). The BTF is the volume of sediment supplied by all the worlds' rivers distributed over the areas of worlds' oceans (from Woolfe & Larcombe, 1998).

	Total sediment accumulation	Terrigenous fraction of sediment	Terrigenous sediment flux to the bed
	$mm.yr^{-1}$	%	BTFs
Upstart Bay 2500-year mean	0.7	70	20
Upstart Bay 6500-year mean	0.45	85	15.8
Upstart Bay & Bowling Green Bay, Intertidal sediments	0.5 - 8.0	95	19 - 300
Cleveland Bay 30-year mean	<0.2	85	<6.8
Cleveland Bay 6000-year mean	<0.25	85	<8.5
Halifax Bay 7000-year mean	<0.1	75	<3
Mid-shelf off Townsville 6000-year mean	0.03 - 0.2	10 – 30	0.12 - 2.4

Fig. 1. Map of the central GBR near Townsville of GBR showing the three-fold sedimentary division of the shelf and the principle locations discussed in the text.

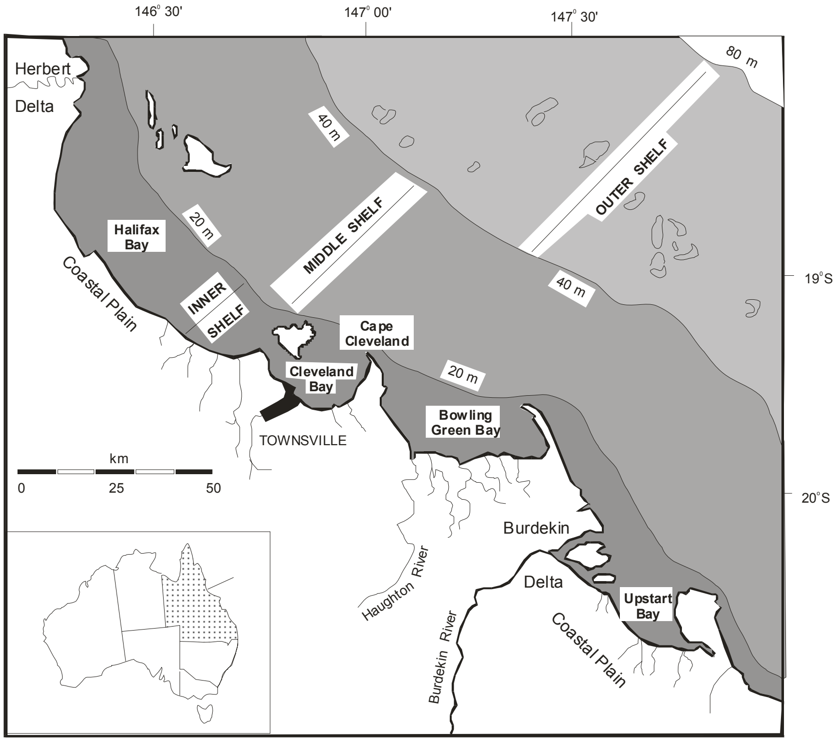

Fig. 2. Current meter data from an inshore mooring in Halifax Bay together with wind data from Townsville. Note how the regular ebb and flood tidal signature is disrupted by SE trade winds for most of the record.

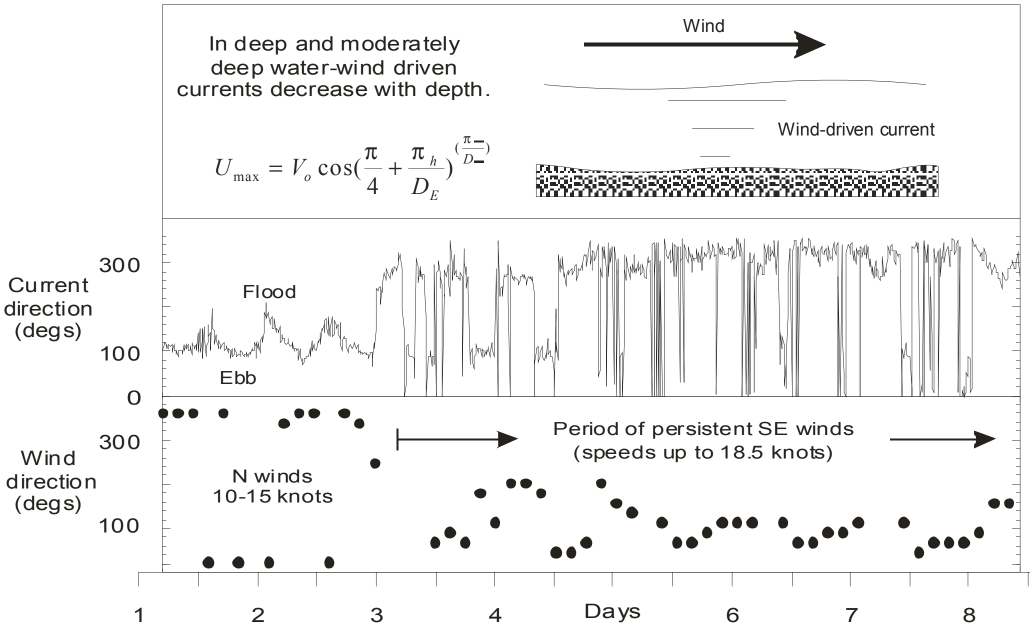

Fig. 3. Cartoon illustrating the principle processes responsible for the resuspension, transport and deposition of sediment in the coastal zone. It should be noted that some of the illustrated processes (i.e. B, E and F, and to a lesser extent D) are not considered to be important within the Great Barrier Reef Lagoon.

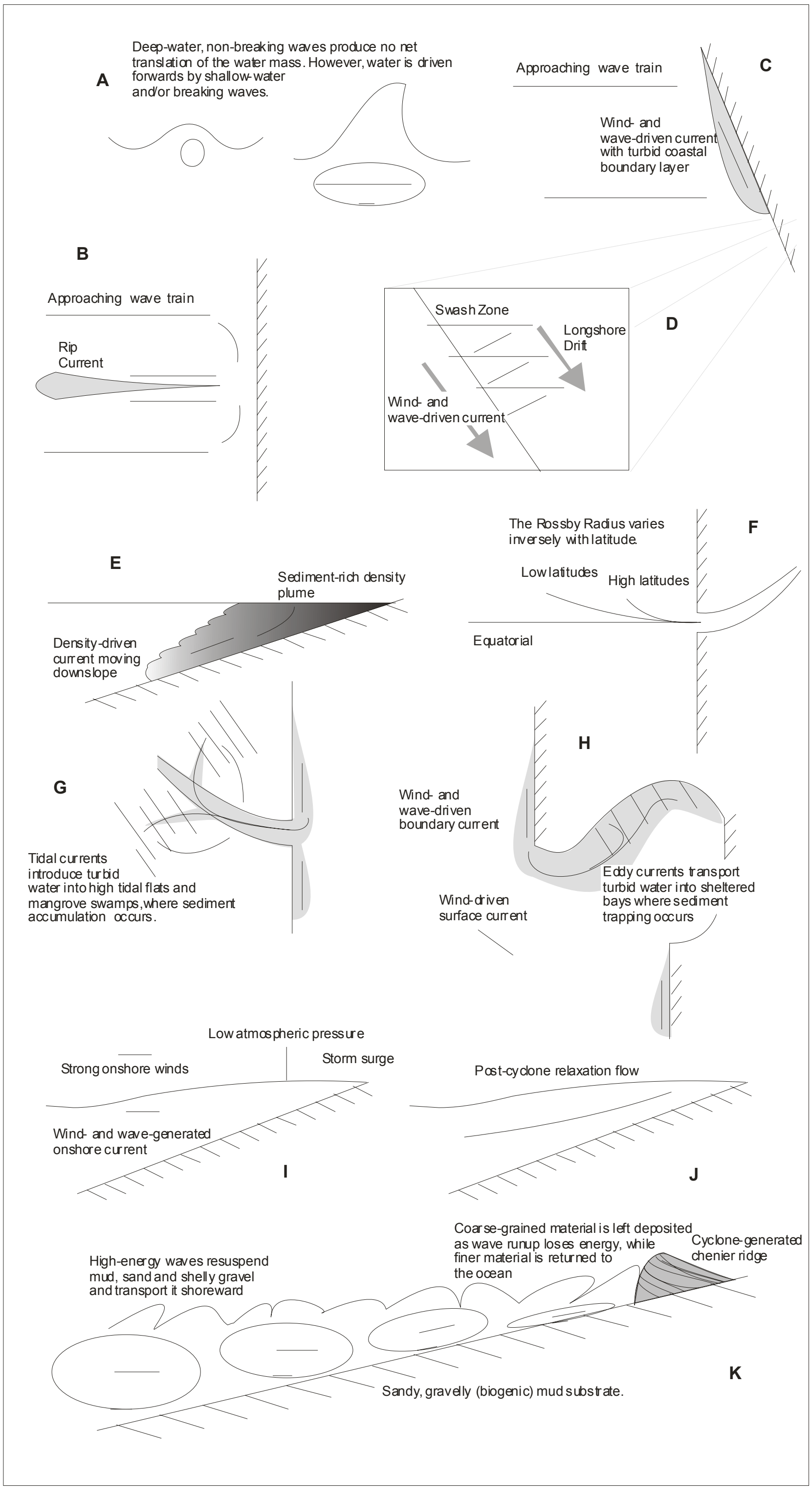

Fig. 4. Map of the Townsville sector of the Great Barrier Reef (see Fig. 1 for place names) showing areas of erosion and deposition along with typical coastal sedimentary deposits. Shaded area depicts an idealised configuration of the turbid coastal boundary layer, where sediment is kept is suspension by wave action, and is driven north by a wind and wave-driven current.