Department for **Planning and Infrastructure**
Government of **Western Australia**

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Your ref: 314/04
Our ref: 862/10/01/0003P
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FILE → DEC 2417-01
POC17801

DEPARTMENT OF ENVIRONMENT
& CONSERVATION
16 MAR 2007
Corporate Information Section
ATRIUM

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- make reference list to geol. terms
- SPP-acid sulphates
- being mid-tide
- Geo reference to surge
- pink copy of strategy
- check area correctly it
- find quote to [illegible] in ERMP

Dr Sue Osborne
C/O The Chairman
Environmental Protection Authority
PO BOX K822
PERTH WA 6842

Dear Dr Osborne

Yannarie Solar Project - Invitation to Comment

I refer to the letter dated 1 December 2006 inviting comments on the proposal referred to in the Environmental Review and Management Programme (Assessment 1521). The Department for Planning and Infrastructure (DPI) provides the following advice and comments for your consideration in assessing this proposal. Specifically, the proposal has been considered within the context of:

- Ningaloo Coast Regional Strategy Carnarvon to Exmouth 2004 (the Strategy)
- State Planning Policy No. 2.6 (SPP2.6)

In summary, the DPI is concerned about:

(a) the potential land-use conflict that will arise by allowing an extractive industry to be established in an area identified as being of high nature conservation value and a priority for inclusion in Western Australia's marine reserve system; and

(b) the inadequate demonstration of the impacts of coastal processes, particularly cyclonic storm surge inundation and sea level rise, on the project area and the implications for development setbacks and the structural integrity of proposed infrastructure.

Ningaloo Coast Regional Strategy Carnarvon to Exmouth

The *Ningaloo Coast Regional Strategy Carnarvon to Exmouth*, released by the Western Australian Planning Commission (WAPC) in August 2004, is a 30-year strategic land use plan that provides the framework for planning for sustainable tourism and land use on the Ningaloo coast including Exmouth Gulf. The Strategy identifies the southern and eastern mangal areas of the Exmouth Gulf and adjacent coastal waters as recommended marine protected areas, consistent with the findings of the Marine Parks and Reserves Selection Working Group (MPRSWG) (1994) – the 'Wilson Report'.

wapc website
wapc.gov.au
LHS initiatives
Ningaloo coast
p38.

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The Strategy states that any development in these areas should be in accordance with the recommendations of the MPRSWG (1994). It is considered that the proposed salt operation would be inconsistent with the recommendation that the eastern side of Exmouth Gulf be included in the marine conservation system. In particular, the MPRSWG (1994) states that the "*reservation of the supratidal flat between the mangroves and the hinterland would be essential to ensure adequate management of the mangal and coastal habitats of the marine reserve.*"

It should also be noted that the northern part of Giralia Station is immediately adjacent to the Southern Field Concentration Ponds described in the proposal. The Strategy identifies Giralia Station as a proposed conservation and recreation area, in recognition of the previous identification of this area for addition to the conservation reserve system. This area has been identified as being necessary to manage adjacent areas of high conservation value in the Exmouth Gulf.

State Planning Policy No. 2.6

The DPI recommends that the EPA use the objectives and guidelines of State Coastal Planning Policy 2.6 when considering the impacts of coastal processes on the proposed development and the implications for development setbacks and the structural integrity of proposed infrastructure.

SPP2.6 is applicable to the coast throughout Western Australia and seeks to ensure that the location of coastal facilities and development takes into account coastal processes including erosion, accretion, storm surge, tides, wave conditions, sea level change and biophysical criteria. It also seeks to protect, conserve and enhance coastal values, particularly in areas of landscape, nature conservation, indigenous and cultural significance. SPP2.6 contains guidelines for the determination of setbacks that protect development from coastal processes by absorbing the impact of severe storms including cyclones, allowing for shoreline movement, sea level rise, and the fluctuation of natural coastal processes.

Development Setback

The eastern side of the Exmouth Gulf consists of a mangrove shoreline backed by algal mats and supratidal salt flats that are up to10 km wide. Importantly, the total relief across these flats is of the order of 20-30cm higher than the edge of the algal mats (Straits Salt, 2006). Inundation of the supratidal flats during elevated water levels is acknowledged in the ERMP.

The ERMP provides a development setback of 40m from the 'inland edge of the algal matt boundary', based on a cursory assessment of sea level rise of 0.38m over 100 years and application of the Bruun Rule. It should be noted that SPP2.6 states that the Bruun Rule is to be applied only to sandy shorelines and that for other shore types, the setback for sea level rise shall be assessed in regard to local geography. In the pre-development scenario, we would expect the extent of inundation for a 0.38m sea level rise at this site to be extensive. The response of the shoreline to this sea level rise is likely to be complex and should be considered in significantly more detail by the proponent.

We would dispute that the proposed 40m setback is a 'conservative overestimate' in this instance. The development setback does not take into account the combined effects of cyclonic inundation, historic shoreline movement, and sea-level rise. The nomination of 'the edge of the algal matt' as the Horizontal Setback Datum, i.e. the point from which a setback is calculated, is also unlikely to be conservative. datum point & advice

In cyclone prone areas, SPP2.6 requires development to be set back from any areas that would potentially be inundated by the ocean during the passage of a Category 5 cyclone tracking to maximise its associated storm surge. It is noted that this would be extremely difficult for this proposal. However the impact of an event of this nature on the eastern shores of the Exmouth Gulf is demonstrated by Knot (2006) and should be considered (Refer Attachment – "Tropical Cyclones and the Evolution of the Sedimentary Coast of Northern Australia" by Jonathon Nott). Post cyclone measurements of debris at Tubrigi Point, which is immediately north of the development area, indicated a depth of flow of 6.8mAHD. mid-tide

The proponent should be asked to provide:

- A detailed assessment of shoreline response to sea level rise over an appropriate planning period at the site, in both the pre-development and post-development scenario. Q (1)
- An assessment of the development setback in terms of the severe cyclonic impact, historic shoreline change and sea level rise. Q (2)

Levee Design

The ERMP notes that the duration of the project is > 60yrs (Table 2-11) and a typical sea levee would be rock armoured and designed to withstand a one in 25 year ARI event. It is noted that 'storm event exceeding the one in 25 year event may result in overtopping, but the structural integrity of the levees will be maintained' (2-35). Q

The ERMP does not provide an adequate assessment of the impact of a severe cyclone upon the structural integrity of external seawalls. It is noted in the ERMP that 'catastrophic failure of the levees is highly unlikely' (2-35), however the engineering detail is not provided to assess this claim. Such an assessment would seem particularly important for designing measures to avoid or mitigate the risk of discharge of hypersaline water and bitterns from the storage ponds into the marine environment during an extreme storm event.

The proponent should be asked to provide:

- A design report that includes the structural design of the external seawall, design conditions, performance of the seawall under events that exceed design conditions and the proposed maintenance of the seawall. Q (3)

The points discussed above have been highlighted as being of most relevance to this submission. The EPA may also note that SPP2.6 and other WAPC planning policies also provide objectives and guidance for a range of other coastal development matters such as contaminated stormwater runoff, acid sulphate soils and the protection of the coastal and marine environment.

Yours sincerely

Greg Martin
Director General

14/3/2007

References
Knot 2006, "Tropical Cyclones and the Evolution of the Sedimentary Coast of Northern Australia", Journal of Coastal Research, 22-1, pp49-62, Jan 2006.

Straits Salt (2006). Yannarie Solar Environmental Review and Management Programme. Straits Salt Pty Ltd.

Journal of Coastal Research	22	1	49–62	West Palm Beach, Florida	January 2006

Tropical Cyclones and the Evolution of the Sedimentary Coast of Northern Australia

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ABSTRACT

NOTT, J., 2006. Tropical cyclones and the evolution of the sedimentary coast of northern Australia. *Journal of Coastal Research*, 22(1), 49–62. West Palm Beach (Florida), ISSN 0749-0208.

A considerable portion of the sedimentary coast of northern Australia is dominated by ridge plains (beach ridges) where the ridges are composed of coarse-grained sands and/or sand and beds of marine shells that rise above the limits of normal (fair weather and noncyclonic storms) wave run-up. Elsewhere, there exist ridge plains composed of lithic gravel, coral shingle, shell (cheniers), and, in one location, a ridge of pumice. These ridge sequences also lie above the zone of normal wave (noncyclonic) processes. There is little doubt that these ridges are deposited by waves and it is likely that only tropical cyclone-generated marine inundations are able to cause the necessary ephemeral rise in sea level in order to emplace them.

Tropical cyclones also cause substantial erosion of the coast. When the marine inundation (surge + tide + wave set-up + waves + wave run-up) or just wave run-up alone overtops coastal dunes (eolian) or ridges where they are unconsolidated, those dunes are eroded vertically and removed. At times, this can result in the deposition of sand sheets that extend inland for several hundreds of meters and taper in thickness landward. The sedimentary coast of northern Australia is composed therefore of a mosaic of landforms that represent the constant interplay between high-intensity, low-frequency events and processes and high-frequency, lower energy processes. The presence of numerous coastal landforms generated by tropical cyclones highlights the importance of recognizing the role of these events in policies concerning the management of coastal landscapes and also the reduction of hazard risks in this region.

ADDITIONAL INDEX WORDS: *Tropical cyclone, sand coast, beach ridge, chenier, dune erosion, wave-deposited sand sheet.*

INTRODUCTION

Tropical cyclones play an important role in the deposition of sedimentary landforms and hence progradation of coasts in northern Australia. They are also highly erosive agents and can completely remove, through wave and surge action, some of these same landforms and also those deposited by eolian processes. Recent observations of the impact of high-intensity tropical cyclones in Queensland and Western Australia and studies of the late Quaternary development of depositional landforms in these locations, suggest that tropical cyclones may play a much more substantial role in shaping tropical sedimentary coasts than previously thought. Evidence is presented here to show that tropical cyclones have likely been responsible for kilometers (both length and width) of coastal progradation in the form of beach ridges composed of coarse-grained sands, lithic gravel, coral shingle, shell (coquina), and mixtures of all four. In this sense, substantial areas of the coast of the Gulf of Carpentaria may owe their origin to this process, while the lengths of coast along Queensland's eastern seaboard and the Western Australian coast shaped by this process are less but still significant. Sand sheets extending hundreds of meters inland and more than a meter thick across back barrier flats also occur, and these, too, are due to cyclone storm tide and waves. Evidence is also presented here to show that storm tides and waves can remove entire multirowed eolian dune systems up to 7 meters high above Australian height datum (AHD) and represent a much more significant erosive agent than wind alone.

TROPICAL CYCLONES—THEIR FORMATION AND CHARACTERISTICS

All of the coast of northern tropical Australia (10–~28° S) is prone to the influence of tropical cyclones. This is because sea-surface temperatures here are normally above 27°C in the months from December to April and because this region lies sufficiently south of the equator to allow for the influence of the Coriolis effect. Tropical cyclones produce both strong winds and a marine inundation. The marine inundation is composed of ①storm surge, ⑤tide, ②wave set-up, ③wave action, ④and wave run-up. Storm surge is an elevation of the sea surface both ahead of and during the passage of a tropical cyclone toward the coast. The surge is a long gravity wave with a wavelength similar to the diameter of the generating tropical cyclone. A surge can be likened to a raised dome of water that inundates the coast. Variations in the height of surges are caused by the intensity ①or central pressure of the cyclone, the forward ②of translational speed of the cyclone, the ③radius

inundat^n components
1 storm surge
2 tide
3 wave set-up
4 wave action
5 wave run-up

Variat^ns in height
1 intensity or central pressure
2 translat^n speed of cyclone
3 radius of maximum winds
4 ∠ approach of storm
5 near-shore bathymetry
6 coastal configurat^n

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of maximum winds, angle of ④ approach of the cyclone track to the coast, the offshore (5) bathymetry, and the (6) coastal configuration or shape of the coastline. Surge heights can exceed 7 m under optimal conditions.

Storm tide refers to the level of inundation resulting from the storm surge and tide combined. Wave set-up is the addition to the water column from broken waves and wave run-up is the uprush of those waves against an object or a sloping surface, such as a beach. Each of these components combined along with wave action produce the marine inundation.

DEPOSITIONAL LANDFORMS

Beach-Ridge Plains

Beach ridges are defined here as a wave-deposited berm or beach often separated by a swale, which in some instances can be inundated by tides and may be capped by an eolian veneer. Foredunes are wind-deposited ridges of eolian sand lying on top of beach deposits and usually separated from other ridges by a lower swash of eolian sands. Cheniers are regarded as deposits of shell and or shell and sand lying upon a layer of mud, which also forms the swale between cheniers. There have been a number of varying hypotheses regarding the specific processes responsible for beach-ridge development, most of which acknowledge the importance of waves (DAVIES, 1967; KOMAR, 1976; TANNER, 1995; TAYLOR and STONE, 1996). The same is true of cheniers (CHAPPELL and GRINROD, 1984).

deposited wind

Wave heights in northern Australian nearshore environment are usually much smaller than in the southern half of the continent. This is due to a number of reasons, including the protection offered by the Great Barrier Reef (GBR) along Queensland's east coast, the shallow epicontinental sea of the Gulf of Carpentaria, and the considerable distance from swell-generating subpolar low-pressure systems that influence the shores of southern Australia. However, at times, tropical cyclones produce waves of considerable size (up to 30 m in deep water) which, unlike the normal fair-weather waves or those produced during episodes of strong trade winds (30–40 knots), are capable of generating swash reaching greater than 5 m AHD.

Substantial sections of the coast of northern Australia are composed of beach-ridge plains and, to a lesser extent, chenier plains. This is particularly the case around the shores of the Gulf of Carpentaria (Figure 1). Here in places up to 80 individual ridges, paralleling the shore, form beach-ridge plains that extend inland for over 5 km. The ridges, along the eastern and southern shores of the Gulf, contain shell-rich layers up to 1–2 m thick interspersed within medium- to coarse-grained sand (RHODES *et al.,* 1980). They rise up to 6 m above mean sea level (tidal range of approximately 2 m) and extend along shore for over 10 km in places. RHODES *et al.* (1980) suggested that the ridges were deposited during tropical cyclones. There are several reasons why this is likely to be the case. First, as mentioned, the ridges here contain distinct beds of marine shells (*Anadara* sp.). Second, their height above sea level places them beyond the range of inundation by normal wave processes but not waves and storm tides generated by tropical cyclones. And third, RHODES *et al.* (1980) found that radiocarbon dates from near the crest and base of a ridge in several locations were nearly identical, suggesting that individual ridges are deposited during the one event (one ridge per event).

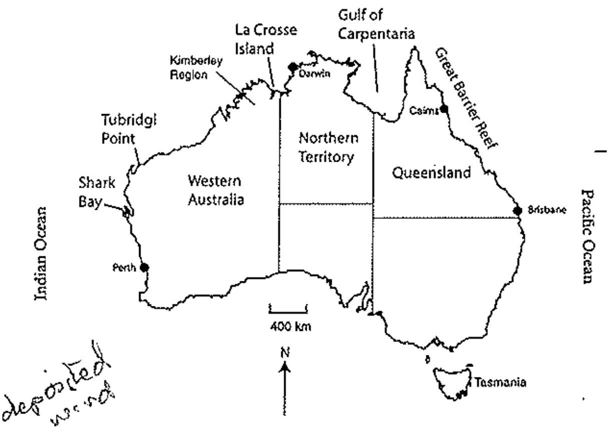

Figure 1. Location map of places named in text.

RHODES *et al.* (1980) and RHODES (1982) suggested that beach ridges and cheniers alternated in their times of formation around the Gulf of Carpentaria depending on sediment supply. Wetter phases of climate during the late Holocene resulted in rivers transporting higher levels of sediment to the coast and therefore beach-ridge formation, and chenier development was favored during drier phases, when shell production in the nearshore zone increased with diminished sediment loads. CHAPPELL and GRINROD (1984) also noted that chenier formation in Princes Charlotte Bay in northeast Queensland was likely a balance between sediment supply and shell production. Here, the cheniers merge into beach ridges along shore and HAYNE and CHAPPELL (2005), and NOTT and HAYNE (2001) used the latter as a record of prehistoric tropical cyclone frequency over the last 2500 years.

Not everywhere, though, do beach ridges contain shells and shell beds that may be taken as indicative of high-energy deposition. In many locations across northern Australia, beach ridges are composed entirely of sand. A sequence of nearly 30 Holocene beach ridges extending inland and paralleling the coast occur at Cowley Beach approximately 130 km south of Cairns (Figure 2). GRAHAM (1993) suggested these beach ridges formed as abandoned berms, which gradually accreted due to normal swash and eolian processes. The height of these ridges, however, up to 5 m AHD, and the texture of the sand (coarse- to very coarse-grained with many particles larger than 1-mm diameter) suggest that their accretion is beyond that capable of normal wave conditions. The region here is dominated by southeasterly trade winds that rarely exceed 30–40 knots except during tropical cyclones. Waves larger than 1 m at shore are rare except during tropical cyclones because there is a limited fetch, being approximately 30–40 km between the mainland coast and the GBR, and the offshore gradient is very shallow (extending from 0 m at shore to approximately 50 m depth at GBR). The waves

Figure 2. Oblique aerial view of beach-ridge plain at Cowley Beach south of Cairns, Queensland. The ridges here are composed of coarse-grained sands to gravel and rise to over 5 m AHD. There are approximately 30 consecutive ridges in the Holocene sequence. (Photo by D. Hopley.)

young ← old

that are generated during normal southeasterly trade wind conditions and winds generated by low-pressure systems that have not developed into a tropical cyclone have limited run-up potential and are unable to reach the crest of the beach ridges at this location. Tropical cyclones appear to be the only mechanism capable of producing waves and surge of sufficient height to be able to deposit a sand ridge of this elevation at this location, irrespective of whether the ridge accretes over a series of events or just one.

The beach ridges at Cowley Beach vary in age from approximately 5000 YBP at the landward margin of the sequence to less than 1000 YBP nearer the coast. Those toward the rear of the beach-ridge plain would have formed when relative sea level was higher (due to hydroisostatic rebound), which, in this region, was approximately 1–1.5 m higher than today (Chappell *et al.*, 1983). Relative sea level would have played a progressively diminishing role in beach-ridge formation toward the present day with sea level having little influence in possibly assisting waves produced during normal fair-weather conditions to generate swash heights equal to the crest height of the ridges after approximately 2500 YBP. The same is true of the Holocene high-energy window, which was a phase during the early phases of the Holocene marine transgression when vertical coral reef growth was outpaced by sea-level rise and the mainland coast of northeastern Australian was subject to more open ocean swells (Hopley, 1984).

Coral Shingle Ridges

Coral shingle ridges occur predominantly around the shores of islands and cays along the length of the GBR (Figure 1). There appears to be little doubt that these features are deposited by cyclone-generated waves and surge for they are composed of clasts too coarse to be transported by wind and there have been several eyewitness accounts of their formation during such tempests (Chappell *et al.*, 1983; Chappell, and Wallensky, 1986; Chivas, Hayne, and Chappell, 2000; Maragos, Baines, and Beveridge, 1973). Coral shingle ridges are nearly identical in form to sand beach ridg-

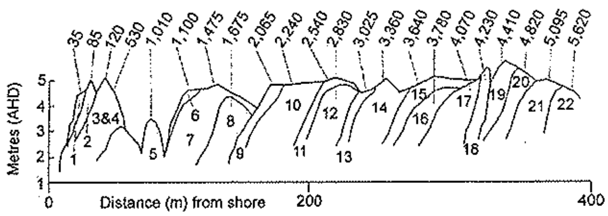

Figure 3. Stratigraphy and chronology (calibrated radiocarbon years) of the coral shingle ridge sequence at Curacoa Island, central Great Barrier Reef (after Nott and Hayne, 2001).

es except they are composed almost entirely of coral fragments eroded from near-shore reefs by wave action and/or offshore accumulations of these fragments (BAINES, BEVERIDGE, and MARAGOS, 1974; DAVIES, 1967; HUGHES, 1999; RASSER and RIEGL, 2002). The offshore accumulations result from a number of erosional processes, such as biodegradation and wave action during both storms and fair-weather conditions (HUGHES, 1999; RASSER and RIEGL, 2002). Coral shingle ridges occur in locations where coral reefs occur close to shore. It is thought that the angle of the offshore reef slope plays a role in determining whether the eroded fragments are transported predominantly offshore or onshore. Steep reef fore-slopes favor offshore transport of fragments, often to depths of greater than 50 m, which is too deep to be reworked and transported by storm waves. Shallow sloping and, particularly, wide reef fronts favor transport onshore and the formation of coral shingle ridges. However, some sites, such as Curacoa Island in the central GBR that are fronted by narrow, steep reef slopes, have extensive coral shingle ridge development on land (HAYNE and CHAPPELL, 2001; NOTT and HAYNE, 2001). These sites with minimal accumulation of coral shingle in the shallow waters of the reef and maximum accumulation of shingle in the deeper offshore waters below wave base (depth to which waves will entrain and transport sediment on ocean floor) suggest that the onshore ridges could have formed from predominantly live coral fragments broken off during storms. At other sites, however, there can be little doubt that onshore ridges were formed from the reworking of existing accumulations of shingle in the shallow waters offshore.

The number of shingle ridges in a sequence varies between locations from 2 to over 20; Curacao Island in the Palm Island Group north of Townsville, for example, has 22 consecutive, shore-parallel coral shingle ridges (Figure 3). The ridges often

Figure 4. Gravel ridge sequence along the east Kimberley coast, Western Australia. The gravel ridge barriers here often impound lagoons. The ridges rise above 5 m AHD.

rise in height to over 5 m AHD and occur predominantly on the sheltered or mainland-facing sides of islands. This suggests that their preservation potential is highest in these locations, as they are likely removed by erosion, possibly through wave attack at their base during fair-weather conditions on the windward-facing coasts. BAINES, BEVERIDGE, and MARAGOS (1974), BAINES and MCLEAN (1976), and MCLEAN (1993) have noted that coral shingle ridges formed by tropical cyclones on Pacific islands and atolls tend to move across the reef flat with time to become welded to former shingle ridges. Hence, they do not tend to be preserved to the same degree as distinct and separate ridges like they do along the GBR.

Shell Ridges

Unlike cheniers, shell ridges do not form as separate features on a mud substrate. Rather, they are much more akin to sand beach ridges except they are composed entirely of marine shells. They are not common around the coast of northern Australia, although they are extensively preserved at Shark Bay, Western Australia. Here, the shells of the species *Fragum erugatum,* otherwise known as the Cardiid cockle, flourish in the hypersaline waters of Shark Bay (Figure 1). There is limited circulation of waters between the open ocean and the deeply indented bays here, particularly Hamlin Pool, because of the formation of the Faure sill, a sand bar that developed during the mid to late Holocene and stretches across the mouth of Hamlin Pool. The limited number of predators of *Fragum erugatum* means that this species thrives in the nearshore environment and provides an abundant supply of shells of remarkably uniform size (5–8-mm diameter), to be transported onshore during marine inundations induced by tropical cyclones. The resulting shell ridges are composed entirely of this shell species and only in the most shoreward ridges does any sand occur; this sand appears to be removed from the ridges with time because the second and third row of ridges inland are devoid of any sand.

There are approximately 40 ridges paralleling the coast and extending inland at Hamlin Pool, and the ridges increase in age with distance inland; the majority of the ridges were deposited from 5500 YBP to the present (NOTT, unpublished manuscript). Pleistocene ridges are also preserved here landward of the Holocene sequence. The Pleistocene ridges differ from the Holocene ones, as the former are composed of a much wider array of shell species, which are also larger in size compared with the single species of uniform size in the Holocene ridges. These larger Pleistocene shells are open-ocean species and suggest that water circulation between the open ocean and the indented bays was much better during the Pleistocene compared with that at present. The shell ridges here extend in height up to 8 m AHD. Such ridges could only, within this very protected and calm-water environment, have been formed by tropical cyclone-induced waves and surge.

Gravel Ridges

Ridges composed entirely of gravel and occasional coral fragments are common along the Kimberley Coast of northwest Western Australia. These ridge sequences form gravel barriers and often impound back-barrier lagoons in embayments along sections of coast dominated by steep rock cliffs (Figure 4). They are particularly common along the western side of Cambridge Gulf north of Wyndham in the east Kimberley region. The gravel ranges in size up to 1.6-m diameter (A-axis) and 1.4 m (B-axis) and have been deposited into sequences of up to 9 ridges paralleling the shore. At La Crosse Island (Figure 1) offshore from the mouth of the Ord River, gravel ridges have been deposited in every embayment and thereby form a discontinuous sequence that surrounds the island. The ridges at two surveyed sites each on opposite sides of the island extend up to 5 m AHD, and radiocarbon samples on coral fragments embedded with the core of ridges from each of seven ridges from these sites show that they were deposited between approximately 5000 YBP until recently (NOTT, 2000). The radiocarbon samples do not show a progressive increase in age with distance inland, suggesting that the ridges are regularly overtopped and reworked by marine inundations.

Interestingly, the most landward ridges within many of the ridge-impounded embayments display concave, circular depressions up to several meters across and 1 m deep. The origin of these features is intriguing because they do not appear to have formed by tree fall and disturbance of the gravels by the uprooting of the tree, as this could be expected to form an asymmetric-shaped depression. There is also no evidence that trees ever grew on the ridges here. And while large saltwater crocodiles are known to inhabit the island, nesting in ridges composed of such coarse particles is not a recognized behavior of this animal, nor is it known to be a feature of turtle nesting, especially considering that the depressions are located on the most landward ridge and a turtle would have to traverse six or more substantial ridges. Similar depressions within gravels and sands have been recognized to have developed during tsunami inundations in Japan (SATO *et al.,* 1995). It is not suggested here that tsunamis are responsible for the circular depressions on La Crosse Island, as the size of the particles composing the ridges here are well within the range of particle sizes able to be transported by tropical cyclone-generated waves (NOTT, 2003a). This part of the Western Australian coast is also not known to have experienced tsunami impact, unlike the Indian Ocean-facing coast of Western Australia during historical time. The size of the gravel particles and the height of the ridges above sea level suggests once again that these features are likely a product of tropical cyclone-generated marine inundation.

Pumice Ridges

A ridge of pumice was deposited at North Mission beach, Queensland, during the marine inundation generated by an intense tropical cyclone on March 10, 1918 (TAYLOR, 1982). The inundation occurred at high tide and was reported to have reached at least 3.5 m above normal sea level. The inundation resulted in the deaths of many people and transported and deposited onto the mainland supplies from a shed on Dunk Island approximately 5 km offshore. Indeed, one large bag of flour was deposited over 3.5 m high in a tree and

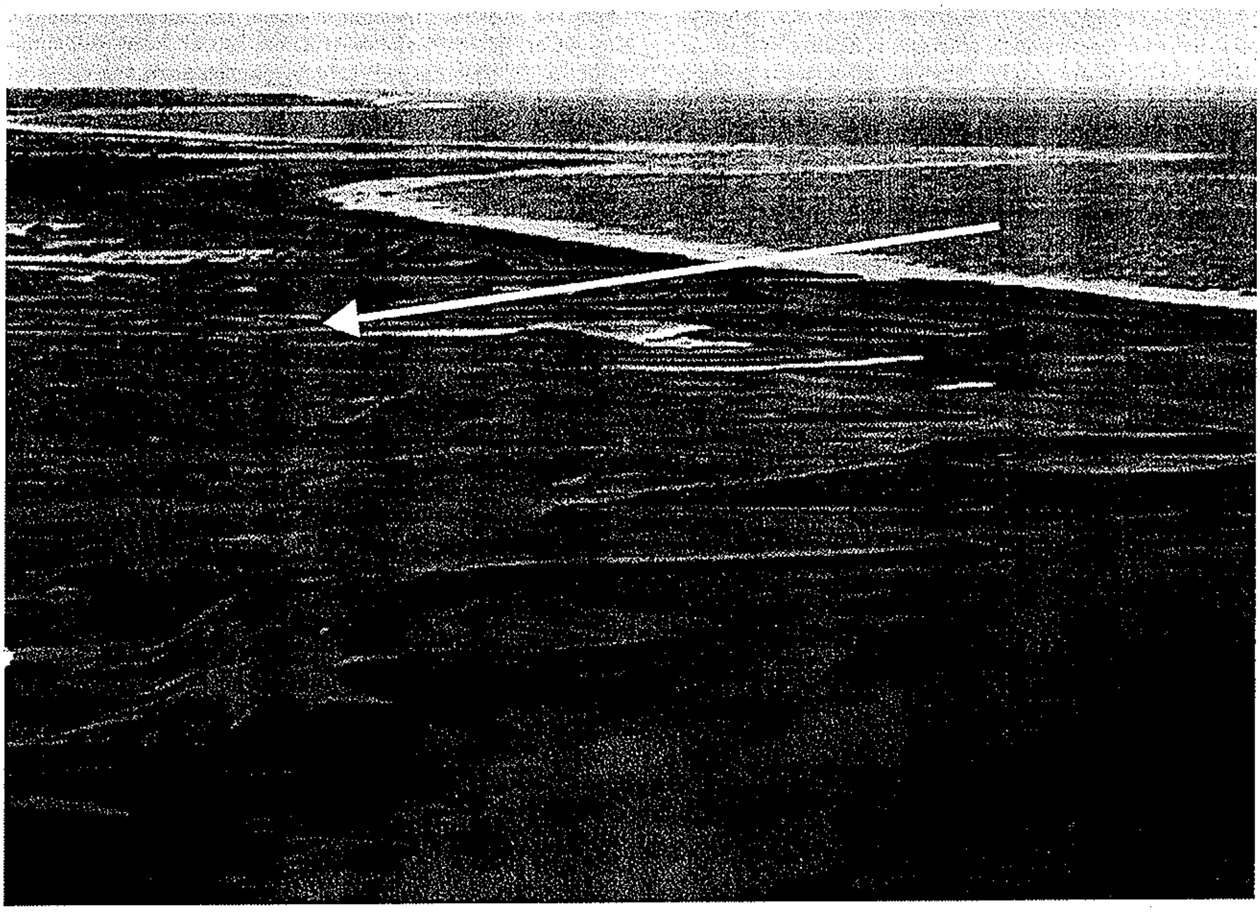

Figure 5. Impact of tropical cyclone Vance (March 1999) on the coastal dune systems of Tubridgi Point, Western Australia. There were three rows of 6-m-high dunes here prior to landfall of Tropical Cyclone Vance. These dunes were completely eroded and hence removed (except for occasional knolls) and the sand transported inland as a sand sheet for 300 m. Arrow shows direction of marine inundation movement onto the coast. The entire area was vegetated with grasses, shrubs, and small trees to 2 m high. Note that all of this vegetation was stripped from the landscape by the marine inundation.

the flour in the center of the bag was still sufficiently dry to be able to make damper (a type of bread) the following day after the maelstrom (TAYLOR, 1982). The crest of the pumice ridge here reaches 5 m AHD and it extends alongshore for approximately 500 m. This is the only reported ridge of pumice deposited during a tropical cyclone so far, and it is not known whether sand was also deposited along with pumice to form this ridge at the time. No sand occurs in the ridge today, for it is composed entirely of well-rounded pumice particles; however, a sand beach ridge (up to 3–4-m-high AHD) at South Mission Beach was reported (TAYLOR, 1982) to have been deposited during this same event.

RIDGE DEPOSITIONAL PROCESSES

It is difficult to know whether wave-emplaced sedimentary ridges are deposited gradually during the storm or as a sedimentary unit that moves landward from an existing offshore accumulation. Alternatively, one ridge could be constructed from a series of sedimentary units deposited during successive storms. SCOFFIN (1993, p. 209) has described coral shingle ridge building as ridges that "have been transported and deposited like large asymmetric waves of sediment; material picked up on the seaward side is rolled up the ridge and dropped down the advancing slope," suggesting that an entire or substantial part of an offshore accumulation of shingle is moved onshore as a single unit during the storm. If, on the other hand, ridges accumulate gradually, then the ridge could be assumed to increase in height over time during the storm. In this instance, wave run-up may play a role in their formation.

HAYNE and CHAPPELL (2001) note that coral shingle ridges contain a number of distinct sedimentary facies or units of sediment. These include storm beach face, berm, crest, and washover facies. Beach face and berm facies include porous, clast-supported, coarse biogenic shingle deposits that occasionally dip seaward but are usually structureless. Crest fa-

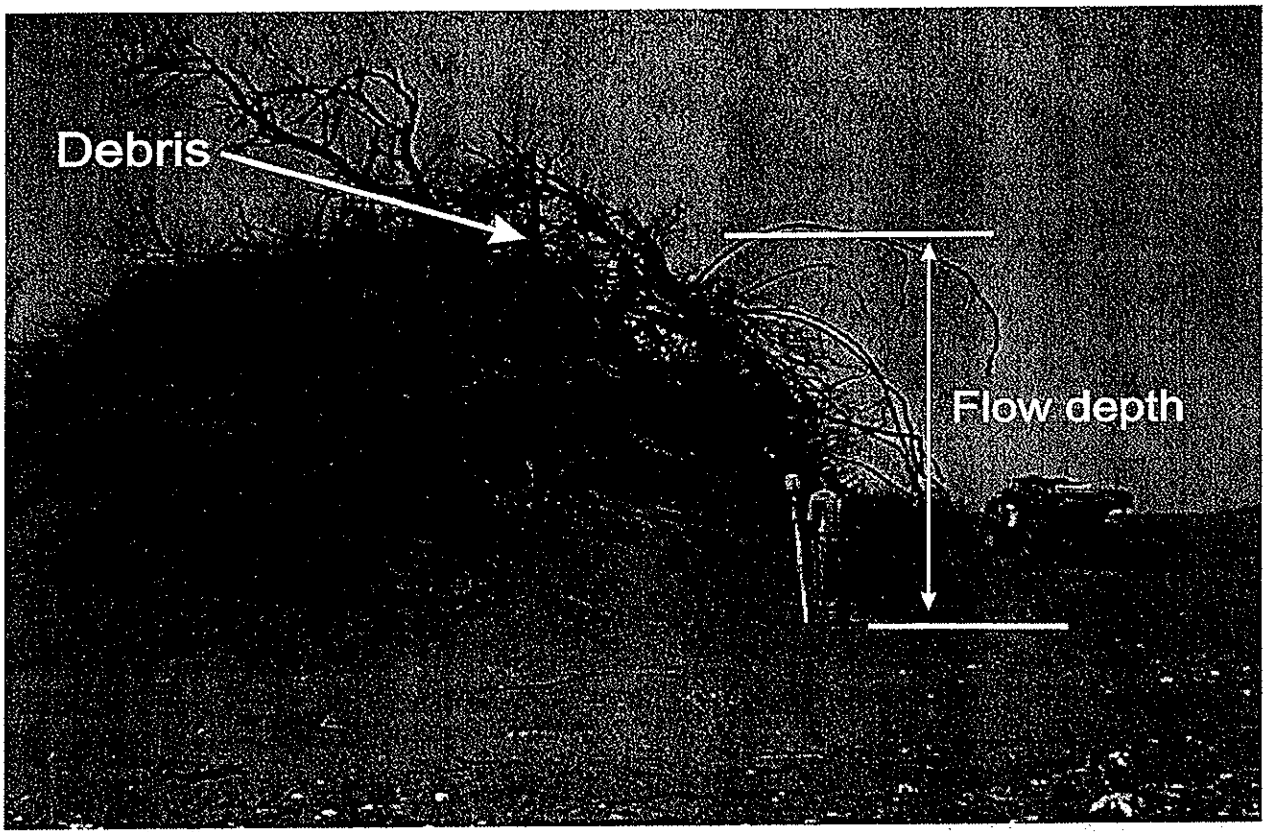

Figure 6. Eroded dune knoll left after inundation by Tropical Cyclone Vance. Depth of flow here, which was at back of beach, was 6.8 m AHD and is marked by debris left in tree on crest of dune knoll.

cies are horizontally bedded and are finer grained than beach face deposits. Washover facies are bedded, dip landward up to 15° and sometimes contain imbricated clasts. Each of these facies or units combine to make a storm deposit. Storm deposits are often separated by ground surfaces, being lenses of pumice pebbles and a weak sooty or earthy palaeosol (ancient soil). These ground surfaces are really former ground surfaces or the surface of the feature that was exposed for sufficient time between individual cyclone events so that some soil development was able to take place. HAYNE and CHAPPELL (2001) note that ridges often contain only one storm deposit, but they note it is possible for two or more storm deposits to occur in one ridge. However, it is clear that the coral shingle ridges along the GBR are frequently overtopped by marine inundations, for pumice layers can sometimes be found across the surface of the ridge sequence and radiocarbon dating of coral clasts scattered across the surface of the ridges often return mixed ages, particularly young ages on otherwise older ridges.

It is likely that all components of an inundation contribute to the deposition of a sedimentary ridge. It is difficult to know to what degree the eventual crest height of a ridge is a reflection of the height of the storm tide plus wave and reef set-up (wave set-up over a coral reef being a separate phenomenon and in addition to normal wave set-up) or just some of these components, or whether wave run-up extending beyond the storm tide level plays a substantial role. However, storm tide events of equal or near-equal height to the ridge crests must occur because the ridges are clearly overtopped by subsequent inundations. In these situations, it is unlikely that the ridge plain is overtopped by wave run-up alone extending above and beyond a storm tide that is substantially lower than the height of the ridge crests. Hence, the overtopping inundation is more likely to consist of a storm tide of at least equal height to the ridge crests because wave run-up alone would not be able to travel over a ridge plain consisting of multiple and separate ridges. Also, observations of historical storm tide-emplaced coral shingle ridges suggest that wave run-up may play an insignificant role in at least some situations (NOTT, 2003b). For example, the 3.5-m-high ridge deposited on Funafuti Atoll during Tropical Cyclone Bebe in 1971 was deposited during a marine inundation (not including wave run-up) that was 5 m above the level of the reef flat, or mean low tide level, and 1.5 m higher than the elevation of the resulting ridge crest (MARAGOS, BAINES, and BEVERIDGE, 1973). A similar situation occurred during the

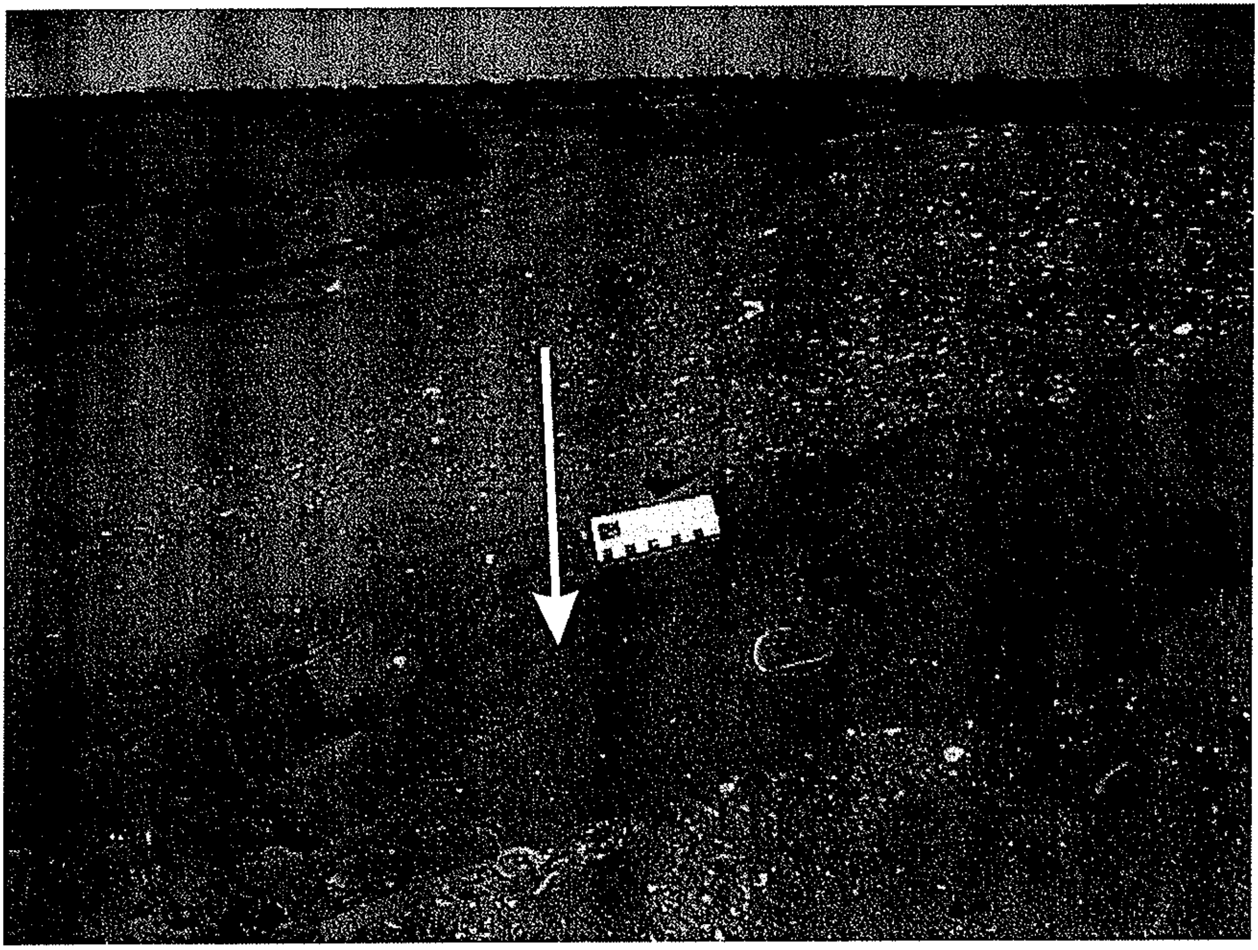

Figure 7. Toe of sand sheet deposited by marine inundation from Tropical Cyclone Vance. Note two sets of tabular cross-bedded foresets suggesting that more than one inundation flooded the coast here during the event.

emplacement of the pumice ridge at North Mission Beach during the intense tropical cyclone of March 1918. Eyewitness observations and results from numerical storm surge and wave models of the event, along with knowledge of the tide level at the time, shows that the storm tide (surge plus tide) and wave set-up combined amounted to an inundation level of 4.7–4.9 m (AHD) (Nott, 2003b); the ridge crest is 4.5–5.1 m AHD. This suggests that wave run-up could have only contributed 0.2–0.4 m of the ridge height at it highest elevation. Elsewhere, where the ridge is only 4.5 m high (AHD), wave run-up does not appear to have contributed to formation of the pumice ridge.

It would appear, therefore, that in at least some instances the height of the crest of coral shingle and pumice ridges is close to or less than the height of the storm tide and wave set-up combined. This does not mean, however, that progressive accumulation or accretion of a ridge cannot occur during the storm. But it does mean that wave run-up may not always be an important component in the marine inundation during ridge accretion. Determining to what extent wave run-up does play a role in ridge accretion is important when attempting to determine the intensity, or central pressure, of tropical cyclones responsible for deposition of prehistoric ridges (Nott, 2003b; Nott and Hayne, 2001).

SAND SPLAYS AND COASTAL DUNE EROSION

Coastal sand dunes are often eroded and diminished substantially in height, when overtopped by storm tides and waves. The eroded sand can be transported inland as a splay or sheet that thins landward (Donnelly *et al.*, 2001; Liu and Fearn, 1993). An excellent example of a tropical cyclone-deposited sand splay occurred when Tropical Cyclone Vance, with central pressure 910 hPa, crossed the Western Australian coast near Tubridgi Point in March 1999. Historically, this was the most powerful cyclone to cross the Australian coast. Winds around the eye were estimated at 300 km/h and Tropical Cyclone Vance generated the strongest ever record-

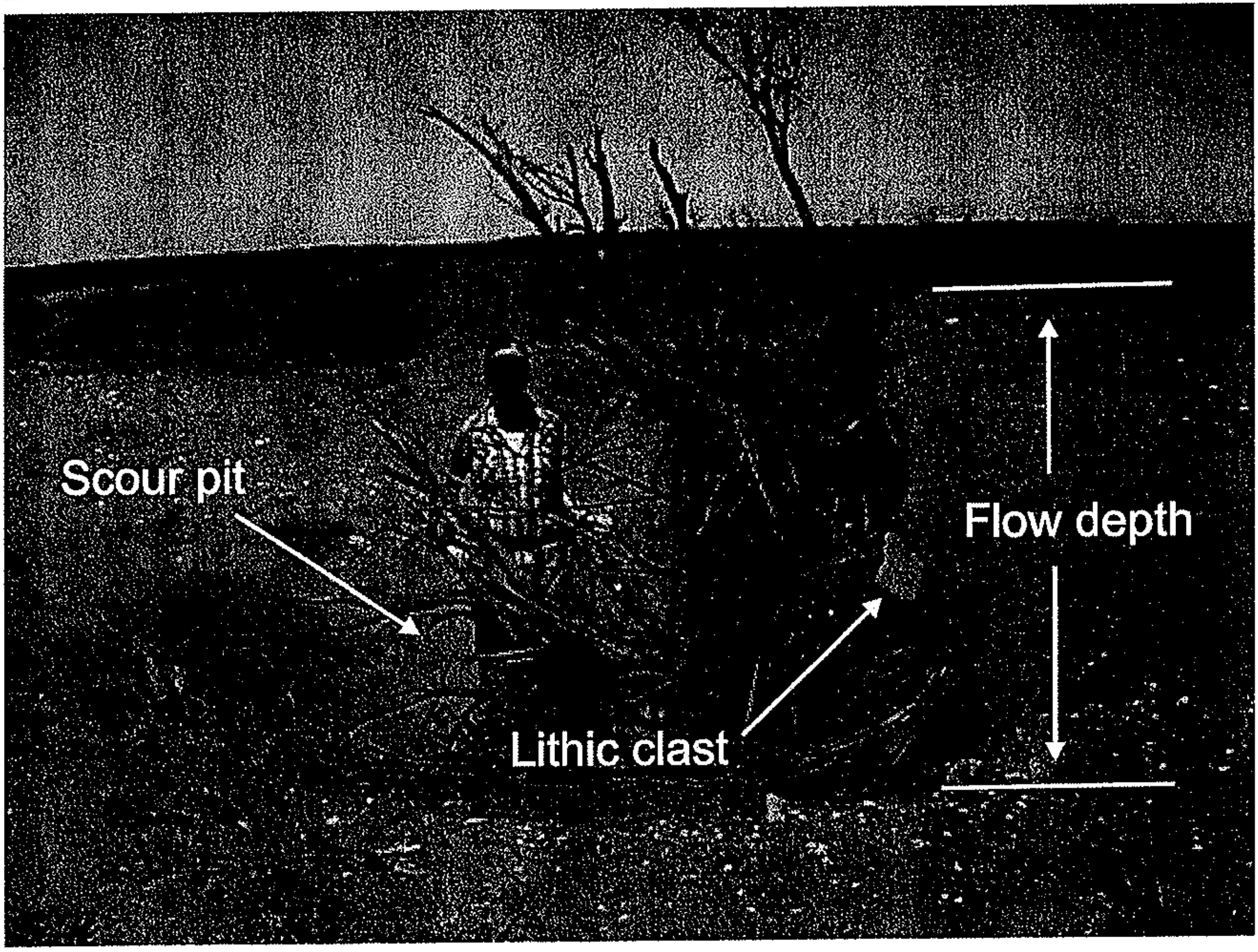

Figure 8. Scour pits and debris ~~and lithic clast~~ in tree. Scouring occurred on landward side of trees. Scour pit here measures about 1 m deep, 3 m wide, and 10 m long. Location is about 200 m inland.

ed wind gust in Australia of 267 km/h at Learmonth, approximately 30 km from the eye. The zone of maximum winds struck a section of coast composed of a sand barrier comprising three rows of parallel dunes approximately 6 m above mid-tide level behind a wide, sandy beach (Figures 5 and 6). In most locations along this section of coast, the first two rows of dunes were completely eroded and the sand transported away, presumably offshore, and the third or most inland dune row was eroded to form a steep scarp. Precisely where the zone of maximum winds struck, however, all three rows of dunes were destroyed and the sand transported inland as an extensive splay approximately 400–500 wide and 200–250 m deep (extending inland from the position of the former first dune row) (Figure 5).

This sand splay decreases in thickness from 1.5 m immediately to the rear of the position of the former third row of dunes to 0.75 m thick at its most inland extent. The splay terminates abruptly at a salt marsh, where it is marked by a steep fronted (~30° angle) toe slope. Sediments within the splay were deposited as steep (~30°) tabular cross-beds (Figure 7). Medium- to coarse-grained sand occur at the base of the unit along with clasts of coral and shells and grades upward into medium- to fine-grained sand.

Lithic gravel measuring up to 25 cm across was also deposited in an imbricated position within the sand sheet inland of the position of the former dunes. The gravel dips toward the ocean, showing it was deposited by the onshore flow. The marine inundation also generated scour pits within the sand splay. These pits measure up to 3 m wide and 1 m deep and occur on the lee (inland) side of tree stumps. The onshore flow was also able to carve channels 1 m deep and several meters wide over distances of several 10s of meters (Figure 8). They were carved by the onshore flow of water rather than water draining from the land, as demonstrated by the imbricated gravels in the sand floor of these channels. All of the vegetation, including clumps of spinifex grasses, which dominated the low-lying salt-marsh plain behind the former dunes, small trees (up to 3 m high), and bushes, were

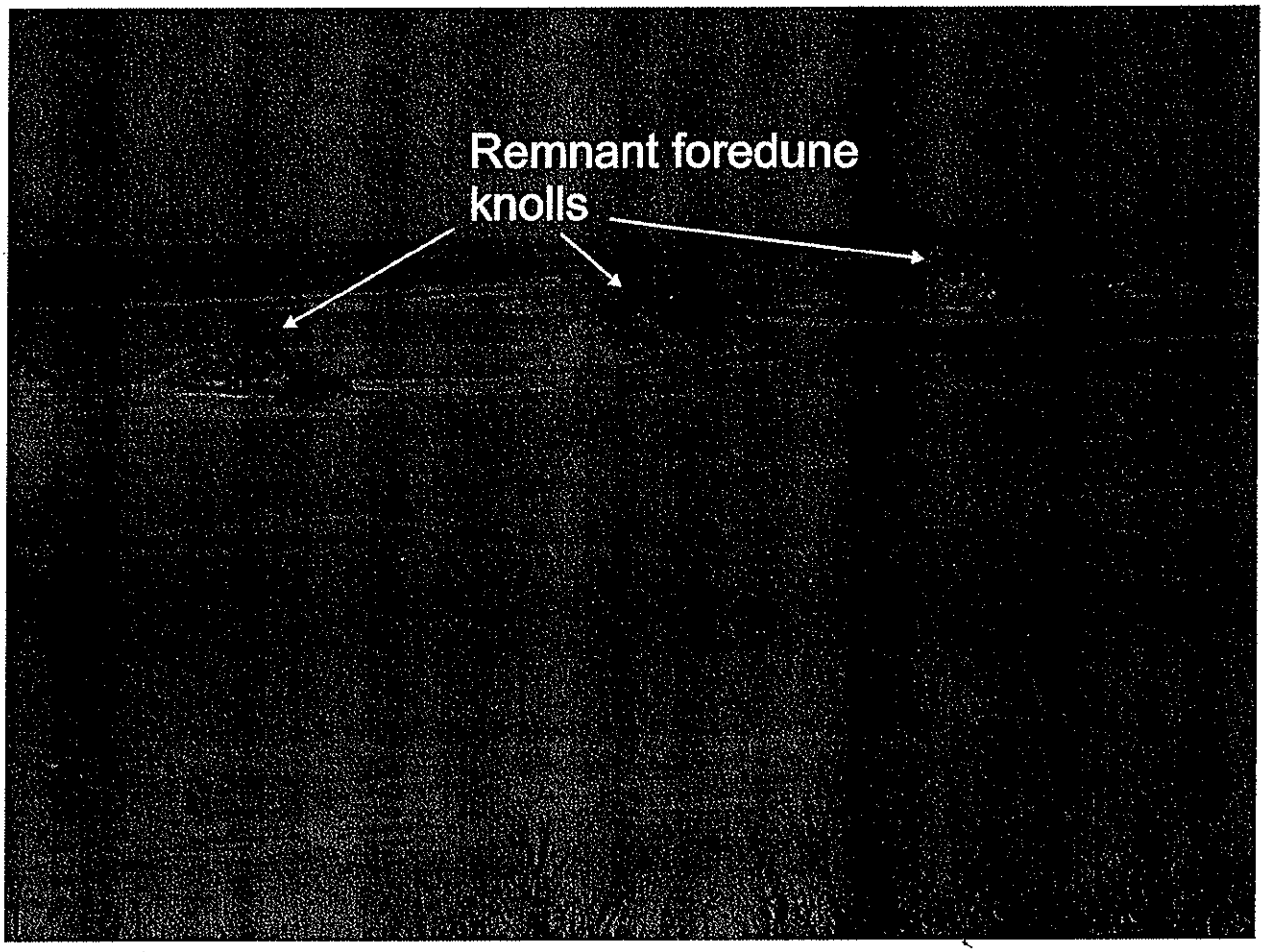

Figure 9. Remnant foredune knolls left after marine inundation during tropical cyclone Chris (February 2001). Marine inundation overtopped foredunes here, removing them completely except for remnant knolls.

stripped from the land surface up to 300 m inland by this flow. Only occasionally were the dead stumps of trees remaining, such as on the crest of an eroded knoll of the former foredune or inland of the former dunes. Debris in these dead stumps show that flow depths were still at least 2 m at 150–200 m inland and flow velocities were also high, as gravel clasts were embedded within the debris at an elevation of 1.5 m above the present ground surface (Figure 8).

The extent of the sand splay (washover sheet), the tabular cross-beds, scour pits, and imbricated gravel suggest that the marine inundation generated by Tropical Cyclone Vance near Tubridgi Point struck the coast with considerable force and moved inland as a reasonably high velocity bore. The presence of similar scour pits and erosional features in beach and dune sands have been determined empirically to occur when flow velocities exceed 4–5 m/s, during the passage of tsunamis across sand barriers (Sato *et al.*, 1995). Also the fact that the flow was transporting lithic gravel clasts as suspended, or at least saltating (bouncing), load 1.5 m high over 200 m inland shows that the flow velocity must have been high. Hence, the flow depth was between 6–7 m high (above the event tide) across the beach here and at least 2 m high 200 m inland. Such flows and the impacts on the coast are more reminiscent of tsunamis than that normally ascribed to storm tides (Kawata *et al.*, 1999).

Extensive dune erosion has also occurred during other intense tropical cyclones striking the Western Australian coast in recent years. Tropical Cyclone Chris (915 hPa central pressure) crossed the coast north of Port Hedland in December 2001. The maximum inundation during this event appears to have occurred along a 500–700-m stretch of sandy coast and, here, dune erosion was greater than elsewhere along the coast. The dunes experienced horizontal erosion or scarp retreat where they were not overtopped by the inundation. The dunes were totally removed with only occasional knolls of dune left intact where the inundation did overtop the foredune (Figure 9) and dune swales behind the frontal dune were scoured where the height of the inundation was great-

~5 m/s

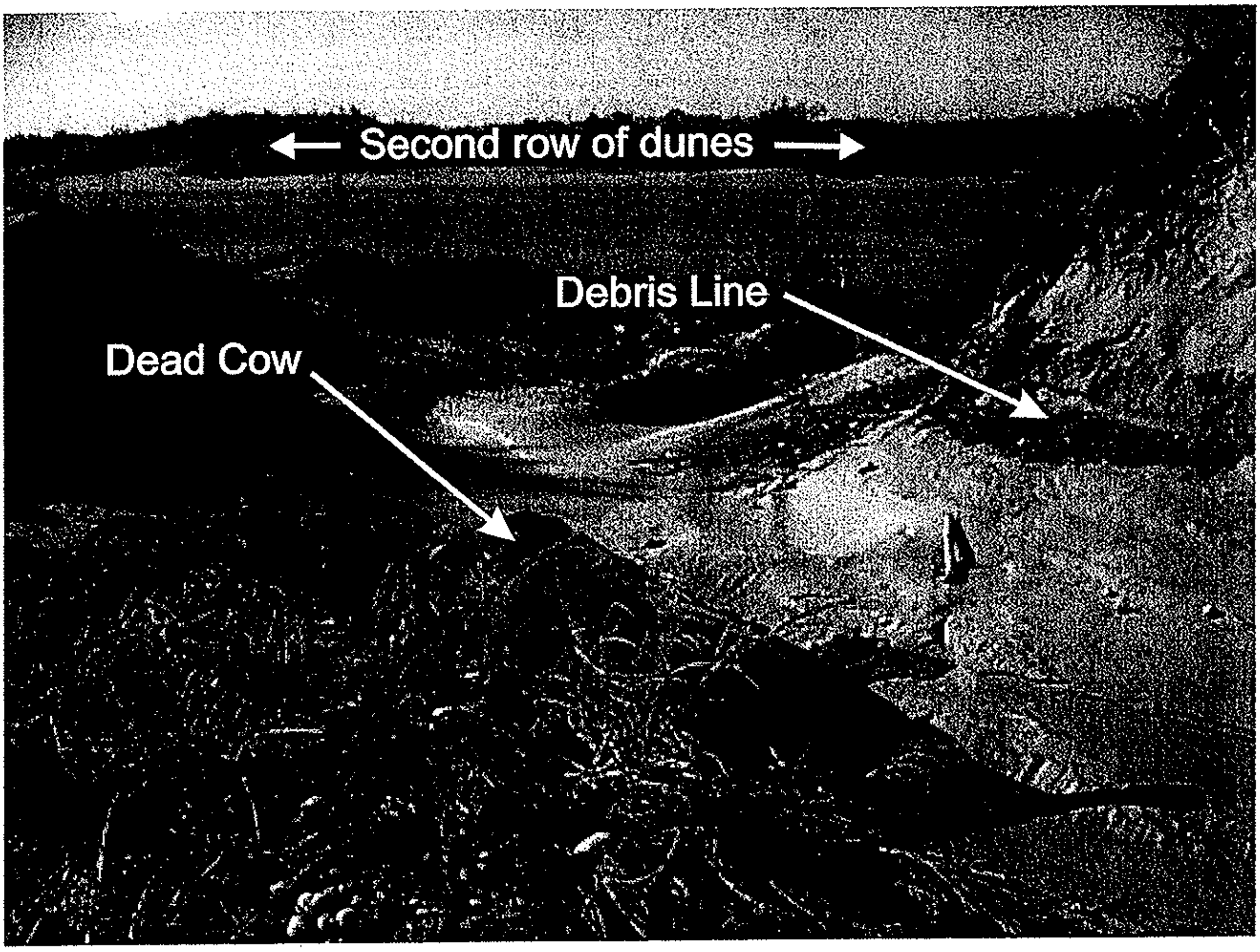

Figure 10. Erosion in third row of dunes at same location as Figure 9. Note cow wedged into scoured opening in dunes and debris line of inundation. Photo highlights that, even if dunes inland of foredunes are not overtopped and eroded, they can still be substantially eroded.

est. Many cows were deposited along the beach during the event and, at one site, a cow was deposited in a narrow opening through the third row of dunes (Figure 10). This opening appears to have been scoured, or at least enlarged, during the cyclone storm tide event, for an oblate-shaped depression has been eroded into the sand floor at the mouth of the opening. Mud was eroded and transported from the swale between the first and second rows of dunes and deposited at the head of this opening well inland of the third row of dunes. The storm tide in this instance penetrated approximately 150 m inland beyond the position of the first row of dunes.

The nature of erosion to the sandy coasts impacted by Tropical Cyclones Vance and Chris is very similar to the erosional impacts of hurricanes in the United States (MORTON and SALLENGER, 2003; SALLENGER, 2000). Based on observations and measurements of numerous hurricane impacts on US sandy coasts, the Federal Emergency Management Agency (FEMA) has noted that, where the dune reservoir (area of dune above the storm still-water level) is greater than 540 square feet (~20 square m per meter length of beach), that dune is likely to experience horizontal erosion only (FEMA, 2003). Where the dune reservoir is less than 540 square feet that dune is likely to erode vertically and be largely removed. In the latter situation, FEMA noted that the marine inundation will penetrate inland beyond the former dune position. While dune reservoirs have not been calculated for the former dunes along the Western Australian coast impacted by Tropical Cyclones Vance and Chris, the resulting styles of erosion and relationship to inundation height were essentially the same (Figure 11).

DISCUSSION

There appears to be little doubt that tropical cyclones play a significant role in shaping substantial sections of the northern tropical Australian coast. This is not to say that these extreme events are the only geomorphic processes operating, for clearly, more gradual processes, such as tides and fair-

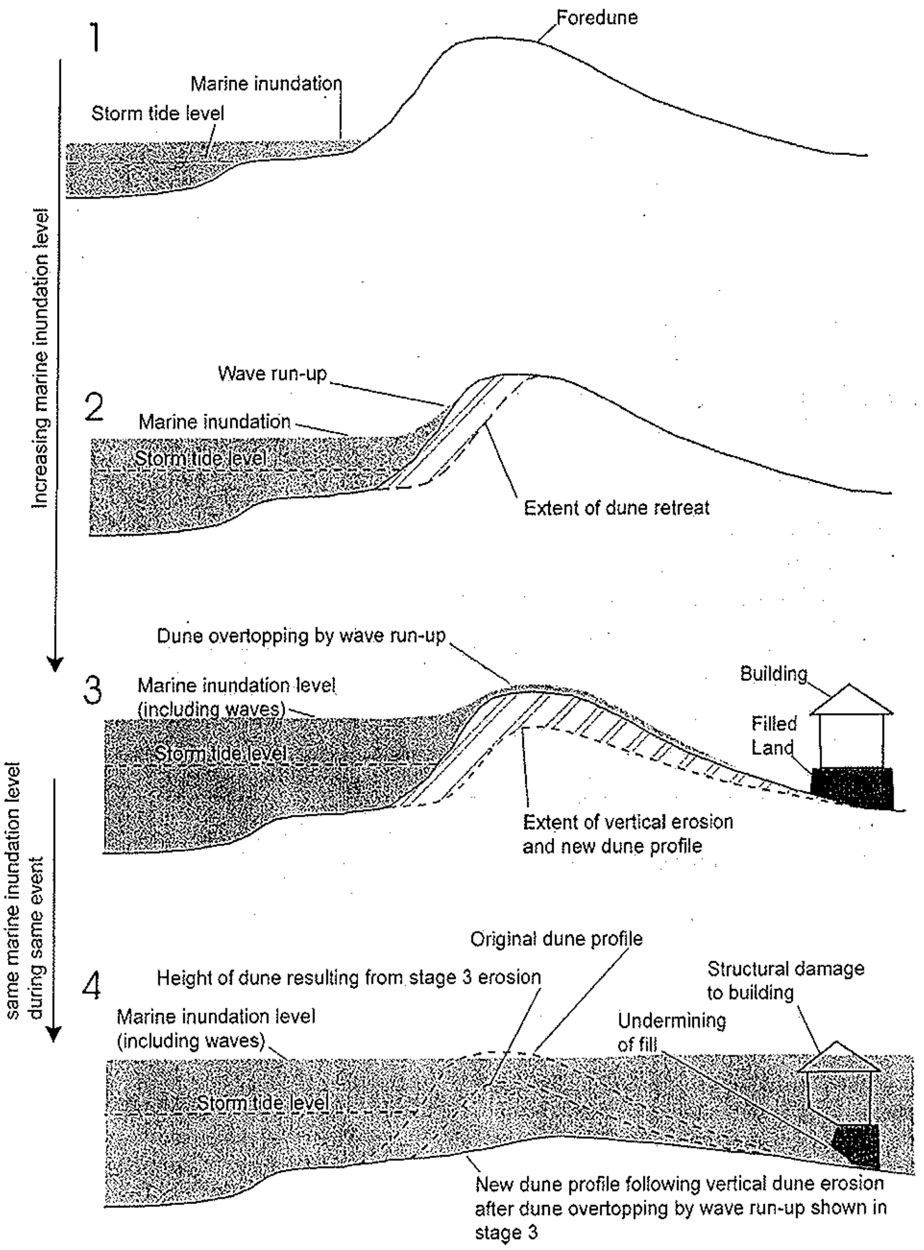

Figure 11. Conceptual diagram of relationship between dune erosion and height of marine inundation. This model is based on observations of impacts of tropical cyclones on eolian sand dunes in Western Australia, such as after Tropical Cyclone Vance and Chris, and also in the United States (FEMA, 2002; Morton and Sallenger, 2003; Sallenger, 2000; USGS, 2003). Where inundation overtops dunes, that dune erodes vertically and can be completely removed. Dune erodes horizontally or scarps when inundation does not reach crest of dune but dune still stays largely intact and can prevent marine inundation from penetrating further inland. Wave-transported sand sheets will occur when the inundation overtops and removes the dune but are unlikely when inundation only results in dune scarping.

weather wind and wave regimes and associated nearshore tidal currents, also play a very important role in shaping beaches, estuaries, and coastal dunes. But there is a suite of landforms that could be seen to be the product of more high-energy, less frequent events that exist in concert with landforms resulting from lower energy processes. The progradation of ridge plain coasts here appears to be primarily driven by tropical cyclone-induced marine inundations. And at the same time, infrequent but substantial erosional events can leave long-lasting imprints on the coast when marine inundations overtop sand dunes and carry the sand inland over hundreds of meters as sand splays.

Little is known of the relationship between tropical cyclone characteristics and the locations of deposition (ridge development) and erosion of coastal dunes and sand splay deposition. The answer may lie in the position of cyclone landfall. Based on observations of recent tropical cyclone impacts, for example, it would appear that ridge development does not appear to occur where the zone of maximum winds crosses the coast. Rather, erosion of dunes and deposition of sand splays seems to occur at these locations. This would suggest that ridge deposition may occur at some distance from the zone of maximum winds, but at this stage, this distance is not known. Alternatively, ridge deposition may be controlled by physical landscape factors, such as the coastal configuration or depth of offshore bathymetry. It may be possible also that ridge development is favored by particular cyclone behaviors, such as the angle of approach toward the coast and/or the translational speed of the system.

The geomorphic imprints left in the coastal landscape by tropical cyclones can be used to reconstruct a record of the frequency and magnitude of these events. Ridges and storm deposits can be dated to obtain a frequency of tropical cyclones and a method to determine the magnitude of the tempest has been developed by Nott (2003b) and Nott and Hayne (2001). Recent work in this area has shown that the historical record of these events in Queensland underestimates by an order of magnitude the frequency of the more intense tropical cyclones in this region. This has significant implications also for policies relating to hazard risk and coastal development, although such data are rarely if ever incorporated into the event time series used by those assessing the risk (Nott, 2003b, 2004). Unlike the United States, where prehistoric data is often incorporated into risk assessments, assessors of hazard risks in Australia rely solely on the short historical record of events from which to determine magnitude/frequency relationships. The difference in approaches between the United States and Australia is likely due to the fact that the United States is often struck by geological hazards and geologists are accordingly employed to understand the hazard better. In Australia, where hazards tend to be predominantly of atmospheric origin, meteorologists, engineers, and physicists, who are much less familiar with the reconstruction and value of natural prehistoric records, are used in hazard-risk assessments. As a consequence, development along the northern Australian coast is allowed to occur in locations that the prehistoric record shows are regularly impacted by extreme-intensity tropical cyclones. Increasing awareness, however, of the significant role that tropical cyclones play in shaping the coast here and the records left, therefore, by these events will help reduce community vulnerability and risk to this hazard.

CONCLUSION

Substantial parts of the coast of the Gulf of Carpentaria, along with coral cays and bedrock islands along the GBR, and sand and shell beach-ridge plain sequences elsewhere along the mainland coast of northern Australia owe their origin to the marine inundations generated by tropical cyclones. Unlike ridge plain sequences in temperate latitudes, those in tropical Australia contain sediments too coarse to have been transported by wind and ridge crests sit at elevations beyond that able to be inundated by normal trade wind-induced waves. Ridges composed of coral fragments, marine shells, pumice, lithic gravel, and coarse- to very coarse-grained sand up to 6–8 m AHD most likely owe their origin to marine inundations generated by extreme-intensity tropical cyclones.

Extensive dune erosion can also occur during such inundations along with deposition of washover sand splays or sheets. Although gradual processes also play a very important role in shaping the sedimentary coasts of northern Australia, the record of less-frequent, high-energy events is also very evident in this landscape. Landforms resulting from gradual low-energy processes are at times completely destroyed by high-energy events, and landforms created by these extreme events are in turn modified by the higher frequency processes. This tropical coast therefore is a mosaic of landforms resulting from different scale energy events.

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DEPARTMENT OF ENVIRONMENT
& CONSERVATION
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Corporate Information Section
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Our ref: 02-038709

- 1 MAY 2008

Mr C J Murray
Acting Director
Environmental Impact Assessment Division
Level 8, 168 St Georges Terrace
PERTH WA 6000

Dear Mr Murray

Yannarie Solar Salt Farm Proposal (Assessment 1521) Supplementary Information

I refer to your letter dated 22 February 2008 inviting the Department for Planning and Infrastructure (DPI) to comment on Straits' modified proposal and supplementary reports for the Yannarie Solar Project (Assessment 1512). In addition, the Minister for Planning and Infrastructure, Hon Alannah MacTiernan MLA, has asked me to thank you for your letter of 22 February 2008 regarding the modified proposal. In response to both letters, the following advice and comments are provided for your consideration.

The DPI has considered the modified proposal within the context of the Ningaloo Coast Regional Strategy Carnarvon to Exmouth and State Planning Policy No. 2.6. The DPI's previous advice and comments of 14 March 2007 (refer attachment), provided in response to Straits original Yannarie Solar Project proposal, remain current with regard to the modified proposal.

In summary, the DPI makes the following points:

- The Ningaloo Coast Regional Strategy Carnarvon to Exmouth 2004 (NCRS), adopted by the WAPC and endorsed by Cabinet, identifies relevant areas within Exmouth Gulf as 'Recommended Marine Protected Areas', consistent with the 1994 findings of the Marine Parks and Reserves Selection Working Group. The NCRS explicitly states that development in these areas should be in accordance with the recommendations of this report.
- The proposal does not adequately demonstrate that the impacts of coastal processes - particularly cyclonic storm surge inundation and sea level rise - on the project area have been assessed, nor does it fully explain the implications for development setbacks and the structural integrity of proposed infrastructure.

The modified proposal contains several changes relevant to DPI's concerns about the impacts of coastal processes. For example, the diesel fuel farm at Hope Point has been relocated to higher ground (8-9m AHD) to reduce the risk of fuel spill in extreme weather conditions, and the setback for the crystalliser and concentrator ponds has been increased from 40m to 100m from the landward edge of the algal mat. With regard to the latter, the increase in the setback distance appears to have been motivated by concerns about the impacts on algal mats and mangroves from seepage. However, this setback distance does not appear to be supported with reference to any detailed assessment of coastal processes.

DPI advises that the proponent should be asked to provide the following:

- A detailed assessment of shoreline response to sea level rise over the expected period of operation at the site;
- An assessment of the adequacy of the development setback in terms of severe cyclonic impact, historic shoreline change and potential sea level rise; and
- Evidence that the proposed structural design of the external seawall, and the proposed maintenance of the structure, are adequate to enable it to withstand severe weather events. Modelling should be based on historical cyclonic storm surge data and potential future weather conditions under climate change scenarios.

Yours sincerely

ROB GILES
CHIEF OF STAFF