Sedimentary Processes and the Pandora Wreck, Great Barrier Reef, Australia

Ingrid A. K. Ward; Piers Larcombe; Richard Brinkman; Robert M. Carter

Journal of Field Archaeology, Vol. 26, No. 1 (Spring, 1999), 41-53.

Stable URL:
http://links.jstor.org/sici?sici=0093-4690%28199921%2926%3A1%3C41%3ASPATPW%3E2.0.CO%3B2-Z

Journal of Field Archaeology is currently published by Boston University.

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at http://www.jstor.org/about/terms.html. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at http://www.jstor.org/journals/boston.html.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is an independent not-for-profit organization dedicated to creating and preserving a digital archive of scholarly journals. For more information regarding JSTOR, please contact support@jstor.org.

http://www.jstor.org/
Mon Oct 10 00:17:58 2005

Sedimentary Processes and the *Pandora* Wreck, Great Barrier Reef, Australia

Ingrid A. K. Ward
Piers Larcombe
James Cook University
Townsville, Queensland

Richard Brinkman
Australian Institute of Marine Science
Townsville, Queensland

Robert M. Carter
James Cook University
Townsville, Queensland

The hydrodynamic and sedimentary processes at the seabed are particularly relevant to wreck formation processes. In conjunction with archaeological work in 1997, seismic and sediment surveys were undertaken around the wreck site of the H.M.S. Pandora *(1791), on the eastern edge of the Great Barrier Reef, northern Australia. Further, wave and current meters were deployed at the wreck site for a one-month period in order to characterize the local hydrodynamic regime.*

At the Pandora *wreck site, tides occur twice daily, and have a stronger ebb tide than flood. The wreck is buried in sediments dominated by the remains of calcareous algae and foraminifera, and laboratory experiments on these sediments indicate that appreciable transport of sediment occurs at the site under the influence of large spring tides. Sedimentation is controlled by tidal and other unidirectional currents, except during major storm events when waves become important. Wreck disintegration can be considered using a model which relates the rate of wreck disintegration to sediment accumulation or removal. It is likely that the* Pandora *has undergone several episodes of burial and exposure, although further evidence is required to establish long-term cycles.*

Introduction

The earliest European navigation of the Great Barrier Reef (GBR) by James Cook (ca. 1770) revealed the dangers of a region strewn with extensive and uncharted coral reefs. Captain Edward Edwards was to discover these dangers when on 28 August 1791 his ship H.M.S. *Pandora*, which had been commissioned to recapture the mutineers of H.M.S. *Bounty*, ran aground on a submerged reef in what is now known as the Pandora Entrance on the eastern edge of the GBR (FIG. 1). The *Pandora* sank the following day in ca. 30 m of water, at 11°22′S 143°59′E, where it remained undiscovered until 16 November 1977. Because of its location in relatively deep waters, the *Pandora* is one of Australia's better preserved shipwrecks and extensive archaeological excavations have revealed details of the British warship and of its travels to various Pacific islands in the 18th century (Gesner 1991). Details are given in various publications of the Queensland Museum (e.g., Gesner 1988, 1993) who were delegated responsibility for excavation and documentation of the *Pandora* wreck. Strong currents and large waves occur at the wreck site, which must have played an important role in the mechanical breakdown of the wreck and redistribution of wreck material over the last 200 years.

Sedimentation and Wreck Disintegration

Most marine archaeological studies have used terrestrial analogies to determine the relationship between archaeological remains and their environment (e.g., Schiffer 1987), but marine environments are often more complex

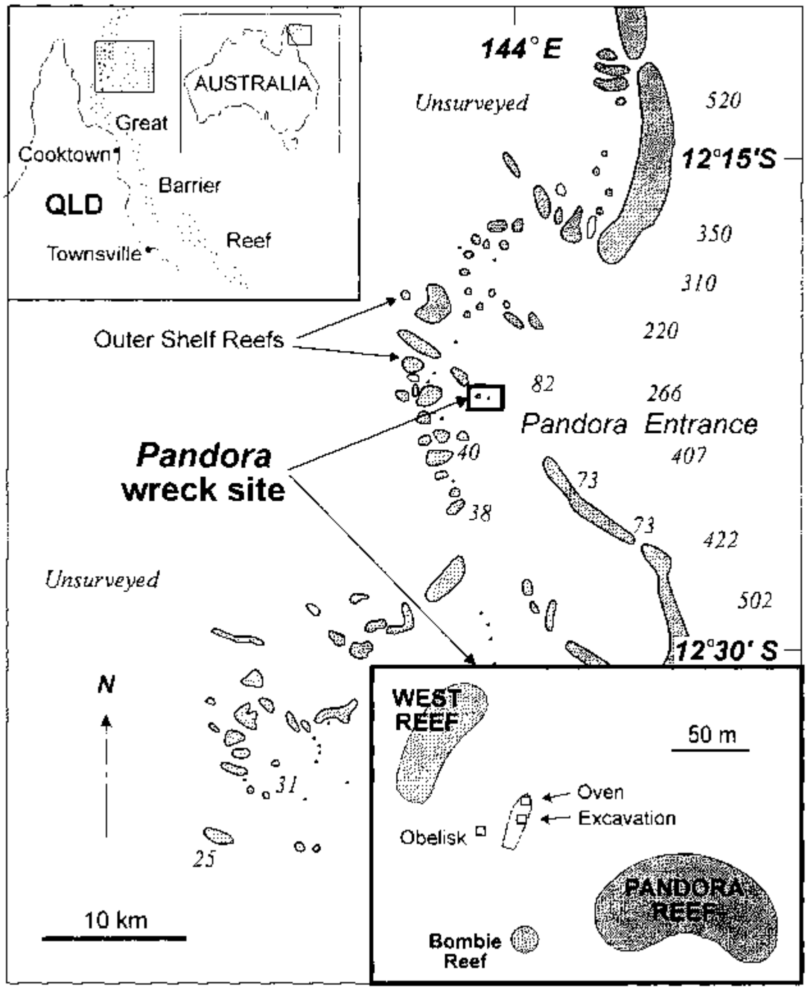

Figure 1. Location map of H.M.S. *Pandora*, which was wrecked on the outer shelf of the Great Barrier Reef in 1791. Inset shows the wreck situated between Pandora Reef and West Reef. Little is known about wreck formation in this poorly surveyed environment. (Spot depths in meters).

because of periodic and episodic sediment disturbance by currents and waves. Gaining some understanding of the general hydrodynamics and sedimentology around a wreck site is important for archaeological understanding, particularly of wreck site formation (Muckelroy 1978; Caston 1979). Wave and current data help assessment of dispersal of material and the nature of sedimentation, and an increased number of site-specific studies of these physical aspects will greatly improve our understanding of their importance in wreck formation.

Within the sediments, complex biological and chemical processes occur that may influence the preservation of organic and inorganic wreck components (Weier 1974; Gautier, Kharaka, and Surdam 1985; Ferrari and Adams 1990), and which themselves will be strongly influenced by variations in sediment accumulation, transport, and removal through time. Ward, Larcombe, and Veth (1998, 1999) have recently argued that the primary control upon wreck deterioration is the nature of sedimentation, including its temporal variation. The rate of wreck disintegration may be considered in terms of relative sediment accumulation or removal (FIG. 2). Overall, the process of wreck formation is continuous, but changes in sedimentation rate will affect physical, biological, and chemical processes, so that disintegration may occur at greatly varying rates over time. Consequently, the life history and distribution of wreck components may vary greatly across a wreck excavation. Improved understanding of the depositional environment provides a framework in which to better predict the nature of the material preserved, and thus the most ef-

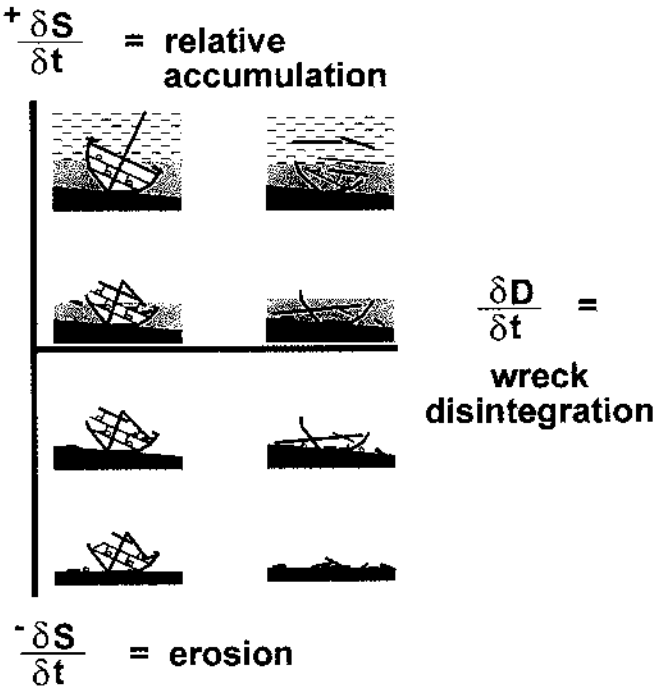

Figure 2. Wreck disintegration (dD/dt) may be plotted against the relative sedimentation rate (dS/dt), which is a first order control on the forces of degradation (physical, chemical, and biological). The combination of wreck deterioration with sedimentation gives rise to several scenarios, which range from the extremes of 1) rapid rates of burial and slow rates of deterioration, resulting in a well-preserved wreck in several meters of sediment (top left); and 2) rapid rates of erosion and deterioration, resulting in very little preservation on a hard exposed seabed (bottom right). The model is independent of time or scale, and is thus applicable to the wreck as a whole or to individual components, and a wide range of timescales (after Ward, Larcombe, and Veth 1999).

fective and least damaging ways to excavate. This paper describes the oceanographic and sedimentary processes that influenced the disintegration of the *Pandora* wreck.

Site Setting

The Pandora Entrance (FIG. 1) is ca. 5.6 km wide and 20–73 m deep (Australia Pilot 1973), on the western side of which a chain of reefs (ca. 10 miles long) form a fan that channels tidal currents on and off the shelf (Carter and Hooper 1993). The *Pandora* wreck lies in ca. 30 m of water on a SE-sloping part of the Pandora Entrance, among three small detached coral reefs, Pandora Reef, West Reef, and Bombie Reef. Three sand cays lie to the SE and SW, within 5 km of the wreck. The bathymetry of the outer-GBR shelf is generally complex because of the presence of coral reefs, banks of accumulated sediment (mainly the calcareous algae *Halimeda*), and erosional features (Orme, Flood, and Sargent 1978; Orme and Salama 1988).

In the northern GBR, currents are generally driven northward by the prevailing SE trade-winds in the months from May to December (Flinders 1814), with irregular currents frequently flowing southwards at other times of the year, such as during the summer monsoon (January–April) when NW or variable winds prevail. North of 10°S, wind-driven currents within a few kilometers of the coast are blocked by a network of reefs, then driven southward in deeper water adjacent to the reef (Wolanski and Ruddick 1981). Superimposed on the seasonal currents are tidal currents, forced from the Coral Sea. Sea-level records at Raine Island, 26 km south of the *Pandora* wreck site, show that the tides occur twice daily and mixed in nature, ranging from 0.5 m to 2.7 m (Wolanski and Thompson 1984). Maximum flood speeds range from 50 cm to 130 cm (Wolanski and Thompson 1984) and are strongly influenced by reef topography (Burrage 1993).

During the summer, cyclones may develop in the Coral Sea (Pickard et al. 1977) or in the Gulf of Carpentaria, tending to move southward, or east across Cape York, some regenerating in the Coral Sea (Hopley 1982). At 10°S, there are about 8 cyclones every 10 years (Lourenze 1981; Puotinen, Done, and Skelly 1997). Severe cyclones, with wind gusts up to ca. 55 m per second and storm surges of ca. 1.6 m, occur about every 50 to 70 years (Gagan, Chivas, and Herczeg 1990). The area of the *Pandora* wreck may thus have been subject to three or four severe cyclones over the last 200 years, as well as more frequent smaller systems. Cyclones are likely to have two major oceanographic effects in the area. Large waves cause strong reversing currents near the bed, and large volumes of ocean water may be forced onto and off the continental shelf because of wind shear at the water surface and raised water level caused by the large reduction in atmospheric pressure at the cyclone's center. The results are reflected as unidirectional currents lasting 1–2 days.

Methods

Oceanography

Measurements of current speed and direction were taken over a monthly lunar cycle from 17 January to 24 February 1997. A Woods Hole SEAPAC directional wave, tide, and current gauge (fixed to a frame at a depth of 33 m) was deployed just south of West Reef (FIG. 3). A tide gauge was positioned off the anchor at the stern of the wreck at ca. 16 m depth. In addition, two Interocean S4 current meters were positioned at the bow and stern of the *Pandora* wreck (FIG. 3). The S4 at the bow (RAN1660) was anchored 1 m off the seabed, and the one at the stern (RAN1710) was anchored 3 m off the seabed.

An indication of regional winds was obtained from the nearest offshore weather station at Coconut Island

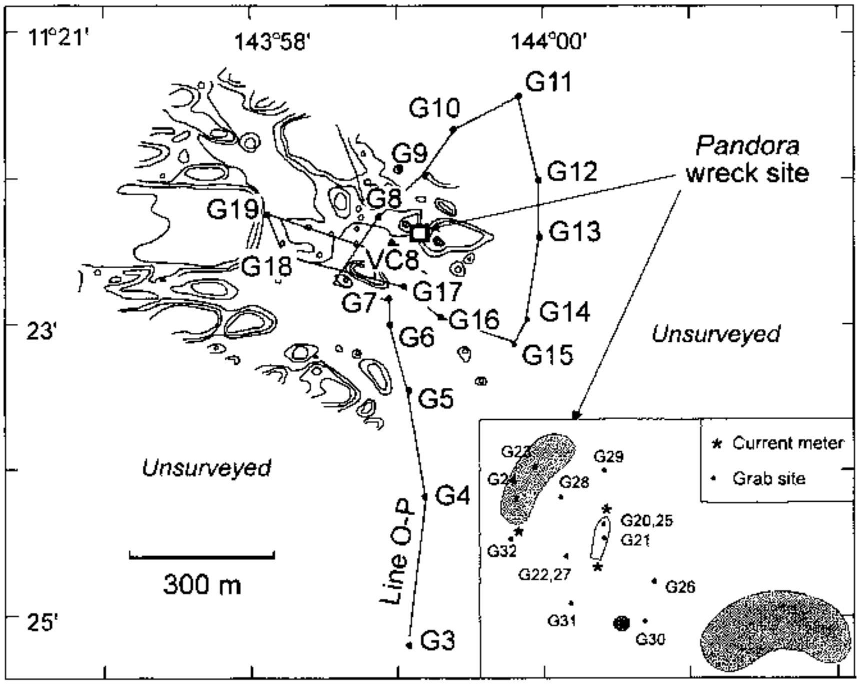

Figure 3. Bathymetric map of the area surrounding the *Pandora* wreck site, obtained from LADS imaging, showing location of seismic survey lines (Line O-P), sediment grab sites, and vibrocore site. (Spot depth in meters). Inset shows location of sediment grab sites and current meter moorings within the wreck site.

(10°3′S, 143°3′36″E), approximately 150 km NW of Pandora Entrance from the Bureau of Meteorology. In early January at the *Pandora* wreck site, SE winds prevailed and during the deployment of instruments winds came from the NNW. Regional wind speeds average 4 m per second but wind data recorded at the wreck site shows a general decrease in wind speed from ca. 15 knots (7.5 m per second) to ca. 5 knots (2.5 m per second) during the period of instrument deployment.

Sedimentology

Following deployment of current and tide gauges, the R.V. *James Kirby* undertook seismic recordings and sediment collection surrounding the *Pandora* wreck site. Lines O and P were run around the marked wreck site (FIG. 3). A total of 19 grab samples were collected along these seismic lines, and an additional 12 grab samples were taken by divers from the *Pacific Conquest* at various sites at the wreck site itself. A single vibrocore (VC8) was obtained near the wreck site.

Laboratory Analyses

GRAIN SIZE

Grab and vibrocore samples were analyzed for grain size using the Malvern Mastersizer long-based laser particle sizer, after wet-sieving through a 1 mm sieve (procedure outlined in Woolfe and Michibayashi 1995). Sub-samples were digested with 10% nitric acid to determine the proportion of non-carbonate material. Most samples comprised over 99% carbonate.

SEDIMENT TRANSPORT

We have no data on observations of movement of bed sediment at the wreck, and no detailed measurement of flow conditions at the seabed. Hence, to provide information on the potential transport of bed sediment at the wreck site, a series of experiments were performed at James Cook University to determine flow conditions at the bed above which bedload transport occurs. Bedload transport depends upon the shear stress imposed upon the bed (Soulsby 1983), which can be calculated for the flume data and then applied to the field site. Samples of bed material from the wreck site (ca. 3 kg) were placed at the base of a glass-walled flume (3 m long, 0.10 m wide, water depths up to 0.30 m), and subject to increasing current speeds. For each speed, the vertical current profile was measured and notes were taken of the extent of bed movement. A laser Doppler current meter system (with FLOware software) was used to measure 30-second average current speeds at 10 mm depth intervals through the

Table 1. Summary of flume results.

Experiment no.	*Shear velocity (cm per second)*	*Mean flow velocities (m per second)*	*Notes on extent of bed movement*
1	0.61	0.14	Mostly no movement, but fine sand grains slide occasionally along the bed.
2	1.92	0.18	Mostly no movement, except occasional fine sand grain is overturned.
3	0.58	0.23	Less than 5% of grains are mobile, with occasional fine sand grains overturned, and large grains are slightly imbricated.
4	0.49	0.26	Less than 5% of grains are mobile, imbrication strong, with small bed defects being generated, and few grains moving.
5	1.07	0.28	5–10% of the bed is mobile, bed gradually becoming armored.
6	0.66–0.72	0.34	10–20% grain being rolled continuously (esp. the finer fraction), incipient saltation.
7	1.5–1.6	0.45	50% of the bed is fully mobile (mainly fine fraction), scouring present, longitudinal features and small bars.
8	3.3–4.1	0.51	100% of grains are mobile, small bedforms (< 10 mm high, 150 mm spacing, migration rate 180 mm per minute).

water column. Eight different speeds were used, with mean flow velocities increasing from 0.14 m per second to 0.51 m per second (TABLE 1). Flow data were fitted to the Von Karman equation.[1] Results are given in Table 1.

Results

Tidal Elevations

The tidal curve from the SEAPAC current meter shows that tides are semi-diurnal and asymmetric (FIGS. 4A, 5A). The curve may be described as a set of two tidal cycles, the first flood and ebb tides of which have a greater range than the second, and are hereafter referred to as major and minor tides respectively. The tides show a neap tidal range of ca. 1.0 m and a spring tidal range of ca. 2.0–2.25 m.

Currents

Data from the current meters indicate that during the spring tidal period, currents are generally stronger and transient eddies may form. The fastest current recorded at West Reef is the major flood (ca. 0.6 m per second) to the NE (FIG. 4B), and the strongest flood recorded was 0.9 m per second. These speeds are of the same order as observed further south at Raine Island (Wolanski and Thompson 1984). Ebb tides flow dominantly SW to west and average about 0.4 m per second during both spring and neap tides.

Over the wreck site itself, divers have observed that the dominant flood tides flow to the NE, but current measurements taken near the seabed indicate that the strongest currents (ca. 0.4 m per second) flow to the south, and occur at the beginning of the major ebb tide (FIG. 5B). The strongest ebb currents of 2.3 m per second and 1.0 m per second were recorded at the stern of the wreck (FIG. 5D). Spring flood tides generally flow to the north or NW, and during the neap tides current speeds are much lower (ca. 0.2 m per second) and flow more toward west (FIGS. 5B, 5D).

The complex current patterns are supported by diver observations:

> Eddies can be up to 100 m across but more commonly about 40 m, and they tend to move slowly around the site. The currents on the site can be running very rapidly on the surface but can be quite workable on the bottom. The thermoclines can be as wide as 10 m and as narrow as 2 m. There seems to be a warm bottom current at times with a cold mid-column current and a warm surface current. However, these will vary in size and over time (Peter Illidge, personal communication 1997).

1. Sediment transport at the seabed is dependent upon the vertical gradient of increasing flow speed away from the bed, i.e., shear in the near-bed flow. This shear can be represented as the shear velocity, U*, where a higher number means greater shear and thus greater sediment transport. Our flow data were fitted to an equation that describes flow shear, the Von Karman equation. The shear velocity, U*, is given by:

$$k\left(\frac{Ua-Ub}{\ln Za-\ln Zb}\right)$$

where k = Von Karmans constant (0.4). This requires a value for the hydraulic "roughness" of the seabed, *Zb*. We have used a roughness length of 0.03 cm (Soulsby 1983).

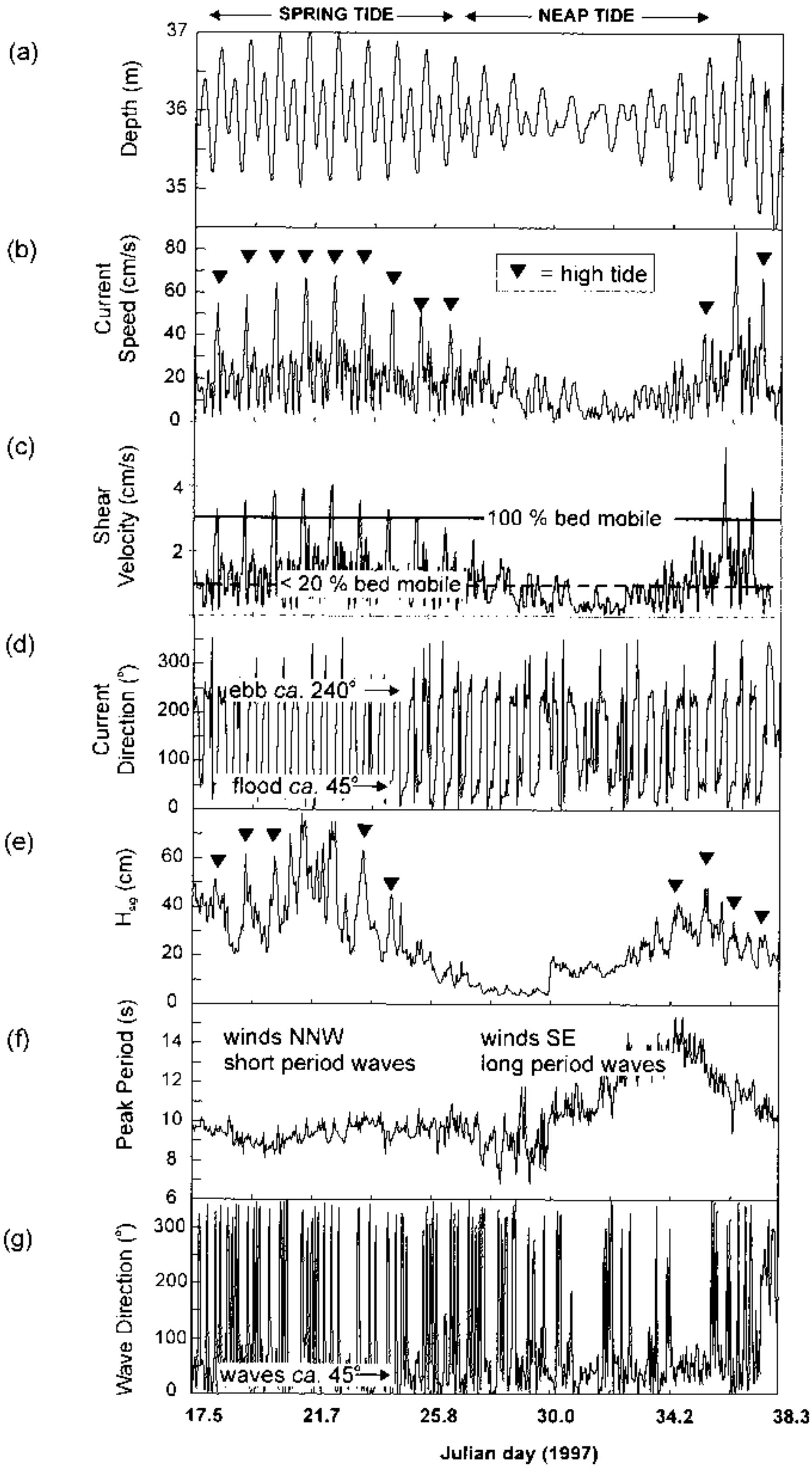

Figure 4. Environmental data just south of West Reef for the period of 17/1/97 to 7/2/97. Data includes a) depth, b) current speed, c) shear velocity, d) current direction, e) significant wave height, f) peak wave period, and g) wave direction at hourly intervals.

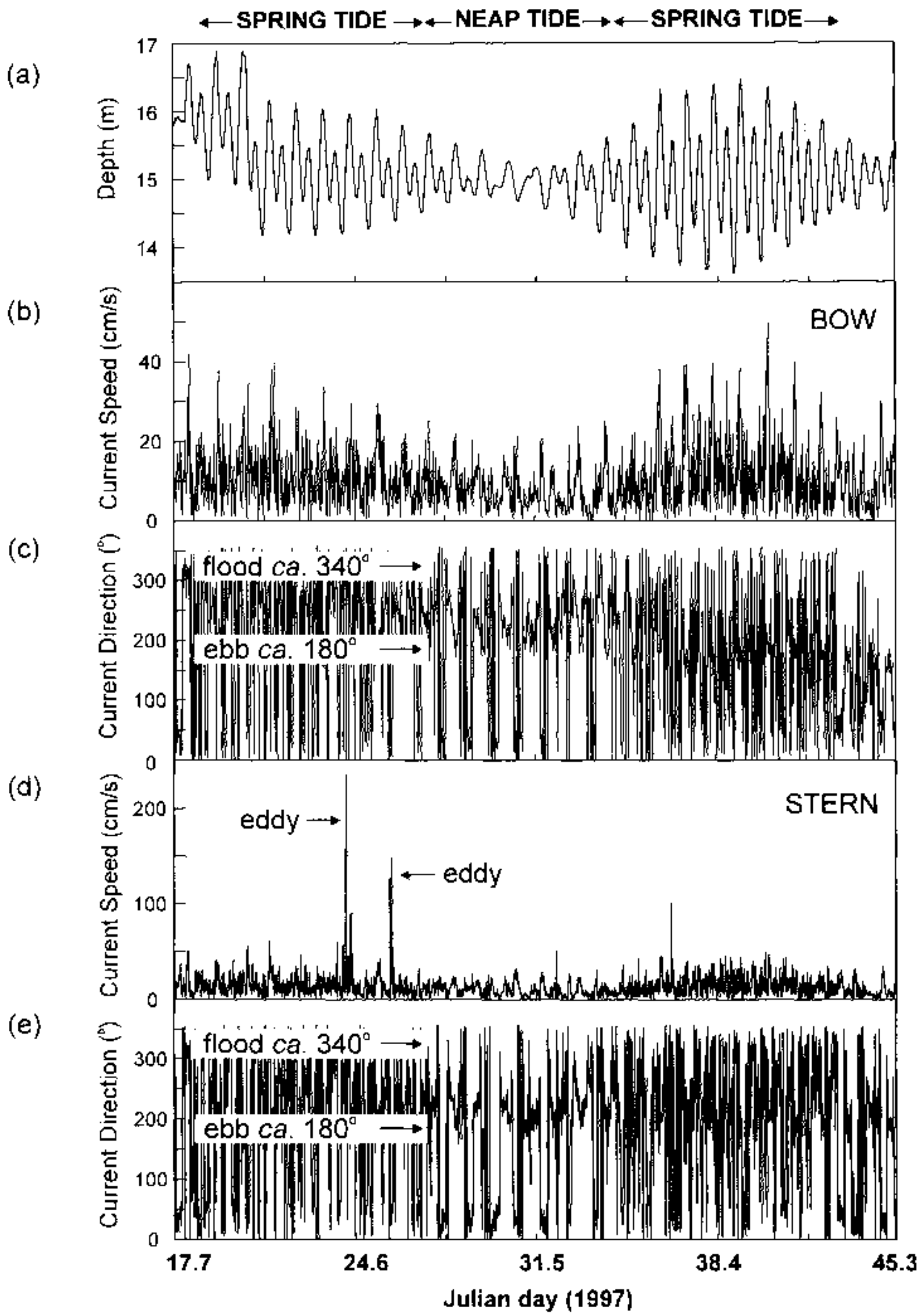

Figure 5. Tide and current data from the bow and stern of the *Pandora* wreck site for the period of 17/1/97 to 13/2/97.

Waves

Current and wave patterns recorded within the wreck site are summarized in Figure 6. South of West Reef records show that wave direction is generally toward the north or NE (consistent with south and SE prevailing winds), where they are most likely refracted around West Reef. Wave height varies with tide and wind direction and ranges from 5 to 70 cm, with maximum wave heights occurring at the time of high tide (FIG. 4E), with waves propagating toward the north. The onset of greater wave heights (FIG. 4E), NE propagating waves (FIG. 4G), and increase in peak period (FIG. 4F), correlates with the onset of SE trades around 30 January (Julian day 30). During the

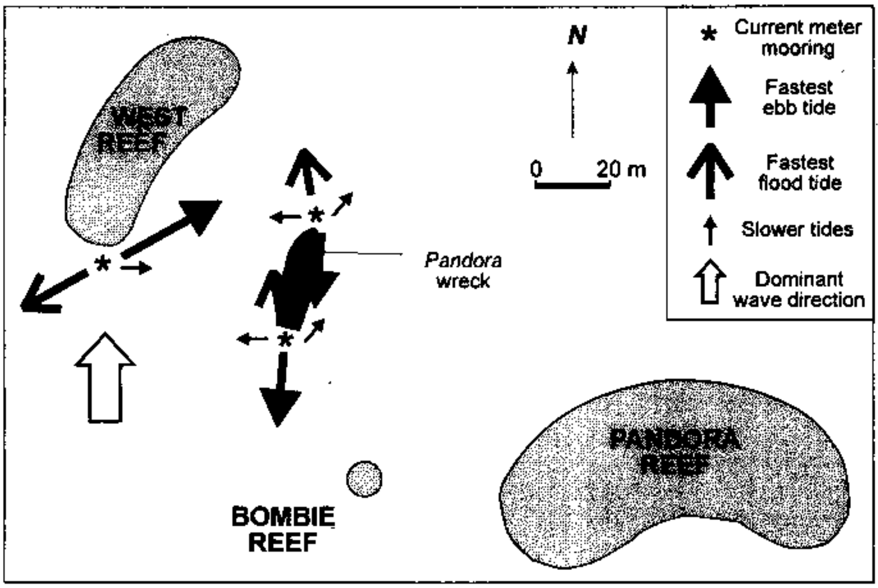

Figure 6. Summary of current and wave data.

month of instrument deployment, peak period generally increases (FIG. 4F), showing an apparent inverse relationship to wind conditions. The highest peak period (ca. 16 sec) occurs toward the end of the period of deployment with the arrival of storm waves from the southern Coral Sea.

Sediments and Geophysics

Seismic surveys around the *Pandora* wreck site (FIG. 7) show similar characteristics to more regional parts (Ward 1998). A prominent sub-bottom reflector (interpreted as Reflector A elsewhere) occurs around the *Pandora* wreck site. The surface boundary is generally sharp with an indistinct, discontinuous parallel sub-bottom reflector (Reflector A) that outlines a sea-floor with considerable relief (ca. -5 to -120 m). This reflector probably outlines the hard-bottom reef platform, which is overlain by a thin veneer of acoustically transparent sediment in much of the area. Elsewhere, the hard-bottom is overlain by banks of acoustically transparent sediment which probably comprise *Halimeda* sediment debris. *Halimeda* is a genus of calcareous green seaweed found throughout the tropics, the plate-like "leaves" of which may form major sediment deposits of the outer shelf of the Great Barrier Reef (Orme and Salama 1988).

SEDIMENT DESCRIPTION

Observations from divers suggest *Halimeda* sediment is thickest on the SE side of the wreck near Pandora Reef, and is rare on the NW side near West Reef. Microscopic analysis of the sediment around the wreck site indicates that the sand is composed of pieces of coral and echinoderm debris (including *Lunillear* sp.), calcareous algae, small bivalves, some gastropods, ostracoda, and foraminifera (including *Alveolinella* sp., *Amphisogina* sp., *Marginopora* sp., *Textularia* sp., and *Scaphodia* sp.). Grab sites G6, G7, G10, G11, and G14 comprised pebble-sized reef rubble (including coral, *Bryazoa* sp., *Halimeda* sp., and *Foraminifera* sp.), with virtually no sand.

Up to 60% of the sediment fraction is greater than 1 mm in size, dominantly of *Halimeda* debris. *Halimeda* material is not obvious in the size fraction less than 1 mm, and results from the laser sizer indicate that the sediment is unimodal and well-sorted. The modal size of the less than 1 mm sediment fraction around the wreck site is less than 620 μm, mostly of foraminiferal and coralgal debris, and further south, near Moulter Cay, modal grain size increases up to 800 μm (FIG. 8), probably related to greater exposure to waves. At the *Pandora* wreck site itself, the modal grain size is larger near both Pandora and West reefs. The modal grain size is also relatively coarse within scour marks associated with larger objects around the wreck such as the oven and the obelisk (FIG. 1), and within scour-pits on West Reef, indicating some in situ reworking of sediment around the *Pandora* wreck.

In the vibrocore taken adjacent to the wreck site (VC8), grain size decreases from carbonate gravel to coarse-sand downcore, with coral rubble at the base of the 30 cm long core. The modal size of the less than 1 mm fraction, however, is constant with depth (ca. 500 μm). There is a clear color change downcore from white to yellow, probably related to the development of anoxic conditions.

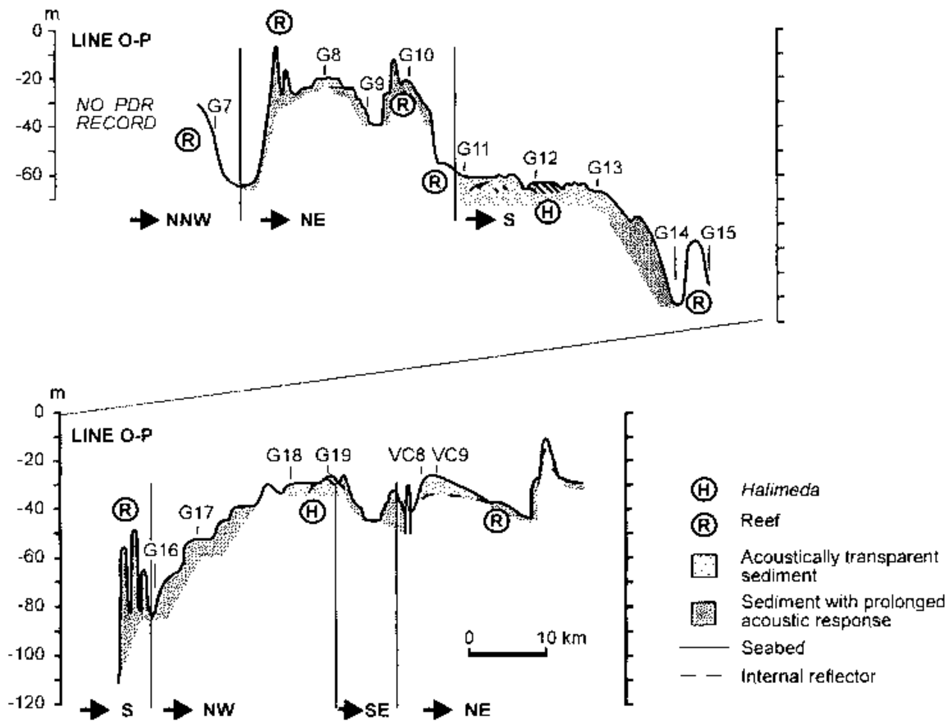

Figure 7. Simplified seismic profiles around the *Pandora* wreck site (track lines on Figure 3), with locations of grab (G) and vibrocore (VC) sites. Note the sharp changes in bathymetry and bottom type.

MINERALOGY

Petrographic studies of undigested (carbonate-free) and digested (10% HNO_3) sediment samples indicate that the sediment is composed of carbonate (aragonite and calcite), quartz, heavy minerals, and pyroxene. X-ray diffraction analyses indicate that the carbonate component, which makes up over 99% of the total, comprises aragonite and calcite. The non-carbonate component is composed of quartz and pyroxenes (augite, ferrosilite), which may be volcanically-derived (Okubo and Woolfe 1995); and heavy minerals including authigenic pyrite (FeS). Visually, the greatest amount of pyritic material is observed in the excavated sediment samples (G21), and previously buried glass decanters, and indicates increasing anoxic conditions with depth.

Discussion

Sediment Stratigraphy

Evidence from sediment cores indicates that the low-relief transparent seismic facies (FIG. 7) that surrounds the *Pandora* wreck (Carter and Hooper 1993) represents *Halimeda*-dominated sediment. The acoustic characteristics are probably indicative of natural carbonate sand, containing little or no wreck debris. Regionally, calcareous remains of *Halimeda* (*H. hederacea* and *H. copiosa*) and foraminifera (*Marginopora* and *Alveolinella*) probably make up to 98% of the surficial sediments (Blakeway 1991).

The strong seismic reflector (Reflector A) has previously been interpreted as part of the Pleistocene carbonate reef platform that extends from the mid-shelf, or a hard layer within the Holocene facies (Searle et al. 1981; Johnson, Searle, and Hopley 1982; Carter and Hooper 1993; Harris 1994). It remains to be determined whether the *Pandora* wreck actually rests on Reflector A, and if so, whether the wreck has scoured down to the hard bottom since 1791, or if the hard bottom was exposed at the time of the wreck, and *Halimeda* sediments have subsequently accumulated around it.

Sediment Transport

The numerous reefs forming the Pandora Entrance protect the *Pandora* wreck from waves generated in the GBR, and strongly influence local currents. The correlation of maximum measured wave heights (ca. 70 cm) with high tide, suggests that water depths over the shallow reefs influence the local wave regime. The broad correlation of long-period ocean swell (period ca. 15 sec) with the SE trade winds indicates that the wreck site is open to region-

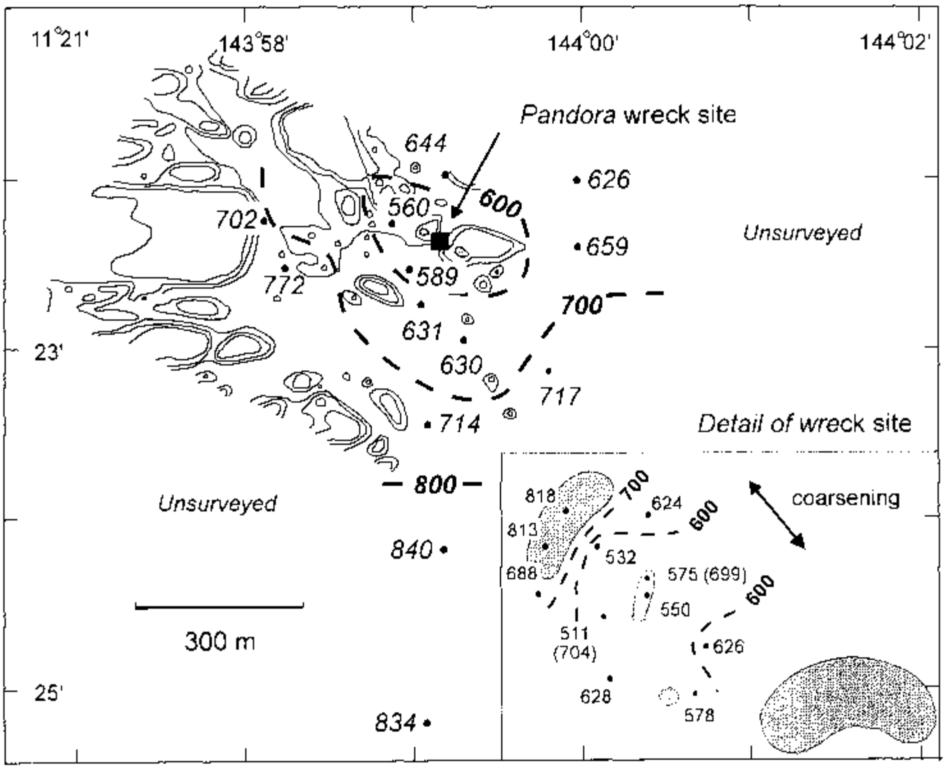

Figure 8. Modal size of the less than 1 mm sediment fraction within (inset) and around the *Pandora* wreck site. Sample sites and contour lines in μm.

al waves generated further south in the Coral Sea. The wave regime at the *Pandora* wreck site thus may vary between one of dominant wind waves or ocean swell waves, according to the prevailing wind.

Currents around the *Pandora* wreck site have a tidal period, but are also influenced by the local reef morphology, with transient eddies probably shed off reefs during peak tidal flows. The superposition of large waves and currents will enhance sediment transport. Our laboratory experiments indicate that appreciable bedload transport occurs when shear velocity (represented by the notational symbol U*) exceeds ca. 0.6–1.0 cm per second. By converting our current data from the wreck site into shear velocity near the bed (FIG. 4C), we can infer that much of the bed is mobile under the influence of large spring tides, independent of waves. The episodic eddies that pass through the site are likely to move appreciable amounts of bed material, although for short periods.

The distribution of the finest sediment fraction in sheltered parts, such as around the *Pandora* wreck, indicates that the regional accumulation transport of sediment is probably mainly controlled by waves. Sheltered from wave action, sediment transport within the wreck site will mainly be controlled by currents, except when long-period swell waves come from the south, such as may occur during major storm events. Within the wreck area, there is likely to be localized burial and exposure of wreck parts through scouring.

From their seismic surveys, Carter and Hooper (1993) concluded that the majority of wreck debris occurs close to the eastern edge of the site on the starboard side of the vessel. This was confirmed by subsequent excavations (Gesner 1993). During our observation period, the strongest current flowed towards the south, and thus, if such currents have dominated since burial, it appears likely that the observed debris probably fell from the vessel when it first sank, rather than having subsequently been transported there by tidal currents. Lighter material may have been transported outside and south of the surveyed area.

In addition to vertical accumulation, consideration should also be made for lateral movement of sediment across a wreck site. Estimating a threshold velocity of 54 cm per second for biogenic carbonate (mean size 610 μm) Harris (1991) calculated the lateral movement of bedforms in the Torres Strait at 0.13 m per day. This threshold velocity is of similar magnitude for *Halimeda* sediment around the *Pandora* wreck site. Thus over the last 200 years, similar bedforms could have migrated a distance of over 9 km, a distance much greater than the extent of the wreck. Previous seismic surveys of the wreck site indicate that the surficial sediment layer exhibits a relief of 1–2 m across sediment dunes (Carter and Hooper 1993). If the presence of the dunes can be confirmed by sediment surveys, then this may be evidence of active sedimentation across the wreck site. The implications for the wreck site are that there may have been many phases of exposure (oxygenation) and (re-)burial as the dunes migrated. Dune migration is likely to occur mostly with strong unidirectional currents (spring tides, eddies, or storm-driven currents). The depth of disturbance by the movement of small bedforms is likely to be less than a decimeter. The return period or frequency of such currents is therefore important to the rate of sediment transport and dune migration (TABLE 2), and consequently to the rate of wreck disintegration by physical, chemical, and biological means (TABLE 3). Anoxic conditions may become re-established within periods of days or weeks.

Around the wreck site, *Halimeda* plates make up most of the greater than 1 mm fraction, and probably represent the accumulation of debris transported from *Halimeda* banks near the wreck site, e.g., behind West Reef (G8 and VC8) and NE of Pandora Reef (G13) (FIG. 7). Assuming the strong sub-bottom seismic reflector at the wreck site represents the Pleistocene-Holocene boundary (ca. 10,000 b.p.), a sediment thickness of 2–4 m over the wreck gives a time-averaged Holocene sediment accumulation rate of ca. 0.03 mm per year. Sedimentation is not constant, however, and episodic events such as storms may induce erosion or accumulation of sediments at the wreck site.

Implications for Wreck Disintegration

Physical, biological, and chemical variables act together in wreck deterioration, but the primary control is the nature of sedimentation. The major environmental processes operating at a wreck site can each depend upon whether the seabed is eroding or is accumulating sediment, through the effects on the physicochemical conditions of the sediment, and the suitability for habitation (TABLE 3). As the wreck deteriorates, its physical influence on the environment (and vice versa) will decrease but the sediment conditions may have been completely altered by the presence of breakdown products of biochemical and chemical processes.

The color change observed downcore in the *Halimeda*-dominated sediments (VC8) is probably related to the development of anoxic conditions, which develop when the rate of organic matter supply and sedimentation exceeds the rate of its decomposition via aerobic bacteria (Curtis 1987). Micro-biological studies around the *Pandora* wreck site have confirmed that sulfate reduction occurs at the surface and down into the sediments, and sulfate reduction decreases with increasing distance from the wreck (Guthrie

Table 2. Characteristics of the main hydrodynamic processes that influence sediment transport at the *Pandora* wreck site.

Process	*Recurrence interval*	*Comments*
Eddies	Days to fortnights	Local burial, scouring (rapid)
Large spring tides	Fortnights	Local sediment transport (movement of dunes?)
Shelf waves (associated with low pressure systems)	Weeks to months (but concentrated in wet season)	Regional sediment transport (movement of dunes?)
Waves	Monthly, seasonally, storms	Long-term enhancement of current-driven bedload transport

Table 3. Some examples of the influence of relative sedimentation on physical, chemical, and biological processes.

Relative sedimentation	*Physical processes*	*Biological processes*	*Chemical processes*
Accumulation	Compaction	Elevation of biostratigraphic layer	Anoxic conditions
		Sulphate- and methane-reducing bacteria dominant	Reduced corrosion
Erosion	Increased exposure to waves and currents	Removal of biostratigraphic layer	Oxic conditions
	Abrasion by moving grains	Oxidizing bacteria dominant	Increased corrosion

et al. 1994). The conversion of dissolved H_2S to pyrite (FeS_2), organic sulfur, or elemental sulfur complexes is suggested from this and other studies (Guthrie et al. 1994), and has significant implications for the formation of acid-sulfate sediments. Resuspension of sediments such as during excavation allows oxidation and neutralization of sediments by seawater, and oxidation of sulfides to sulfuric acid, which may temporarily advance degradation of the artifacts and hull of a wreck. Sediment resuspension may also occur during major storms, which may promote oxidation of sulfides, but it is likely that only the upper few centimeters are mobilized, and the system may be buffered to some extent by seawater and the carbonate-rich sediments. In contrast, the depth of archaeological excavation is significantly greater, with great potential impacts on metal and non-metal components from the resultant acid-rich water between the grains within the sediment column.

Conclusion

Despite some initial and ongoing studies, the environment of the *Pandora* wreck on the outer-shelf of the GBR remains poorly understood. Preliminary data presented indicate that currents and waves at the wreck site are influenced by the surrounding reef morphology. Tides are semidiurnal and asymmetric, with a stronger ebb than flood, and transient very fast eddies form around reefs mainly on the dominant ebb tide. Wave direction is generally north or NE, and wave height varies with tide and wind direction. Sediments around the wreck comprise a coarse fraction dominated by *Halimeda* debris and a finer fraction (less than 1 mm) dominated by foraminiferal material. Limited grain size data of the finer fraction indicate that regional sedimentation is probably controlled by waves. In the more sheltered wreck site, sediment transport is influenced mainly by currents, particularly under the influence of large spring tides when shear velocity exceeds ca. 0.6–1.0 cm per second. High resolution records of wave and current data, combined with seabed observations would allow a more accurate prediction of the movement of sediment, for example, during high energy periods. More detailed seismic and sediment surveys on and around the wreck area would help determine whether sedimentation is source- or transport-controlled.

The rate of sedimentation and wreck disintegration is intimately linked to the return frequency and magnitude of various hydrodynamic processes. In addition, wreck disintegration is enhanced by the short-term and localized intensive excavation (e.g., Guthrie et al. 1996 on the *Pandora*), the effects of which contrast with the broader effects of storm events in this region. The life history and preservation of the *Pandora*, and other wrecks, can be better described and predicted from an understanding of the sedimentary processes that operate in the depositional environment.

Acknowledgments

We thank the crew of the R.V. *James Kirby*, and Kevin Hooper who assisted with fieldwork at the *Pandora* wreck site. Peter Illidge and the diving team of the *Pacific Conquest* deployed and retrieved the current meters, with the assistance and goodwill of Peter Gesner and Michael St. James. We thank James Delgado and an anonymous referee for their positive comments.

Ingrid A. K. Ward is a graduate student at James Cook University. This work forms part of her M.A. degree and her other publications address the geochemistry of marine sedimentary environments. Mailing address: School of Earth Sciences, James Cook University, Townsville, Queensland 4811, Australia.

Piers Larcombe is currently an Australian Research Fellow, with publications in a variety of sedimentological fields including sediment transport, marine geology and sea-level change.

Richard Brinkman is an experimental Scientist at the Australian Institute for Marine Science. His current research activities include modelling of littoral processes and wave dynamics.

Robert M. Carter is a professor of Earth Sciences, and currently a holder of a prestigious Special Investigator Award from the Australian Research Council. His work has included paleontology and the sedimentary effect of sea-level changes, presently focusing on paleoceanography.

Australia Pilot
1973 *East Coast of Australia from Outer North Head to Cape York.* Vol. 3. Sixth edition. Taunton, U. K.: Hydrographer of the Navy.

Blakeway, David
1991 "Sedimentary Sources and Processes in Outer Shelf, Slope and Submarine Canyon Environments, Northern Ribbon Reefs, Great Barrier Reef, Australia." Unpublished honors thesis, James Cook University, Townsville.

Burrage, Derek M.
1993 "Coral Sea Currents," *Corella* 17: 135–145.

Carter, Robert M., and Kevin Hooper
1993 "Shallow Seismic Survey of *Pandora* Wreck Site," unpublished report for Queensland Museum.

Caston, F. G.
1979 "Wreck Marks: Indicators of Net Sand Transport," *Marine Geology* 33: 193–204.

Curtis, C. D.
1987 "Inorganic Geochemistry and Petroleum Exploration," *Advances in Petroleum Geochemistry* 2: 92–139.

Ferrari, Ben, and Jon Adams
1990 "Biogenic Modifications of Marine Sediments and Their Influence on Archaeological Material," *International Journal of Nautical Archaeology and Underwater Exploration* 19: 139–151.

Flinders, Matthew
1814 *A Voyage to Terra Australis.* London: G. and W. Nicol.

Gagan, Michael K., Alan R. Chivas, and L. Herczeg
1990 "Shelf-wide Erosion, Deposition, and Suspended Sediment Transport During Cyclone Winifred, Central Great Barrier Reef, Australia," *Journal of Sedimentary Petrology* 60: 456–470.

Gautier, Donald L., Yousif K. Kharaka, and Ronald C. Surdam
1985 "Relationship of Organic Matter and Mineral Diagenesis," *SEPM Short Course Notes* No. 17. Tulsa, OK: SEPM.

Gesner, Peter
1988 "The *Pandora* Project: Reviewing Genesis and Rationale," *Bulletin Australian Institute of Maritime Archaeology* 12: 27–36.

1991 *H.M.S.* Pandora, *an Archaeological Perspective.* Brisbane: Queensland Museum Press.

1993 "Managing *Pandora's* Box, the 1993 Expedition," *Bulletin Australian Institute of Marine Archaeology* 17: 7–10.

Guthrie, Jodie N., Linda L. Blackall, David J. W. Moriarty, and Peter Gesner
1994 "Wrecks and Marine Microbiology: Case Study from the *Pandora*," *Bulletin Australian Institute of Maritime Archaeology* 18: 19–24.

Guthrie, Jodie N., Linda L. Blackall, David J. W. Moriarty, and Peter D. Nichols
1996 "Decomposers of Shipwreck H. M. S. *Pandora*," *Microbiology Australia* 17: 17.

Harris, Peter T.
1991 "Reversal of Subtidal Dune Asymmetries Caused by Seasonally Reversing Wind-Driven Currents in Torres Strait, Northeastern Australia," *Continental Shelf Research* 11: 655–662.

1994 "Incised Valleys and Backstepping Deltaic Deposits in Foreland-basin Setting, Torres Strait and Gulf of Papua, Australia," *SEPM Special Publication* 51: 97–108.

Hopley, David
1982 *The Geomorphology of the Great Barrier Reef: Quaternary Development of Coral Reefs.* New York: John Wiley and Sons.

Johnson, David P., David E. Searle, and David Hopley
1982 "Positive Relief Over Buried Post-glacial Channels, Great Barrier Reef Province, Continental Shelf, Australia," *Marine Geology* 46: 149–159.

Lourenze, R. S.
1981 *Tropical Cyclones in the Australia Region July 1909 to June 1980.* Canberra: Australian Government Publishing Service.

Muckelroy, Keith
1978 *Maritime Archaeology.* New York: Cambridge University Press.

Okubo, Chris, and Ken Woolfe
1995 "As Much as 90% of the Terrigenous Sediment Reaching the Outer Reef Is Volcanic," in Piers Larcombe and Ken Woolfe, eds., *Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts.* Townsville: CRC Reef Research Centre, Research Symposium Proceedings, 107–110.

Orme, Richard G., and M. S. Salama
1988 "Form and Seismic Stratigraphy of *Halimeda* Banks in Part of the Northern Great Barrier Reef Province," *Coral Reefs* 6: 131–137.

Orme, Richard G., Peter G. Flood, and Graham Sargent
1978 "Sedimentation Trends in the Lee of Outer (Ribbon) Reefs, Northern Great Barrier Reef Province," *Philosophical Transactions of the Royal Society of London* A 291: 85–89.

Pickard, George L., Jean-René Donguy, Christian Henin, and Francois Rougerie
1977 *A Review of the Physical Oceanography of the Great Barrier Reef and Western Coral Sea. AIMS Monograph Series.* Vol. 2. Canberra: Australian Institute of Marine Science.

Puotinen, Majeta L., Terry J. Done, and Chris W. Skelly
1997 *An Atlas of Tropical Cyclones in the Great Barrier Reef Region: 1969–1977. CRC Reef Research Centre Technical Report* 19. Townsville: CRC Reef Research Centre.

Schiffer, Michael B.
1987 *Formation Processes of the Archaeological Record.* Albuquerque: University of New Mexico Press.

Searle, David E., Nicholas Harvey, David Hopley, and David P. Johnson
1981 "Significance of Results of Shallow Seismic Research in the Great Barrier Reef Province Between 16°10´S and 20°05´S," *Proceedings of the 4th International Coral Reef Congress, Manila* 1: 139–144.

Soulsby, Richard L.
1983 "The Bottom Boundary Layer of Shelf Seas," in B. Johns, ed., *Physical Oceanography of Coastal and Shelf Seas.* Amsterdam: Elsevier, 189–266.

Ward, Ingrid A. K.
1998 "Sedimentary History of the *Pandora* Wreck and Surrounds." Unpublished Masters thesis, James Cook University, Townsville.

Ward, Ingrid A. K., Piers Larcombe, and Peter Veth
1998 "Towards New Process-orientated Models for Describing Wreck Disintegration: An Example Using the *Pandora* Wreck," *Bulletin Australian Institute of Maritime Archaeology* 22: 109–114.

1999 "A New Process-based Model for Wreck Site Formation," *Journal of Archaeological Science* 26: 561–570.

Weier, Lucy
1974 "The Disintegration of Inorganic Materials Under the Sea," *Bulletin of the Institute of Maritime Archaeology* 11: 131–163.

Wolanski, Eric, and Barry Ruddick
1981 "Water Circulation and Shelf Waves in the Northern Great Barrier Reef Lagoon," *Australian Journal of Marine and Freshwater Research* 32: 721–740.

Wolanski, Eric, and Richard Thompson
1984 "Wind-driven Circulation on the Northern Great Barrier Reef Continental Shelf in Summer," *Estuarine, Coastal, Shelf Science* 18: 271–289.

Woolfe, Ken J., and Katsu Michibayashi
1995 "'Basic' Entropy Grouping of Laser-derived Grain-size Data: an Example from the Great Barrier Reef," *Computers and Geosciences* 21: 447–462.