Chapter 7. Turbidity and Hydrodynamics

7.1. Introduction

A total 1340 hours of continuous high resolution time-series hydrodynamic and turbidity data were recorded at Paluma Shoals (671 hours of data) and Phillips Reef (669 hours of data) between Julian days 248 and 276 (1995). These data were taken to quantify near-bed turbidity values (NTU) and identify the hydrodynamic conditions which may transport sediment at both reef sites. A summary of the general hydrodynamic processes from both data sets is presented. The two datasets are compared, and turbidity maximums and minimums described in detail and discussed in relation to the hydrodynamic processes *ie.* wind, wave and current direction, wind velocity, significant wave height (H_{sig}) and tidal elevation.

7.2. Hydrodynamic Processes

Wind (Figures 7.1 to 7.8)

Wind data were recorded at 3-hourly intervals at Townsville Airport (data provided by the Townsville Bureau of Meteorology). Larcombe and Ridd (1993) note that wind speeds offshore (Davies Reef) are generally higher than at the coast. Therefore, although the wind data is presented with other data from Phillips Reef it does not form a precise record for the reef itself.

During the survey period wind velocities were mostly < 10 m/s (18.5 knots) and from the SE, E and NE. The seabreeze effect is sometimes prominent in these data, whereby wind speeds tend to increase in the late afternoon and evening and become on-shore and more shore normal *ie.* E to NE rather than E to SE (e.g. 30-100 & 200-400 hours). During periods of NE winds (e.g. ca. 400-438 hours) wind velocities are less variable and range between 5 m/s and 8 m/s. Winds from the N generally have reduced wind velocities (e.g. 133-137 & 160 hours).

Waves

Wave spectra may be conveniently divided into wind waves (with short wave periods) and swell waves (with longer wave periods). The period of these waves is related to the duration of the winds and fetch. Swell waves are associated with longer duration winds and a longer fetch and can travel along the GBR for hundreds of kilometres. Wind-waves are locally generated and have a shorter fetch. For descriptive processes the wave spectra in these data have been arbitrarily separated into:

- "Swell waves", with wave periods > 6 seconds;
- "Transitional waves", with periods between 5 and 6 seconds and
- "Wind-waves", with wave periods < 5 seconds.

Waves-Paluma Shoals (Figures 7.1 to 7.4)

During the instrument deployment period wave directions were mostly toward the W and the SW (e.g. 0-200 & 200-400 hours). Wave conditions ranged between calm and stormy, with swell waves peaking at H_{sig} of 0.50 m (e.g. ca. hours 213) transitional waves at Hsig 0.50 m (e.g. ca. 225 hours) and wind-waves at H_{sig} 0.80 m (e.g. ca. 204-205 hours). Increased swell and wind-wave activity at Paluma Shoals is associated with periods of E to SE winds (e.g. hours 200-400) and winds from the NE (e.g. hours 400-430).

Periods of fluctuating wave spectra are produced by the seabreeze effect, whereby the moderate E-SE winds (morning) coincide with the dominance of swell waves because the wind-waves were absent, whereas during the afternoon the NE seabreeze produces wind waves (e.g. ca. 240 & 318 hours). This leads to a fluctuation between wind wave and swell waves because swell waves are dominant in the morning but their signal may be overprinted by wind waves during the afternoon and evening.

Waves - Phillips Reef (Figures 7.5 to 7.8)

These data from Phillips Reef indicate that most waves were directed towards the N. Wave conditions at Phillips Reef also ranged between calm and stormy, with swell waves peaking at H_{sig} of 0.30 m (ca. 282 hours) transitional waves at H_{sig} 1.0 m (e.g. ca. 203 hours). Wind waves, as defined above were always subordinate. These waves tend to have longer minimum wave periods (at ca. 5.2 seconds) compared to (ca. 4 seconds) Paluma Shoals (e.g. hours 250-300) *ie*. the lower limit of the wave period is higher. These shorter wave periods at Paluma Shoals may be related to the water depth (ca 3-6 m) *ie*. as shorter period waves approach the coast they interact with the sea-bed, reducing their height and energy.

Tides - Paluma Shoals and Phillips Reef (Figures 7.1 to 7.8)

These data cover two complete spring-neap tide cycles. The tidal cycle at Paluma Shoals and Phillips Reef is semi-diurnal with a diurnal inequality. Maximum tidal range at springs tides were 3.4 m at Paluma Shoals (ca. 51-57 hours) and 3.35 m at Phillips Reef (ca.. 51-57 hours). The tidal curve during neap tides is suppressed, with a maximum range of 0.6 m at Paluma Shoals and 0.4 m at Phillips Reef. (ca. 228-235 hours).

Tidal and Wind-Driven Currents - Paluma Shoals (Figures 7.1 to 7.4)

There is a strong tidal signal in the current direction data. At Paluma Shoals the flood tide currents are greater than the ebb. Current velocities during flooding spring tides were up to 20 cm/s (ca.. 50-51 hours). Currents generally move towards the W and NW during the flood tide, and during the ebb, the weaker current (mostly < 5 cm/s) flowed to the N then to the NE, *ie.* shore normal, away from the coast (Figure 7.9). Neap tides were associated with a NW-flowing current which moved parallel to Paluma Shoals, with current velocities primarily < 10 cm/s (e.g. hours 200-255). This current was associated with moderate winds from the E, SE and the NE (200-260 hours). Therefore, the currents during spring tides are dominated by tidal currents, whereas during neaps they have been influenced primarily by winds.

Tidal and Wind Driven Currents - Phillips Reef (Figures 7.5 to 7.8)

Current velocities from Phillips Reef had a strong tidal signal, with current velocities peaking at ca. 19 cm/s, coinciding with the flooding spring tides (ca. 38-40 hours). During neap tides current velocities were depressed, peaking at ca. 9 cm/s. Tidal currents at Phillips Reef were generally clockwise in nature rotating a full 360^0 (ca. 104-116 hours) whereby the tidal ellipse displays a clockwise rotary character "*ie.* the movement of a particular parcel of water will over time, describe a series of ellipses each described in a clockwise direction" (Larcombe & Ridd, 1993 p22). During neap tides currents were slow (<10 cm/s) and moved toward the N to the NE to E during high to low water. These current were associated with moderate E to SE winds (ca. 240-249hours).

7.3. Near-bed Turbidity - Paluma Shoals and Phillips Reef

Introduction

Turbidity values at Paluma Shoals are highly variable, with turbidity reaching a maximum of 175 NTU (ca., 204 hours) and a minimum of 10 NTU or less for up to 88 hours (400 to 488 hours). These turbidity values rise and fall rapidly and on occasion turbidity increased from <10 NTU to 100 NTU in only 3 hours (e.g. 20-23 hours). Turbidity values at Phillips Reef were less variable and lower in magnitude. Extended periods occurred where turbidity fluctuated between 8 and 10 NTU and maximum values were only 15 NTU (e.g. 200-400 hours).

Turbidity and hydrodynamic data have been delineated into periods of high and low turbidity "events" to examine the potential causes and differences of turbidity at Paluma Shoals and Phillips Reef (Table 7.1)

Event	Maximum NTU Paluma Shoals	Maximum NTU Phillips Reef	Cause Paluma Shoals	Cause Phillips Reef
A 20-80 hours	96 NTU	14 NTU	Transitional & wind-waves, shallow water & strong SE, E & NE winds. Sediments available for resuspension are mostly muddy sands.	Depth of water allows less wave energy to reach the sea-bed. No wind-waves were present. Tidal currents are important at Phillips Reef for sediment resuspension. Sediments available for resupension are gravelly muddy sands.
B 160-185 hours	175 NTU	14 NTU	Swell, transitional & wind- waves associsated with strong SE, E and NE winds & the shallow water depth. Transitional and Wind waves are more influential	As above Tidal currents
C 400-500 hours	12 NTU	14 NTU	H_{sig} of waves & low enrgy swell waves insufficent to resuspend sediment.calm-period.	As above Tidal currents

Table 7.1. *Summary of the of the main causes of turbidity, and difference in turbidity between Paluma Shoals and Phillips Reef for each of these identified turbidity events (Figures 7.1-7.8). Maximum turbidity values at Paluma Shoals are an order of magnitude greater than Phillips Reef and are only lower during low wave heights (e.g. 405-415 hours).*

Event A (hours-20 to 80. Figure 7.1)

At Paluma Shoals near-bed turbidity values during event A ranged from 3-96 NTU. The rapid rise in turbidity occurred ca. 7 hours after the onset of transitional and wind-waves with H_{sig} of up to 0.6 m. The increased wave height is associated with winds from the SE, E and the NE with wind velocities up to 8 m/s. Turbidity rapidly increased from 10 NTU 96 NTU in 3 hours during low tide and the flooding tide following the onset of the wind-waves (ca. 40 hours) turbidity values then decreased to ca. 50 NTU during high tide slack water (45 hours).

A change in wind direction from the S and a decrease in wind velocity (< 3m/s) are also associated with these diminished turbidity values. Turbidity then rapidly increased coincident with low water and the flooding tide (ca. 50-53 hours) winds from the SE, E and NE and an increase in the wave amplitude (transitional /swell waves). Turbidity then fell away during winds from the S and the subsequent lower amplitude wind-waves .

The turbidity peak at Paluma Shoals mirrors the onset of winds from the SE, E and NE winds which produced transitional and wind-waves (< 6 seconds). The lag of 7 hours between the onset of the wind waves and increased turbidity values may be the result of changes in water depth. There is a tidal signal in these turbidity data, with turbidity values increased at low tide and lower turbidity around high water. However, by themselves, tidal currents appear to have a minimal affect on near-bed turbidity because during periods of low wind-wave amplitude turbidity values are generally < 18 NTU. Therefore, raised turbidity values are primarily associated with waves, and shallow water at Paluma Shoals.

During the same survey period at Phillips Reef near-bed turbidity values ranged between 5 and 14 NTU. Anomalous turbidity values up to 1300 NTU (single data points only) were probably the effect of biofouling before instrument-self cleaning, or small fish and crustacea passing the nephelometer optics. Turbidity values rose from 10 to 14 NTU associated with tidal currents. Turbidity values rose on the flood tide and decreased at high tide slack water and on the ebb tide. The wave direction was toward the N and NW. The tidal currents rotated a full 360^0 during a tidal cycle N to N (ca. 104-116 hours) There is no apparent turbidity signal in these data.

There is an increase in the turbidity values at Phillips Reef during periods of the SE, E and NE winds and the subsequent transitional waves (ca. 2060 hours). However, the wind data are from Townsville Airport and therefore do not form a precise record for the reef itself. There is a tidal signal in these data irrespective of the waves, forming only minor fluctuations due to variations in the current velocities of the flood and ebb tides. However, turbidity values are an order of magnitude lower than those at Paluma Shoals. Therefore, the water depth at Phillips Reef (ca. 16 m) probably allows less wave energy reach the sea-bed and distribute sediment.

Event B (hours-180 to 270. Figures 7.1, 7.2, 7.3 & 7.4)

At Paluma Shoals near-bed turbidity values gradually increased from 2-175 NTU over a 29-hour period (ca. 180-210 hours) following the onset of winds from the SE, E and NE. These winds are also associated with the gradual rise in the H_{sig} of waves (swell, transitional and wind waves) from 0.18 m to a maximum of 0.8 m over the same duration (174-203 hours) and the occurrence of a NW-directed current. Wave direction was primarily towards the W and SW. There is a clear pattern between fluctuating turbidity values, changes in the wind direction, wind velocity and the subsequent period of higher waves. Higher turbidity values (up to 175 NTU) were coincident with increased wind velocities, longer wave periods and winds from the SE and E. Winds from the NE are coincident with wind-waves and rapid increases in turbidity values. Turbidity troughs are associated with reduced wind velocities from the S (ca. 218 Hours). These data suggest a similar scenario to Event A.

Near-bed turbidity values at Phillips Reef ranged between 9 and 14 NTU during Event B. Wave height increased from 0.15 m to 1.0 m in 29 hours associated with SE, E and NE winds. Waves were from the N with periods mostly < 5.5 seconds (transitional waves). Currents were slow (<10 cm/s) and flowed from the N to the E during the course of the neap tide (flood to ebb respectively) and are associated with moderate E to SE winds (e.g. ca. 228-233 hours).

There is a small tidal signal in these turbidity data however there is no discernible elevation in turbidity values associated with the occurrence of the wind-waves.

Event C (hours-400-500. Figures 7.3, 7.7)

At Paluma Shoals near-bed turbidity values during Event C were mostly < 10 NTU. Winds were from the N and NE with wind speeds up to 8 m/s but mostly < 5 m/s. The tidal elevation ranged between ca. 4 and 7 m with a distinct tidal signal in these current data. Flooding tidal currents flowed W and the ebb current to the NE (e.g. ca. 410-422 hours). The wave periods fluctuated between 4 and 7 seconds and H_{sig} remained < 0.20 m. Waves were towards the W to SW.

There is a distinct tidal signal in the turbidity data with turbidity maximums (12 NTU) at low water and minimums at high water (0-2 NTU). Significant wave heights during Event C were minimal (ca. 0.10 m) and wave periods are relatively long (up to 7.5 seconds) (e.g. 400-430 hours). Wind velocities from the NE and the N are low (mostly < 5 m/s) which may explain the absence of wind-waves. During these periods of low wind and transitional waves, turbidity values are up to an order of magnitude lower.

At Phillips Reef, turbidity values ranged from 4 to 14 NTU. Winds were from the N and NE with wind speeds up to 8 m/s but mostly < 5 m/s. Currents ranged between 10 and 22 cm/s. The currents rotate a full 360^0. Waves were low with H_{sig} of < 0.15 m and were from the N and NW. Wave periods ranged between 5.5 and 7.5 seconds. There is a distinct tidal signal in these turbidity data with turbidity maximums at low tide and troughs associated with high water. There is no apparent resuspension of sediment associated with waves.

7.4. Summary

- Maximum turbidity values were an order of magnitude greater at Paluma Shoals (175 NTU) than Phillips Reef (15 NTU) and generally were higher.
- Strong winds from the SE, E and NE were associated with swell, transitional and wind-waves and an increase in the wave height (H_{sig}) at Paluma Shoals and Phillips Reef. However, wind-waves were subordinate at Phillips Reef.
- Most winds are associated with the formation of a NW-moving residual current at Paluma Shoals.
- Winds from the SE and E were associated with swell waves and increases in turbidity values up to 175 NTU at Paluma Shoals.
- Winds from the NE were associated with wind-waves, which increase in height rapidly due to their local generation. These winds were associated with turbidity values up to 100 NTU at Paluma Shoals.
- These data suggest that even low amplitude wind-wave events resuspend sediment at Paluma Shoals, but not at Phillips Reef because of the greater depth there.
- There is a distinct tidal signal in these turbidity data from Paluma Shoals and Phillips Reef, with higher turbidities associated with the flooding tide and low water. However, by themselves, tidal currents have minimal effects on turbidity.

7.4. Sediment Availability and Transport

Paluma Shoals and Phillips Reef are influenced by the same regional hydrodynamic processes because they are only separated by ca. 12km, so more local hydrodynamic factors (including water depth) may be important in influencing the energy available to mobilise sediment. Therefore, if sediments require more energy to be resuspended because of grain size characteristics, *ie*. gravels and sands compared to muds, then the availability of sediment for resuspension may be reduced. However, once in suspension, transport processes residual currents will be important factors in the distribution of these sediments.

The surfical sediment sediments seaward of Paluma Shoals are predominately muddy sands, sandy muds and gravelly muddy sands (Figure 7.9) and on the reef top itself muddy sands and sandy muds. Therefore, there is a large source of fine-grained sediment (*ie.* silts and clays) available for resuspension during swell, transitional and wind-wave events. The surficial sediments surrounding Phillips Reef are mostly gravelly muddy sands (Figure 7.9) and there is less fine-grained sediment available for mobilisation at Phillips Reef and this may partly cause the lower turbidity values.

After resuspension by waves moving toward W-SW, sediment transport is influenced by wind-driven and tidal currents. At Paluma Shoals currents flowed toward the NW up to 20 cm/s during the flooding tide, enhancing the turbidity values. Current movements were toward the N and NE or away from the shoals during the weaker velocity ebb tides. During neaps, the tidal signal in these current data were suppressed and currents flowed toward the NW (Figure 7.9). These currents are associated with winds from the SE to E. Therefore suspended sediment is moved onshore by waves and transported predominately toward the NW by a resdual current which flows parallel to the seaward edge of the shoals.

During flooding tides silts and clays may be moved landward into Sleeper Log and Two Mile creeks, to settle during high water. The well-sorted nature of the intertidal sand adjacent to Paluma Shoals suggests that little or no mud is being deposited between the beach barrier and the reefs. However, settling of sediment does occur on the reef top and corals (Chapter 6). These reefs may act as a sediment sinks for the finer-grained sediments due of the presence of turfing algae (*Pandia* sp.) which entrap sediment (Purcell, 1996). The formation of eddys behind coral heads and bombies may assist in trapping sediment. This is probably not happening on a large scale because the corals at Paluma Shoals would now be swamped by sediment. These sediments are probably resuspended at low tide by wave action. During the lower velocity ebb tide some sediment may be transported offshore for short distances before settling on the low tide. The NW directed current combined with the N and NE movement of the ebb tide may inhibit sediment settlement on the shoals.

Currents at Phillips Reef are generally clockwise in nature during spring tides, and flow toward the N, NE and E during neaps. Wave direction was toward the N. There is a tidal signal in these turbidity data with turbidity values increased at low tide and the flooding tide but reduced at high tide and the ebb. Because these currents rotate about an ellipse sediment transport may be limited.

The variations in near-bed turbidity were therefore a function of surficial sediment distribution, wind direction and hydrodynamics. At Paluma Shoals the complex interaction between these processes results in raised turbidity but limited sediment settling. These processes at Phillips Reef culminate in low turbidity values and therefore limited sediment resuspension and transport.

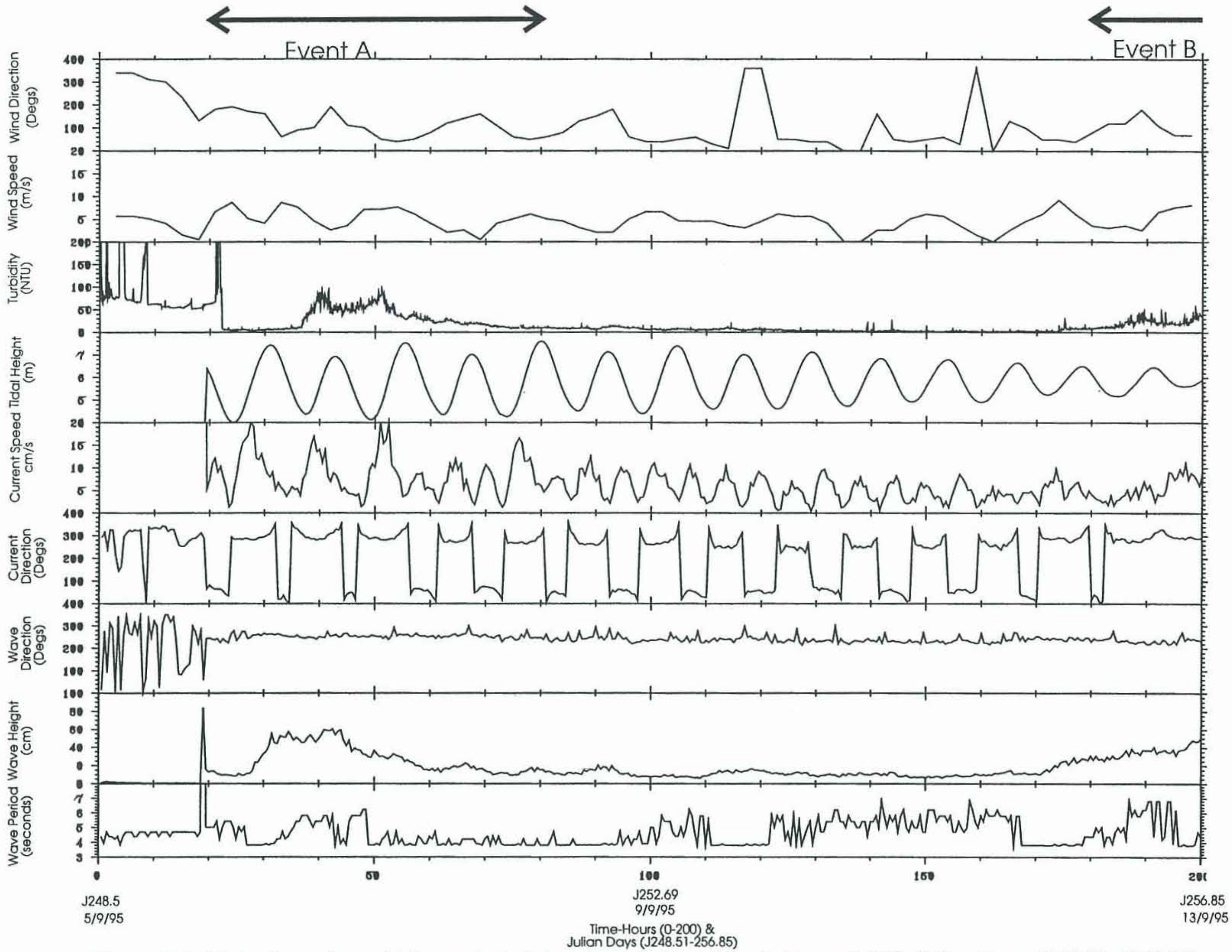

Figure 7.1. *Hydrodynamic, turbidity and wind data from Paluma Shoals (hours 0-200, Julian Days J248.51-J256.85).*

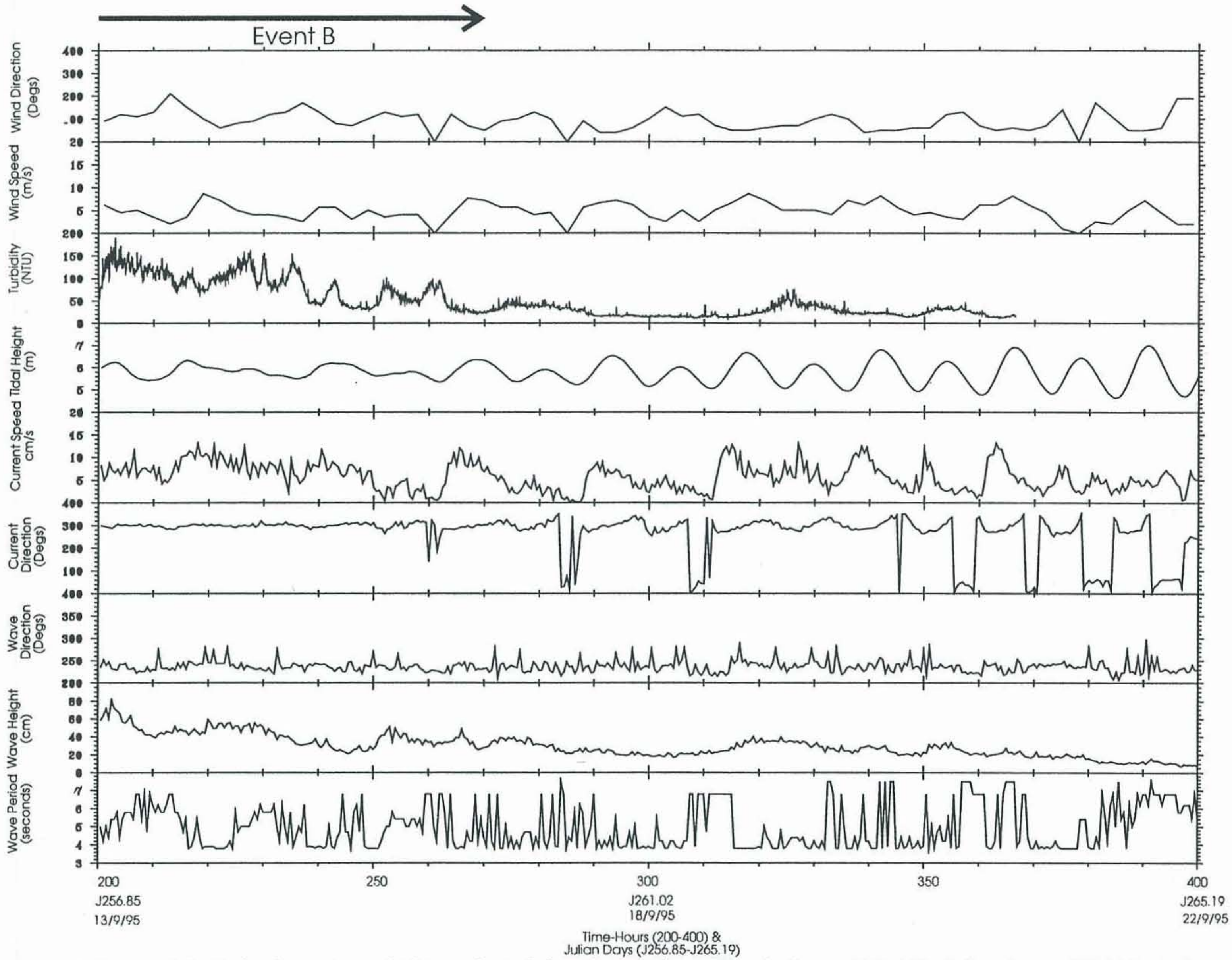

Figure 7.2. *Hydrodynamic, turbidity and wind data from Paluma Shoals (hours 200-400, Julian Days J256.85-J265.19).*

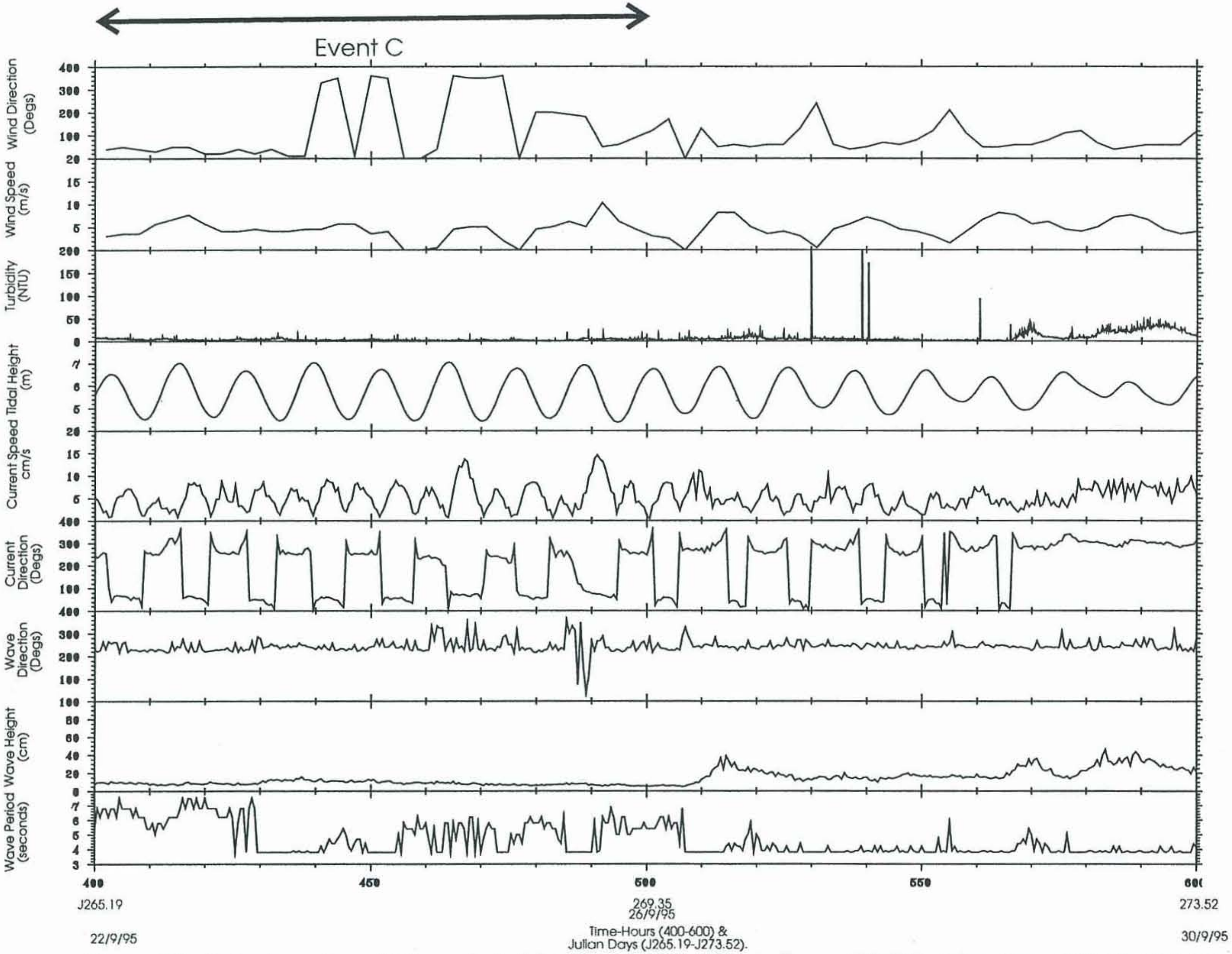

Figure 7.3. *Hydrodynamic, turbidity and wind data from Paluma Shoals (hours 400-600, Julian Days J265.19-J273.52).*

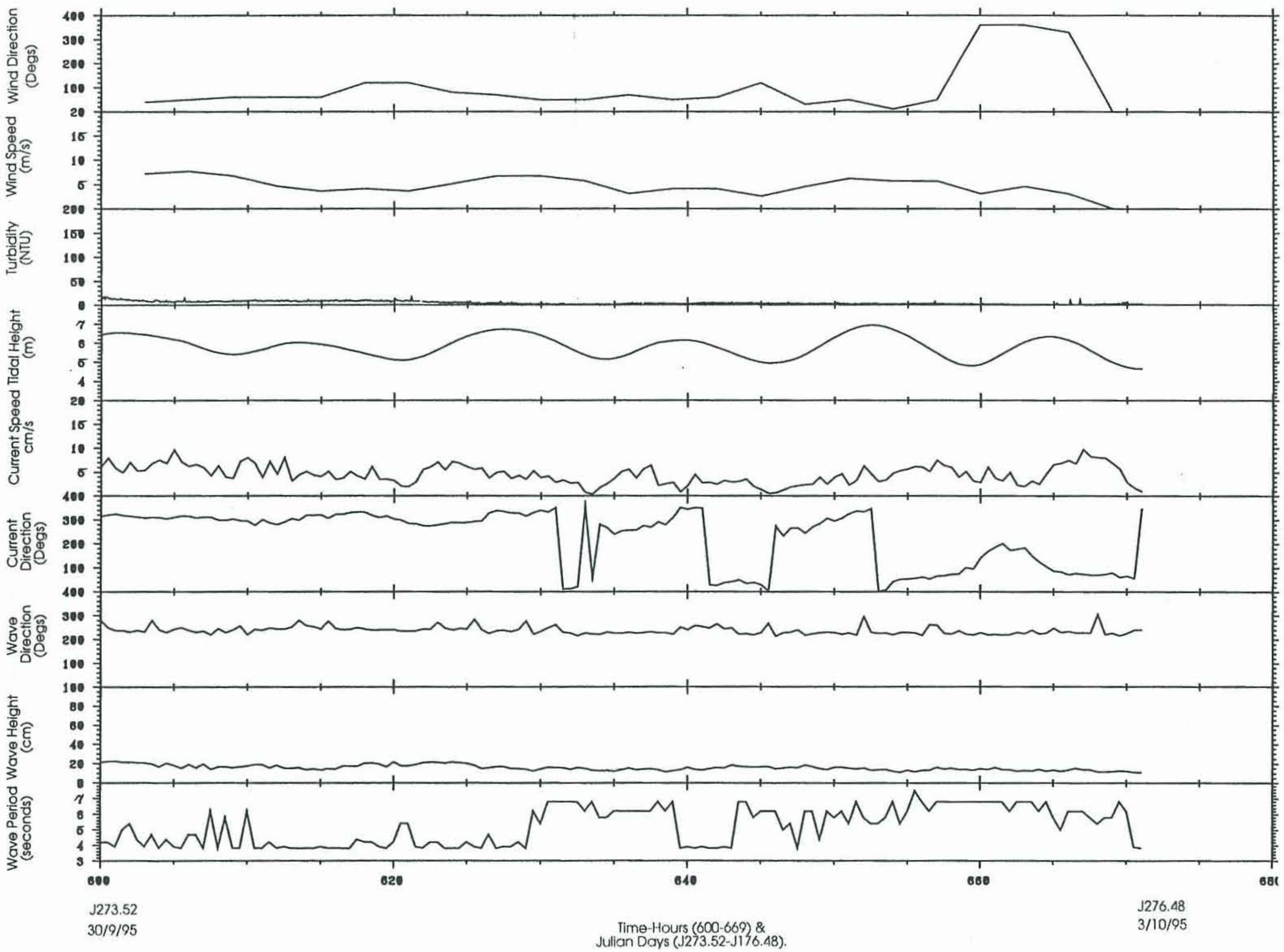

Figure 7.4. *Hydrodynamic, turbidity and wind data from Paluma Shoals. Note different X axis scale than previous (hours 600-669, Julian Days J273.52-J276.48).*

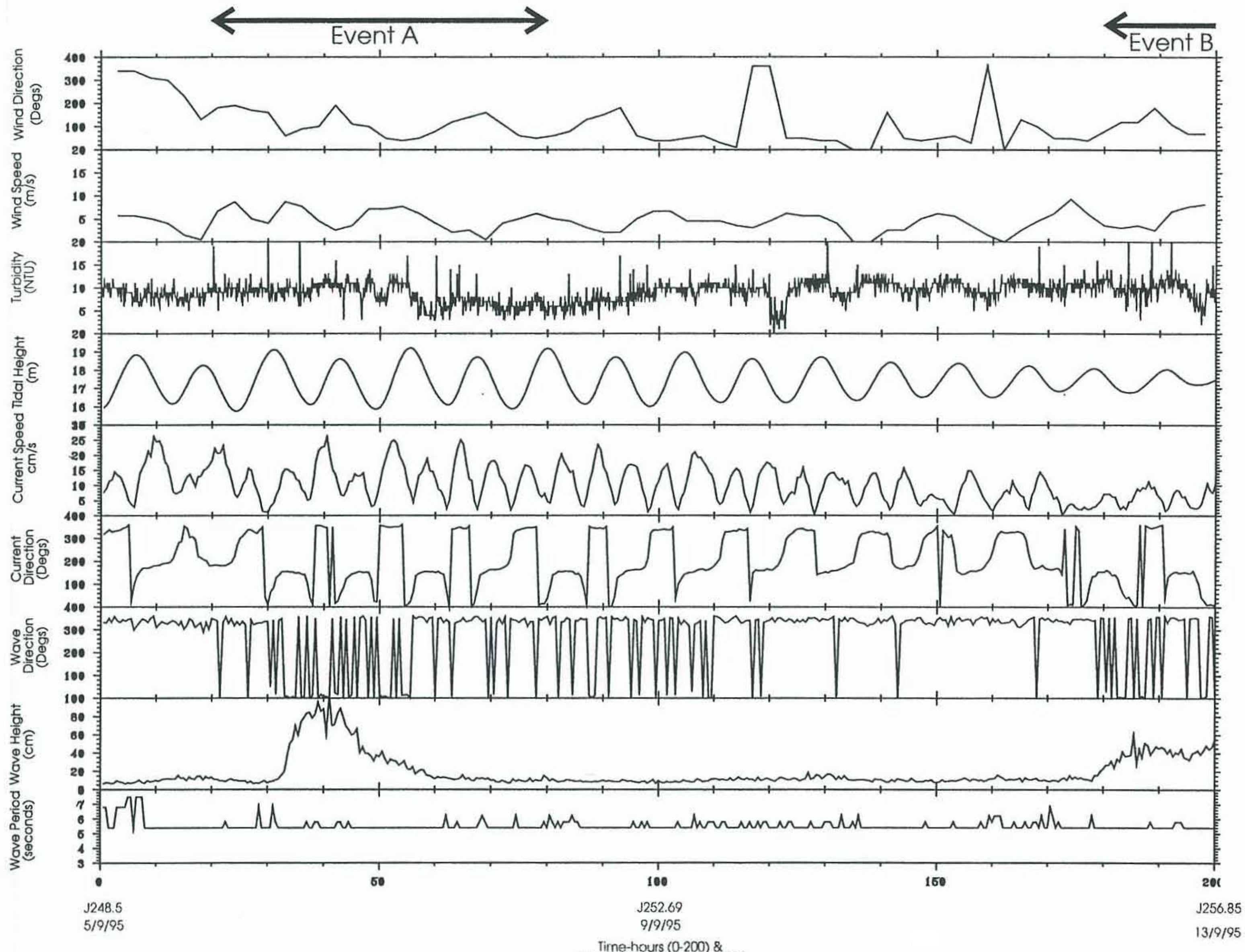

Figure 7.5. *Hydrodynamic, turbidity and wind data from Phillips Reef (hours 0-200, Julian Days J248.51-J256.85).*

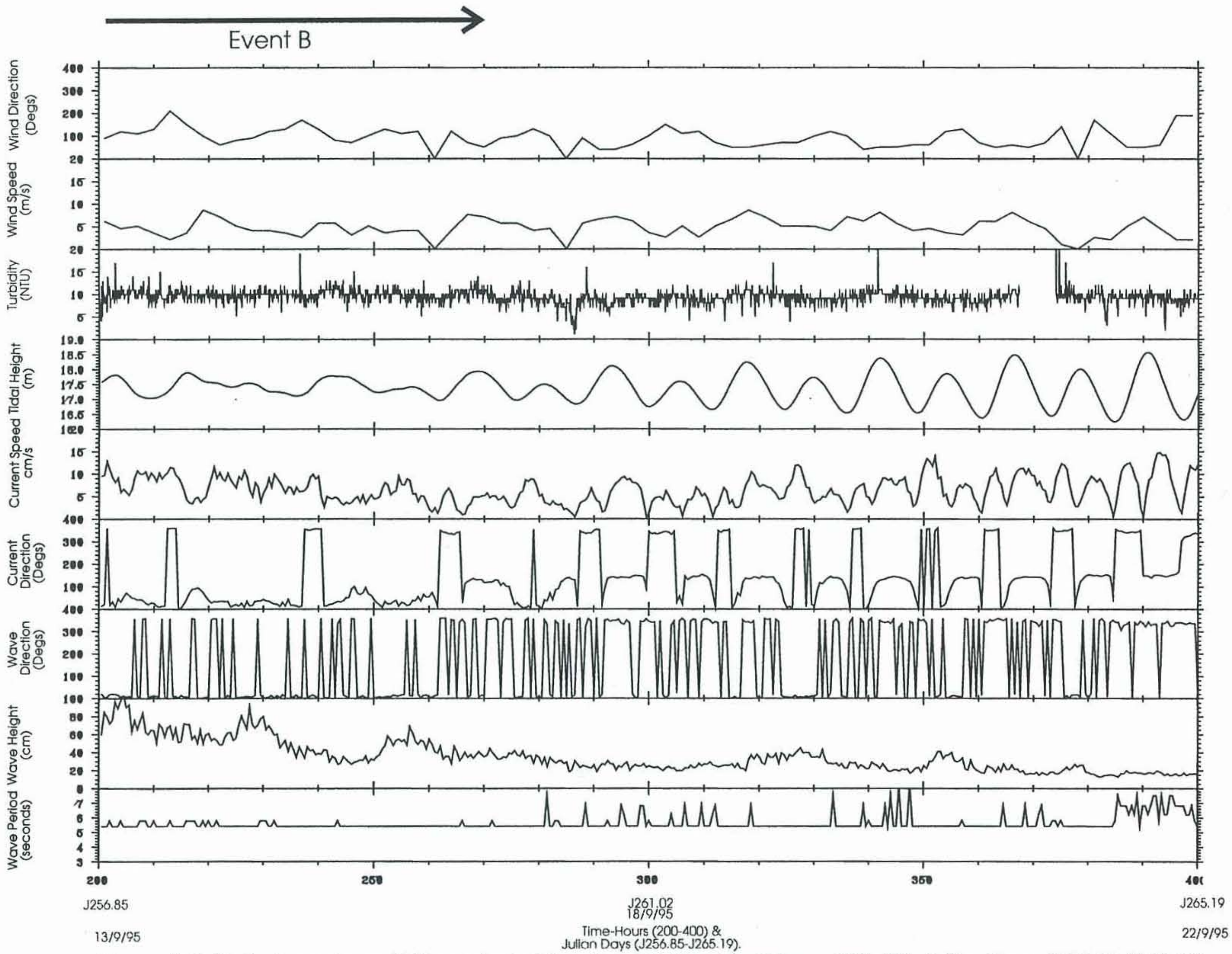

Figure 7.6. *Hydrodynamic, turbidity and wind data from Phillips Reef (hours 200-400. Julian Days J256.19-J265.19).*

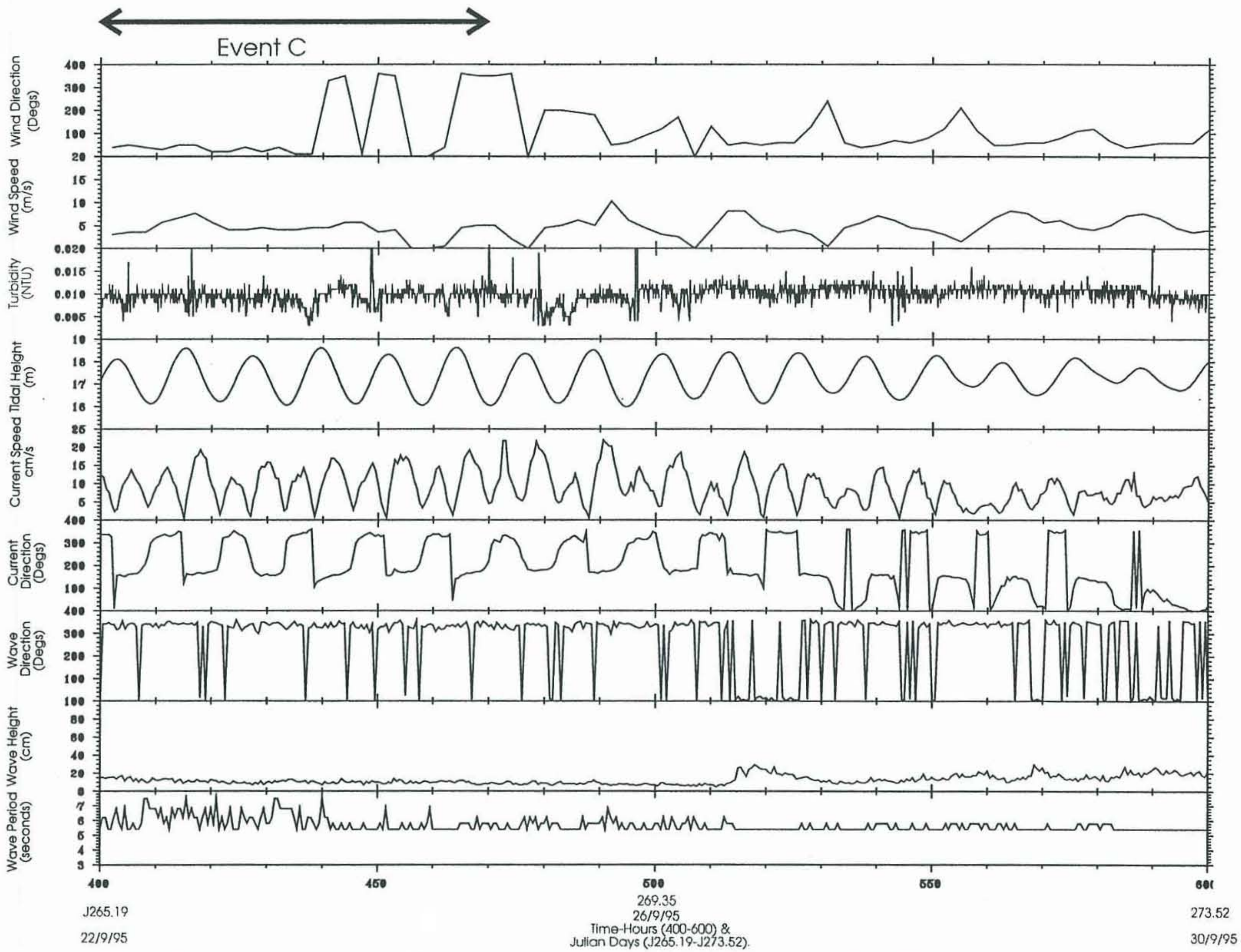

Figure 7.7. *Hydrodynamic, turbidity and wind data from Phillips Reef (hours 400-600. Julian Days J265.19-J273.52).*

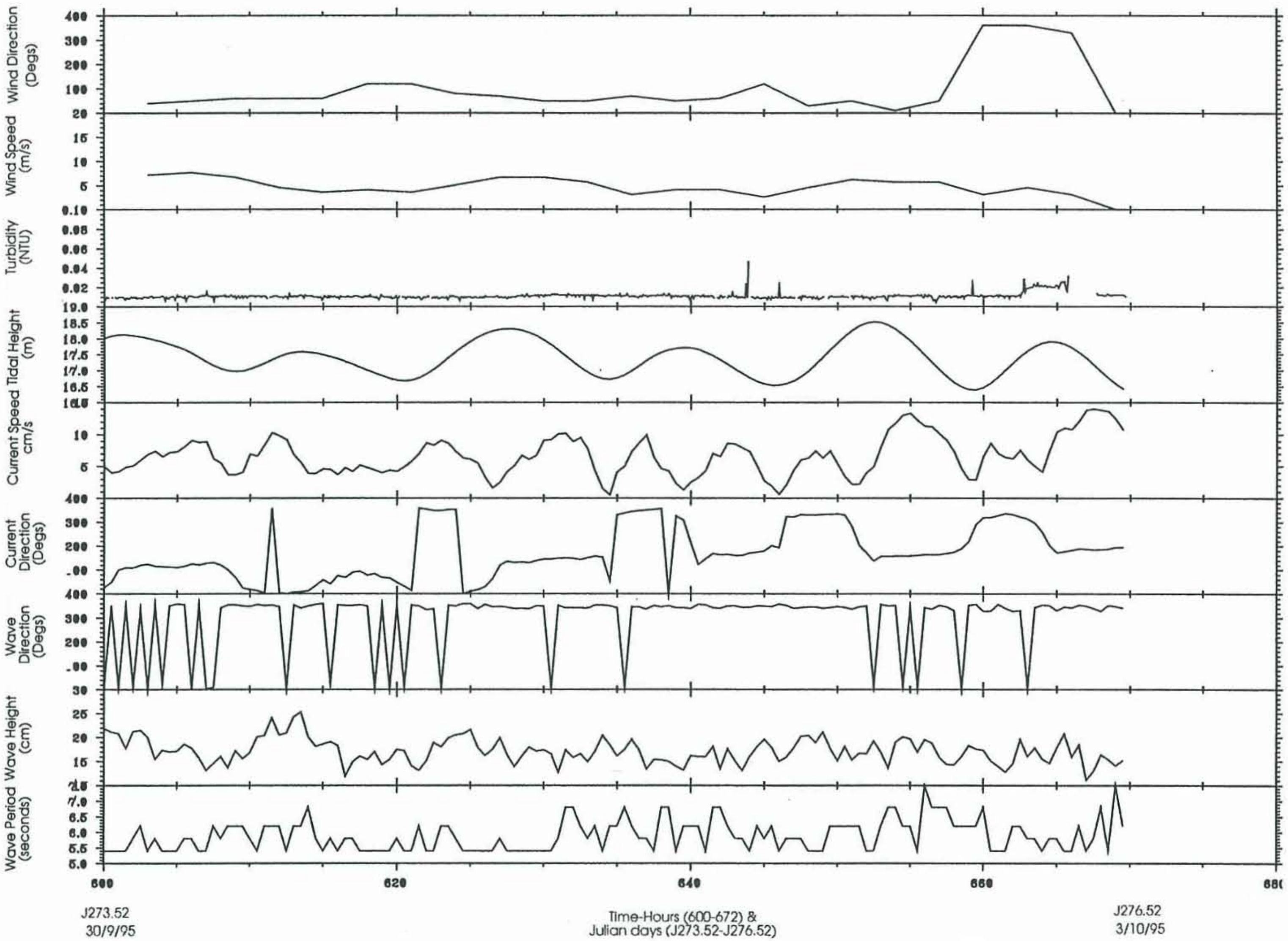

Figure 7.8. *Hydrodynamic, turbidity and wind data from Phillips Reef (hours 600-672, Julian Days J273.52-J276.52).*

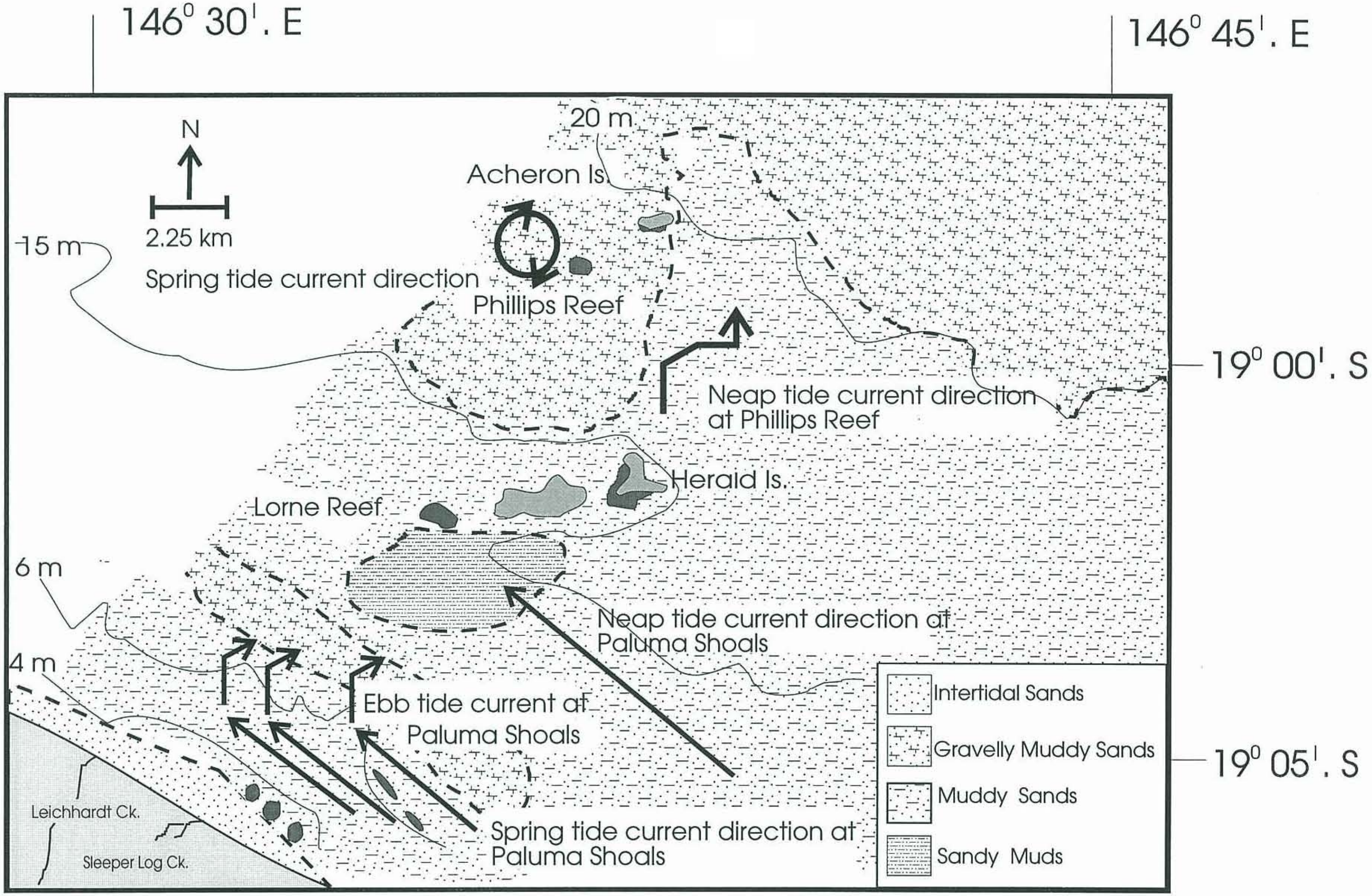

Figure 7.9._Surficial sediment distibution of the inner-shelf of southern Halifax Bay and tidal current directions. SE, E and NE winds are associated with these currents. Note the different current directions and surface sediments at both reefs._

Chapter 8.0. Discussion and Conclusions

8.1. Introduction

Taxonomic, seismic, vibrocore stratigraphy, surficial sedimentology, turbidity and hydrodynamic data were collected from Paluma Shoals and Phillips Reef located in Halifax Bay, Central Great Barrier Reef, Australia. These data sets were compiled to detail the sedimentary, hydrodynamic and turbidity regimes surrounding these two coral reefs. The aims of collecting these data were:

1. To examine, identify and compare the turbidity regimes and the hydrodynamic processes at Paluma Shoals and Phillips Reef.
2. To examine, identify and compare the sediment distribution patterns adjacent to Paluma Shoals and Phillips Reef; and,
3. To identify the potential causes of differences in turbidity values (NTU) between Paluma Shoals and Phillips Reef.

The conclusions of these three aims are presented in section 8.5.

Three main implications arose from the collection and collation of the data set, they include:

1. The corals at Paluma Shoals exist in water conditions widely inferred within the literature as being detrimental to coral growth and distribution;
2. "Turbid water reefs" such as Paluma Shoals are potentially common and are healthy diverse populations.
3. That during coral reef initiation (c.a. 6.8 ky B.P.) sediment dynamic, hydrodynamic and therefore turbidity regimes may have been similar to those of today.

8.2 Implication 1: The corals at Paluma Shoals exist in water conditions widely inferred within the literature as being detrimental to coral growth and distribution

Several workers have attempted to detail the degree of impact associated with turbidity on coral growth and distribution (Rogers, 1979; Pastorock and Bilyard, 1985; Cortes & Risk; and Stafford Smith, 1992). Attempts to document the threshold tolerance levels of corals to sediment accumulation and turbidity may have proved difficult because:

- There are substantial intra-specific differences in the behavioural responses of corals to turbidity (Stafford-Smith, 1992) *ie.* some species are better adapted to turbid conditions than others.
- Research has been primarily based on post-mortum studies, and involved clearly defined experimental parameters (Hubbard, 1988).
- The temporal and spatial variation in local and regional hydrodynamic, sedimentary and geological environments of many reefs are different (Woolfe & Larcombe, 1996).
- Studies have been short-term and of limited scope, capable of documenting impacts at a given point in time, and thus incapable of relating changes in the level of impact to natural variations in the environment (Rogers, 1990).
- Prior to the development of instruments capable of collecting high resolution time-series data, collection methods provided little information on temporal changes in near-bed turbidity and hydrodynamic processes (Larcombe & Ridd, 1993).

The levels of turbidity experienced by the corals at Paluma Shoals do appear to be higher than those sighted in widely referenced studies. For example, Cortes and Risk (1985) documented the effects of a reef under stress (summarised Table 8.1), and published turbidity threshold levels which were inferred to induce a range of organism responses. They noted that "high concentrations (>5 mg/l^{-1}) of suspended particle matter will result in stress to the coral community". These data appear to be in contrast to that collected from Paluma Shoals because these corals are subjected to turbidity levels of up to 175 mg/l^{-1} (maximum), and yet appear to be a healthy population.

Cortes and Risk (1985) suggest that high concentrations of resuspended sediment (>30mg-cm^{2}day^{-1}) may be deleterious to a coral community. Data from Magnetic Island suggests that the fringing reefs of the island are exposed to resuspended sediment loads of 120mg-cm^{2}day^{-1} (Hopley and Van Woesik, 1988). Hoyal (1986) estimated resuspended sediment loads (averaged over a seven months) at Cape Tribulation reefs to be 112mg-cm^{2}day^{-1}. These examples suggest that the corals inhabiting the near-shore waters of the central and northern GBR coastline experience water conditions well outside those published as detrimental to coral growth and diversity.

The Cape Tribulation reefs display the highest species diversity of corals on the GBR with a record 141 species (Vernon, 1987). Based on x-radiograph studies, *Porities* sp. corals from near-shore fringing reefs display growth rates of >10mm year compared to >7mm year for outer shelf reef corals (Hopley and Van Woesik, 1988). Cortes and Risk (1985) also suggest that low live coral cover and low coral recruitment may result from high resuspended loads. At Paluma Shoals .the live coral cover of 28-54%, and the presence of juveniles (indicating recruitment), is suggestive of a healthy and diverse population. The implications of these comparisons are that the threshold tolerance levels of corals to turbidity have not yet been established and therefore the significance of such thresholds are questionable.

8.3. Implication 2 - "Turbid water reefs" such as Paluma Shoals are potentially common.

Numerous workers note that a basic requirement in the development of coral reefs is the presence of a hard, immobile substrate upon which coral larvae can initiate (Hopley & Partain, 1986; Fisk & Harriot, 1989; Babacock & Davies, 1991). The corals at Paluma Shoals are developed upon a stable Pleistocene gravel substrate of unlithified granitic and volcanic clasts. The morphology of these reefs and the distribution of these corals appears to be related to the availability of the underlying substrate. These Pleistocene gravels appear common along the coast of Halifax Bay and there is documentation of other reefs established within the coastal boundary layer, including Lady Elliot Reef and Cattle Creek. At Paluma Shoals the regional and local hydrodynamic, and sediment dynamic regimes combine to produce turbid water conditions but which keep them largely swept of accumulating sediment. Because of their close proximity similar conditions may exist on Lady Elliot and Cattle Creek reefs. Therefore, the conditions at Paluma Shoals may not be unique and 'turbid water reefs' may indeed be common.

Proposed features of a reef under stress according to Cortes and Risk (1985).	Contradictory evidence from the Great Barrier Reef, Australia.
1. High concentrations of suspended particle matter (> 5 mgl^{-1} ca. 5 NTU).	1. Paluma Shoals 175 NTU (max) 100 NTU for extended periods (days). • Magnetic Island, SSC of up to 115 mgl^{-1} (Hopley and van Woesik, 1988). • Cape Tribulation Fringing Reefs, SSC of up to 120 mgl^{-1} (Hopley & van Woesik, 1988).
2. High concentrations of resuspended sediment (> 30 mg $^{-2}$ day^{-1}).	2. Magnetic Island, 120 mg cm^{-2} day^{-1} (Hopley & van Woesik, 1988). • Cape Tribulation, 112 mg^{-2} day^{-1} Averaged over a 7 month period (Hoyal, 1986).
3. Large amounts of terrigenous material trapped in coral skeletons.	3. Muddy reefal limestone's occur throughout the geologic record e.g. Devonian Tor Bay & Plymouth Reef complexes, England (Burchette, 1981),Western Slovenia-Triassic(Car et al), Vicetin, NE Italy-Oligocene (Frost, 1981). • Modern Cape Tribulation Reef sediments contain >50% terrigenous material (Johnson and Carter, 1987).
4. Reduced coral growth rates and species diversity.	4. Cape Tribulation reefs have the highest diversity of corals on the GBR 141 species, 3 not recorded elsewhere on the GBR (Vernon, 1987), with hard coral cover much higher than 'outer' reefs. Palm Islands-more species have been recorded here than anywhere else in the world (Hopley and van Woesik,1988). • Based on x-radiograph studies of *Porites,* inshore-fringing reefs have the fastest growth rates (>10mm/yr) compared to offshore reefs (<7mm/yr) (Hopley and van Woesik, 1988).
5. Low live coral coverage except for monospecific stands of siltation tolerant species.	5. Paluma Shoals-28-54% live coral cover.
6. Morphology changes in surviving coral species.	6. Some compression of the biotic zone is present due to depth (Ayling & Ayling, 1987).
Size distributions of corals shifted towards larger colonies indicating low recruitment.	• Cape Tribulation- No reduction in recruitment(Fisk et al, 1989). 7. Juveniles are present at Paluma shoals indicting coral recruitment.

1. **Table 8.1.** *The proposed features of a reef under stress according to Cortes and Risk (1985). Note the differences in suspended sediment concentrations between the figures presented by Cortes and Risk and those from the GBR. (Modified from Cortes & Risk, 1985)*

8.4. Implication 3 - During coral reef initiation (c.a. 6.8 ky B.P.) sediment dynamic, hydrodynamic and turbidity regimes may have been similar to those of today.

The corals at Paluma Shoals appear to be adapted to the periodic inundation of highly turbid water and episodic sediment accumulation associated with swell and windwave events and riverine discharge (flooding). The possible implications of these modern environmental data suggest that reef growth may not only persist in these "highly turbid" conditions, but may also have initiated under similar hydrodynamic and turbidity regimes and may provide a modern analogue to reef initiation of the entire GBR system.

Prior to the Holocene transgression (>10.5 ky B.P), Reflector A was exposed and the 'Pleistocene gravel deposits' which form the Paluma Shoals reef substrate were located ca. 30 km inland on the late Pleistocene to early-Holocene coastal plain (Hopley & Murtha, 1975; Larcombe et al., 1995). With post-glacial sea-level rise (ca .10.5 ky B.P) the Holocene coastline began to retreat. During the transgression (8.5-5ky B.P) the deposition of the mud flat, channel fill and mangrove facies upon the Pleistocene acoustic basement would have occurred, forming a mangrove dominated coastline. As sea level continued to rise the marine bay fill facies (seismic facies T_1) formed a thin veneer of modern marine sediment over the relict mangrove (seismic facies T_2) and channel fill deposits (Seismic facies Ch_1, Ch_2,& Ch_3). Cater, *et al*., (1993) notes that since ca. 5.7ky B.P. 4m of the terrigenous dominated bay fill facies has accumulated within Cleveland Bay. Vibrocore data from this study suggests that 1.7m of bay fill sediment has accumulated since sea-level stasis.

Using the Larcombe *et al* (1995) sea level curve it can be calculated that the maximum age of Paluma Shoals is ca. 6.8ky. Therefore, assuming regional winds and hydrodynamics were similar to the modern regime, the turbidity values of inner-shelf Halifax Bay would have been similar during the transgression to those of modern water conditions. This suggests that coral reefs which underwent initiation on the modern outer-shelf during the transgression did so in sedimentary, hydrodynamic and turbidity regimes similar to those presently experienced by Paluma Shoals. Paluma Shoals and possibly other inner- shelf reefs may form modern analogues to reefs that underwent initiation 8.5-5ky B.P.

8.5. Conclusions

Taxonomic Evaluation

- The corals at Paluma Shoals experience water conditions outside the known "established" tolerance levels for turbidity.
- Paluma Shoals are a series of five near-shore patch reefs located in ca. 2.5-6m of water within the inner-shelf terrestrial sediment wedge of southern Halifax Bay, Central Great Barrier Reef. The reefs are developed upon a stable Pleistocene gravel substrate of unlithified granitic clasts. The highly mobile muddy sands deposited between the patch reefs possibly inhibit further coral recruitment and lateral reef development.
- Phillips Reef is a single patch reef situated. 15km north of Paluma Shoals at a depth of ca. 16m. Done (1992) describes Phillips Reef as a shingle-covered reef developed upon submerged Permo-Carboniferous granite.
- The taxonomic survey (Watson, 1996) of Paluma Shoals indicated that total coral cover on the leeward reef flat (53.4±3%) was almost twice that of the windward reef flat (27.9±3.3%). The presence of juveniles was also detected at both the leeward and windward reef flats. The presence of juveniles (<5cm) suggests that coral recruitment is occurring. These data suggest that the corals at Paluma Shoals are part of a healthy diverse population.

Seismic and Vibrocore Stratigraphy

- From 79 km of high resolution seismic images, eight seismic facies were identified within the study area. These facies are consistent with those identified by previous investigations. Of the eight facies identified, four are considered post-glacial, two are inferred as Pleistocene to early post-glacial and two are Pleistocene deposits. A bay-wide, shallow, laterally extensive sub-surface reflector has been identified as Reflector A (as defined by Johnson *et al.*, 1982). These facies include:
  1. **Reflector A -** Within the study area Reflector A is identified as a strong irregular reflector, sub-parallel to the modern sea floor. It is defined as the first non-marine to marine disconformity intersected beneath marine post-glacial sediments.
  2. **Facies T4 -** The Pleistocene acoustic basement which underlies all other Pleistocene and post-glacial sediments.
  3. **Channel deposits Ch1, Ch2 and Ch3 -** These sediments form the fill of the incised Pleistocene surface and are interpreted as fluvial and/or estuarine fill deposited during sea-level rise and/or channel abandonment.

4. **Facies T2** - A homogeneous acoustically transparent seismic facies that commonly drapes or fills underly*ing* topography. These sediments are interpreted as mangrove and/or coastal plain sediments deposited in the intertidal zone of Halifax Bay during the Holocene transgression.
5. **Facies T1** - A laterally extensive acoustically transparent uniformly dipping facies which tins both in a shoreward and seaward direction. This facies forms the modern bay-fill.
6. **Facies P1** - A prolonged continuos reflector with a slight hummocky or undulating surface which forms irregular and steep sided mounds and platforms. Interpreted as modern reef growth.

Seven vibrocores were collected to ground truth the seismic profiles. Four post-glacial facies were identified on he basis of grain size, stratigraphic relationship and mineralogy. These are:

1. Marine bay fill - This facies is typically comprised of olive grey, poorly sorted bioturbated muddy sand and sandy mud. The marine bay fill facies represents modern marine sedimentation and overlies all other post-glacial sediments.
2. Mud flat facies - This facies is comprised of a dark grey massive micaceous sandy mud with shell fragments and organic rich fine grained lamina. Stratigraphic and lithological data suggests that these sediments represent mud flat deposits.
3. Channel fill facies - This facies was described in vibrocores which penetrated nested channel deposited identified from seismic profiles. The deposits are composed of a massive dark grey bioturbated sandy mud, interbedded with 1-30mm thick layers of well sorted sub-angular to sub-rounded fine sand. These sediments may represent abandoned channels.
4. Mangrove facies - This facies is comprised of stiff massive dark grey mud with minor wood fragments and yellow grey oxidised muddy sand patches. These sediments are analogous with those from modern mangroves and are thus interpreted as being deposited in a mangrove system.

Surficial Sedimentology

- A total of 135 surficial sediment samples were collected from the study area. Based upon field and laboratory observations and high-resolution laser diffraction grain size analysis the study area has been divided into marine inner-shelf and coastal facies assemblages.
- The coastal facies assemblage includes:

1. Pleistocene gravel deposits;
2. Intertidal sand flats
3. Intertidal sand bars and beach barrier complex; and,
4. Mangrove and tidal channels.

- The marine inner-shelf facies assemblage includes:
  1. The modern bay fill comprised of sandy muds, muddy sands and gravelly muddy sands;
  2. Coral reef sediments.
- Entropy analysis of grain size distributions from 58 inner-shelf and coastal sediment samples resulted in statistical clusters which were visually discrete. Seven entropy groups were defined and high resolution grain size maps compiled. High resolution grain size mapping of the inner-shelf of Halifax Bay was successful in. producing a map which mirrored the distribution of the surficial sediment facies assemblage.
- The surficial sediment seaward of Paluma Shoals are predominantly muddy sand, sandy mud and gravelly muddy sand and on the reef top, muddy sand and sandy mud. Therefore, there is a large source of fine grained sediment available for resuspension.
- The surficial sediments surrounding Phillips Reef are mostly gravelly muddy sand. Therefore, there is less fine grained sediment available for mobilisation.

Turbidity and Hydrodynamics

- A total of 1340 hours of continuous high resolution time-series hydrodynamic and turbidity data were recorded at Paluma Shoals (671 hours) and Phillips Reef (669 hours) between Julian days 248 and 276 (1995).
- Maximum turbidity values were an order of magnitude greater at Paluma Shoals (175 NTU) than Phillips Reef (15 NTU) and generally were higher.
- Strong winds from the SE, E and NE were associated with swell, transitional and wind-waves and an increase in the wave height (H_{sig}) at Paluma Shoals and Phillips Reef. However, wind-waves were subordinate at Phillips Reef.
- Winds were associated with the formation of a NW-moving residual current at Paluma Shoals.
- Winds from the SE and E were associated with swell waves and increases in turbidity values up to 175 NTU at Paluma Shoals.

- Winds from the NE were associated with wind-waves which increase in height rapidly due to their local generation. These winds were associated with turbidity values up to 100 NTU at Paluma Shoals.
- These data suggest that low amplitude wind-wave events resuspend sediment at Paluma Shoals but not at Phillips Reef.
- There is a distinct tidal signal in these turbidity data from Paluma Shoals and Phillips Reef with higher turgidities associated with the flooding tide and low water. However, by themselves, tidal currents have minimal effects on turbidity values.
- These data suggest that Paluma Shoals and Phillips Reef are influenced by the same regional hydrodynamic processes. Therefore the variations in near bed turbidity values at Paluma Shoals and Phillips Reef are a function of local surficial sediment distribution, wind direction and hydrodynamics. At Paluma Shoals the complex interaction between these processes results in high turbidity values but limited sediment settling. At Phillips Reef the limited sediment resuspension and transport (low NTU values) may be attributed to the reefs depth and coarse grained nature of the surface sediments.