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Abstract

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Keywords

tsunami, Holocene, Western Australia

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The Holocene paleo-tsunami history of West Australia

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West Australian coastlines experienced several tsunamis in mid-Holocene times. To expand our knowledge about Holocene tsunami events in West Australia, the authors extended the previously studied spatial scale to include the central- and south-western coastlines. Several of the discovered events were mid- and young Holocene (≤1000 yr BP) tsunami impacts on the outer coast of the Cape Range Peninsula. Five hundred kilometres to the south between Cape Cuvier and Point Quobba, additional tsunami evidence exists on top of steep cliffs over a coastal stretch of 30 km. The sedimentary signature of two tsunamis is documented in this area by wide ridges comprised of sand, shell, and clasts (including coral fragments) at heights of 12–30 m asl and 300–500 m inland. Enigmatic boulders (20–100 tons) appear as cliff-top megaclasts up to 100 m inland. Here, radiocarbon dating revealed a minimum of two tsunami events: at 5700 yr BP with waves depositing sandy ridges far inland and at approximately 1000 yr BP with waves depositing boulders originating from the marine environment. As the first dates are congruent with previously published results for the Learmonth region 500 km to the north, we assume that the same mid-Holocene tsunami hits this long coastal section as well. The southwestern coast of West Australia from Cape Naturaliste to Albany also shows signs of impacts by extreme waves. Here, huge granite boulders (80–400 tons) were dislocated and transported to heights up to 10 m above sea level. The most prominent dislocated boulders were positioned at Merchant Rock (Cape Naturaliste National Park), at Islet near Nanarup, and in Cave Bay close to Albany.

1. Introduction

Australia is the continent that contains the most evidence of tsunamis occurring during the Holocene. Whether this fact reflects the true distribution of strong Holocene tsunamis or instead reflects the young age of paleo-tsunami research as a discipline (i.e., tsunamis occurred elsewhere but evidence has not yet been discovered) is an open question. Regardless of the answer, accumulations of tsunami deposits have been found in many places along the coast of Australia (Young et al., 1992; Bryant et al., 1992; Young et al., 1996; Bryant et al., 1996; Nott, 1997; Bryant, 2001; Bryant and Nott, 2001; Nott, 2003a,b, 2004a,b; Switzer et al., 2005; Dominey-Howes, 2007).

Compared to modern tsunamis, like those that occurred in Papua New Guinea in 1998 and Andaman–Sumatra in 2004, most of the Australian paleo-tsunamis belong to the category of mega-events. The south coast of Australia is not very suitable for preserving coastal sediments because it is characterized by cliffs along the Nullarbor Plain. Nevertheless, the south coast and the central and southwest coasts of the state of West Australia are areas that provide evidence of these events. In this overview we add observations and dates from the Cape Range Peninsula to Albany. However, many remote places that might contain evidence of tsunamis remain to be investigated.

Fig. 1 shows a map of West Australia with all known sites that contain paleo-tsunami deposits. The source areas and processes for all of these paleo-tsunamis are mostly unknown. Beside seismo-tectonic events that occur in distant locales, e.g. the Sumatra rupture (1974, 2004) or Chile (1960), submarine slides are good candidates for producing mega-tsunamis. Meteorite impacts into the sea are another possibility, as in the case of the Carpentaria Gulf and possibly along the west coast of the continent (Bryant et al., 2007).

Review articles about typical tsunami deposits (e.g., Dawson et al., 1991; Dawson, 1996; Dawson and Shi, 2000; Dominey-Howes et al., 2006) may give the impression that tsunamis generally leave sand sheets in the coastal landscape and that paleo-tsunami research must concentrate on these deposits. Extended sedimentation of fine deposits and their preservation in the geological record, however, is only possible on low lying and flat coastlines. Instead, coarse materials — in particular large boulders — those are mostly beyond the reach of storm waves and too large for storm wave transport are more salient markers. These boulders survive unchanged for millennia and often show signatures of their dislocation from the sea in the form of boring bivalves or incrustations of marine organisms such as coral, vermetids,

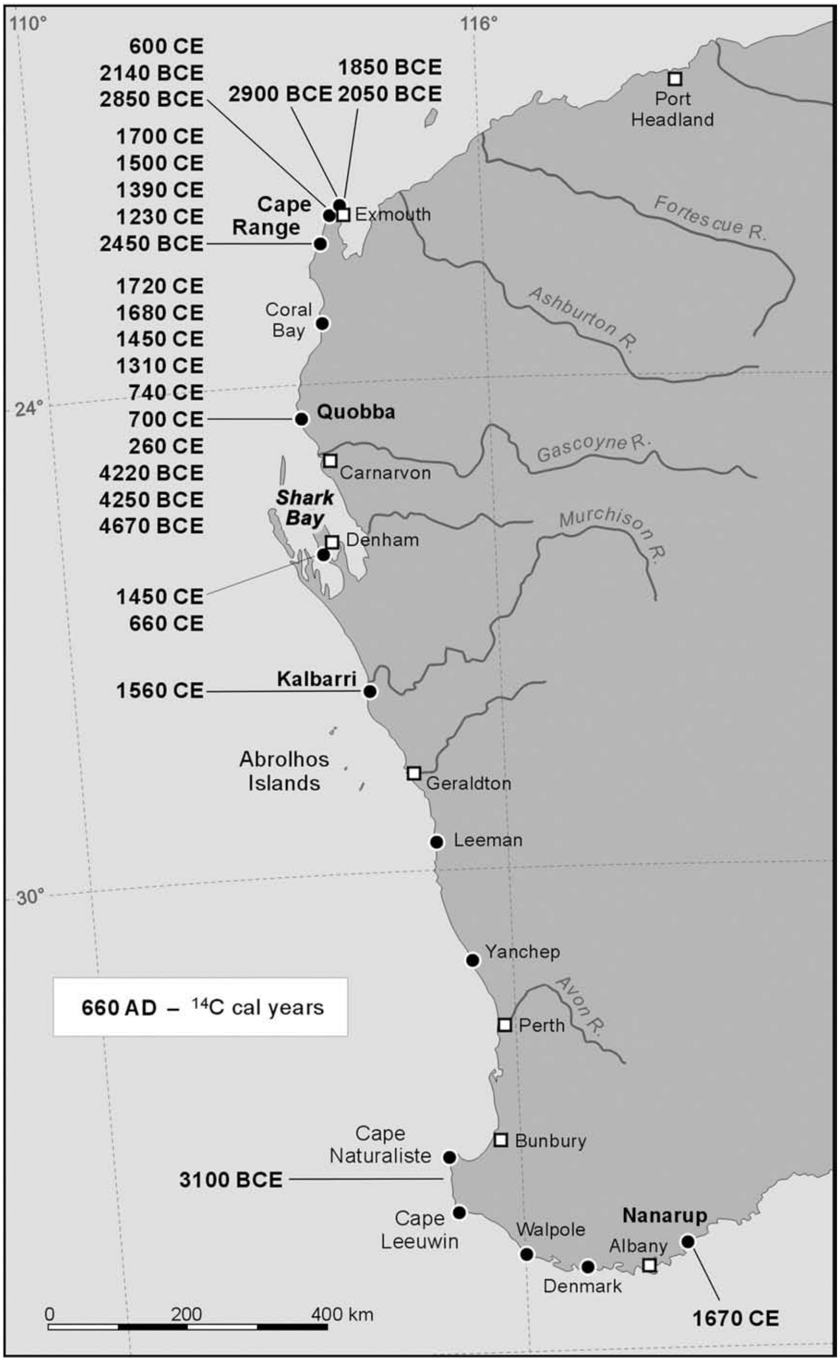

Fig. 1. Sites with paleo-tsunami signatures and event dates along the coastline of West Australia.

tubeworms, calcareous algae, oysters, or barnacles. Using these markers it is possible to unravel the paleo-tsunami history of the Australian continent. The new results discussed in this paper refer mostly to boulder sedimentation. Although fine sediments have the potential to better document the limits of inundation, they are hidden under the surface and do not leave an obvious morphological signature in the coastal landscape. Additionally, they may be altered by processes such as bioturbation and stream flow.

2. Area descriptions, methods and material studied

The data presented in this paper extend previous field observations to the south along the western coast of Australia. We concentrated our field work mainly on the outer coasts of the Cape Range Peninsula near Exmouth, Coral Bay and the southern section of Ningaloo Reef; the Quobba area from Point Quobba to Cape Cuvier; inner Shark Bay; Kalbarri National Park; and the southwest area from Naturaliste/Leeuwin National Park to Albany/Nanarup. Remarkable deposits — in particular large boulders in the coastal landscape — were mapped and inspected as to a possible origin. Where possible, we sampled for radiocarbon dating marine organisms attached to boulders or deposited onshore (scleractinean corals and shells) beyond the reach of modern storm waves. Samples were dated by Beta Analytic Inc. Absolute data are given here initially as conventional ages in radiocarbon years BP (before 1950). Sample dates were calibrated using the MARINE 04 database, with INTCAL04 radiocarbon

Fig. 2. Boulder ridge with large beachrock fragments from the Northwest Cape displaying well-developed imbrication.

age calibration (Stuiver et al., 1998). Carbonate results were corrected for global (300–500 yr) and local (−5±20 yr) reservoir. Besides the absolute dating, all geomorphology and sedimentology information from the coastal environment that might provide relative age indicators were compared with the absolute ages. The following sections describe and discuss the results from the studied areas.

3. Results and analyses

3.1. Cape Range Peninsula

The Cape Range Peninsula is an anticline with up to five uplifted Pleistocene coral reef terraces along the west coast. The peninsula is fringed by the Ningaloo Reef along its entire length (Veeh et al., 1979; Lane, 2004; Wyrwoll et al., 1993) characterised by small gaps only in the northern part. A raised reef from the last interglacial runs uninterrupted along the coast. While creeks do not dissect this reef, they do discharge a lot of quartzite pebbles across it to the shoreline. Embayments have sand beaches and dunes; whereas platforms cut in reef rock and protecting the coastline from higher wave energy occur along straight coastlines or promontories. Wave energy at the coast is diminished because the crest of Ningaloo Reef lies 1–2 km offshore and the intervening lagoon is only a few meters deep. Mangroves occur in places, even on open coastlines. During cyclones, however, a storm surge of many meters may develop. Thus, during these exceptional storms higher waves may reach the mainland coast where they may form cobble ridges such as the one approximately 2.5 m high formed by Cyclone *Vance* in 1999. The ridge is composed mostly of quartzite fragments brought to the coast from the hinterland by streams. Cyclone *Vance* was “one of the most powerful storms on Earth” (Nott, 2004a), with a central pressure of nearly 900 hPa, winds up to 250 km/h, and a path that directly crossed the Cape Range Peninsula. Because of the short time span since this cyclone occurred, all deposits from this storm remain fresh and provide an excellent example of what extreme storms may deposit along this coastline: well-rounded rock fragments, coral, calcareous algae, and thick *Tridacna* shells up to 100 m inland and 3 m asl (above sea level). Close to Northwest Cape these storm deposits lie up to 5 m asl because here

Table 1
Summary of 26 samples with age dates

Lab.-Nr.	Location	Material	$^{13}C/^{12}C$ ratio	^{14}C yr BP conv.	Cal. age IntCal 04
222975	NW-Cape	Coral	−2.6	4660±70	2900 BCE (3090–2820 and 2790–2780 CE)
222976	NW-Cape	Coral	−2.1	3830±70	1850 BCE (2010–1650 CE)
222977	NW-Cape	Coral	−0.3	4010±40	2050 BCE (2180–1950 CE)
222972	Vlamingh Lighthouse	Oyster	+1.2	1820±60	600 CE (450–690 CE)
222973	Vlamingh Lighthouse	Coral	+0.2	4070±70	2140 BCE (2340–1950 CE)
222974	Vlamingh Lighthouse	Coral	+1.6	4560±50	2850 BCE (2900–2670 CE)
222968	Mandu rampart	Coral	−0.5	580±50	1700 CE (1650–1870 CE)
222969	Mandu rampart	*Tridacna gigas*	+1.4	800±40	1500 CE (1450–1590 CE)
222970	Mandu rampart	Coral	−0.6	990±60	1390 CE (1290–1450 CE)
222971	Mandu rampart	Coral	−1.2	1190±70	1230 CE (1060–1320 CE)
235698	Mandu Creek	Coral	+2.0	4350±50	2450 BCE (2660–2430 BC)
235645	Quobba	Limpets	+1.3	550±50	1720 CE (1660–1900/1920–1950 CE)
235647	Quobba Island	*Crassostrea* sp. AMS	+1.0	610±40	1680 CE (1640–1810 CE)
229172	Quobba Island	Boring bivalves AMS	+1.5	890±40	1450 CE (1400–1490 CE)
222978	Quobba Blowholes	Boring bivalves AMS	−1.2	1060±40	1310 CE (1280–1400 CE)
229661	Quobba	Coral	−1.2	1630±40	740 CE (680–840 CE)
235648	Quobba	Boring bivalves AMS	+0.8	1670±40	700 CE (660–790 CE)
235646	Quobba Island	Calcareous algae	−4.3	2110±40	260 CE 150–360 CE
222979	Quobba Dune	Limpets: *Patella* (*Scutellastra*) *laticostata* (Blainville, 1825)	+1.3	5740±40	4220 BCE (4310–4100 CE)
235643	Quobba	Limpets: *Patella* (*Scutellastra*) *laticostata*	+1.5	5780±60	4250 BC (4350–4130 CE)
235644	Quobba	Limpets	+1.6	6170±60	4670 BC (4790–4510 BC)
222980	Shelly Beach, Shark Bay	*Fragrum erugatum*	+3.1	890±40	1450 CE (1400–1490 CE)
222981	Shelly Beach, Shark Bay	*Fragrum erugatum*	+2.6	1760±40	660 CE (580–700 CE)
222982	Kalbarri	Limpets: *Patella* (*Scutellastra*) *laticostata*	+0.8	730±40	1560 CE (1490–1660 CE)
229171	Merchant Rock	Tubeworms	−3.3	4460±50	3100 BCE (3350–2920 CE)
222983	Nanarup W	Limpet AMS	−0.1	630±50	1670 CE (1560–1810 CE)

Dates were calibrated using the MARINE 04 database, with INTCAL04 radiocarbon age calibration (Stuiver et al., 1998). Carbonate results were corrected for global (300–500 yr) and local (−5±20 yr) reservoir.

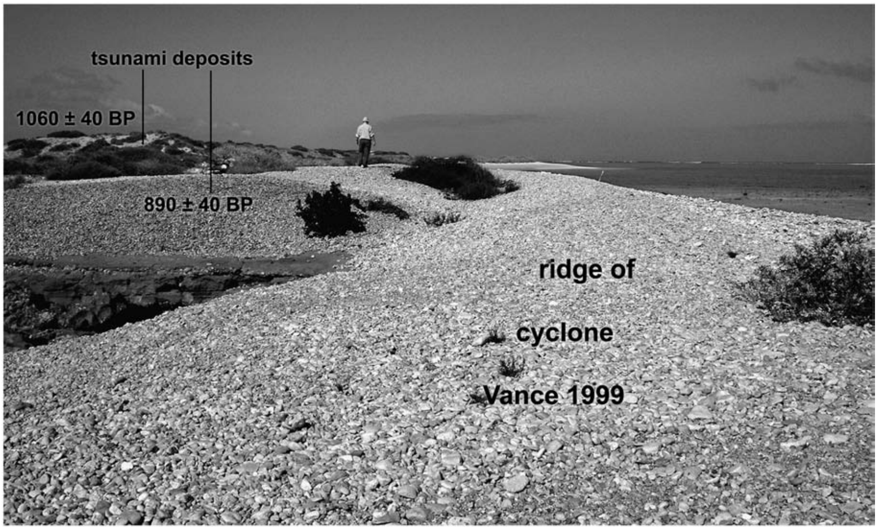

Fig. 3. The light coloured beach ridge deposited by cyclone Vance (1999), 2.5 m high, can be distinguished from older landward and higher deposits at Mandu Creek.

the reef has gaps that allow larger waves to reach the mainland coast without substantial loss of energy.

In contrast to this evidence of an extreme cyclone, other coastal deposits composed of much larger fragments are found higher and farther inland. Nott (2004a,b) reported absolute ages from oysters encrusted on large boulders in the North West Cape region of 1680 yr BP, 1260 yr BP, 940 yr BP, and 755/700 yr BP. The boulders form ridges up to 1 km in length and several meters in height. Nott and Bryant (2003) also published 14 radiocarbon ages from samples collected along the northwest coast of Australia. Sand ridges with shells near Learmonth in the inner part of Exmouth Gulf yielded ages of 5870 yr BP and 1350 yr BP; oysters and molluscs collected from Cape Leveque yielded ages of 330–1110 yr BP; and seven conventional radiocarbon ages from Point Samson ranged from 370 to 2490 yr BP. A piece of coral in a valley 1 km inland was dated to 5300 yr BP. From these data, Nott and Bryant (2003) concluded that multiple tsunamis likely occurred between 5500 and 6000 yr BP and between 1200 and 750 yr BP.

Along the Northwest Cape and near the Vlamingh Lighthouse, boulder ridges exist 30–80 m inland that are many hundreds of meters long lying 4–7 m above sea level. They are composed of single boulders weighing up to 10 tons and with a good imbrication in places (Fig. 2A and B) and angular clasts of beachrock with a few fragments of coral originating from the fringing reef. Six conventional radiocarbon

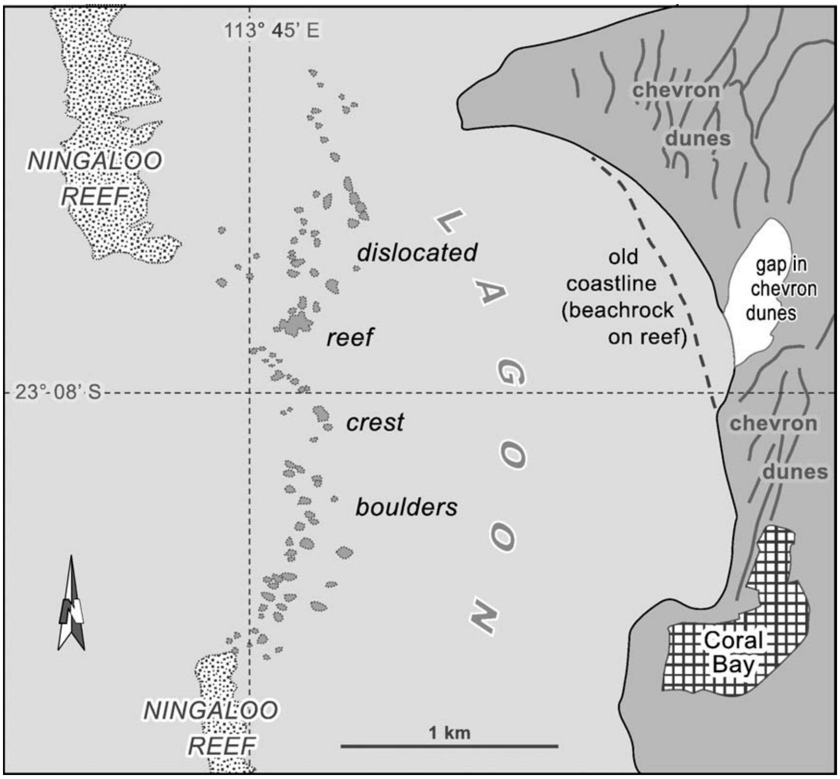

Fig. 4. Sketch of the Coral Bay area showing a gap in Ningaloo Reef, where giant slabs of the reef crest have been dislocated and deposited in the lagoon several hundred meters away from the crest.

ages on the corals yielded ages of 3830–4660 yr BP (see Table 1 and Fig. 1), which shows that these high boulder ridges are old features. One age from a cluster of oysters weighing about 1 ton was younger at 1820 yr BP (see Table 1 and Fig. 1). These oyster clusters grow in front of the boulder ridge on top of beachrock outcrops and are transformed by bioerosion into mushroom rocks, which are easily eroded by storm waves. The oysters are severely weathered. This single sample may not represent a tsunami event.

Along the central west coast of Cape Range, the storm ridge formed by cyclone *Vance* (1999) was deposited on an older discontinuous rampart (Fig. 3). The highest of these older deposits are composed of quartzite cobbles and isolated coral and large *Tridacna* shells that are stained brown by weathering. The deposits reach 6–7 m asl and occur up to 100 m inland. Five radiocarbon ages from these deposits (Mandu) ranged from 580 to 4350 yr BP, while a higher sand ridge containing many clasts and shells dated at 1190±70 yr BP (see Table 1 and Fig. 1). We conclude that an event much stronger than a category 5 cyclone, and most likely a tsunami occurred along the west coast of Cape Range several hundred years ago, and along the northern part of Cape Range ~4000–4500 yr BP. The greatest inundation and run up reached at least 300 m inland and 12 m asl near Vlamingh Lighthouse, depositing isolated boulders and large shells in a sandy matrix.

3.2. Coral Bay

The coast of Coral Bay is sheltered by the Ningaloo Reef, because the reef crest breaks nearly all waves. The 1–2 km wide lagoon is up to 7 m deep. In this area, the reef has a gap up to 2 km wide (Fig. 4). Analysis of satellite images suggests that this gap is the result of wave destruction of the exposed reef front. Huge blocks of the reef (up to 20 m long) have been thrown into the lagoon over a distance of several hundred meters, forming a ridge up to 600 m wide, which now is encrusted with younger living coral. The destructive waves came from the southwest. Opposite the gap in the reef, an embayment has been eroded into the general coastline and the chevron dune belt about 200 m wide and up to 500 m inland. We have no absolute age data from Coral Bay, but the destruction of Ningaloo Reef and the embayment certainly are the result of an extreme tsunami impact.

3.3. Quobba

The Quobba area, known for its famous blowholes, extends 30 km from Quobba Island in the south to Cape Cuvier in the north. The coastline consists of 3–6 m high cliffs in the south that rises to more than 20 m in the north. The cliffs are interrupted by small pocket beaches. The foreshore is shallow and breaks higher swell and storm waves. At the cliff top, gently sloping upward topography is broken by small benches grading into a sandy area with smaller ridge-like features, all covered by old shrub. The crest of the first sandy ridge lies approximately 12–15 m above sea level at a distance of 250–400 m from the cliff line (Quobba dune in Table 1). The whole slope atop of the cliff (Quobba in Table 1) is covered for kilometres alongshore by single and clustered large boulders with weights ranging from about 10 to more than 100 tons (Fig. 5). The size of the boulders diminishes inland, with ones of several tons still present more than 200 m inland of the cliff. In places, a strip of sand, derived from the strongest modern storm waves exists at around +7 m asl.

The large boulders show signs of weathering (small tafoni and karstification). Most are derived from the cliff itself, but about 20% of them exhibit holes made by boring bivalves and/or are encrusted by vermetids indicating a marine origin. All boulders, including ones of 100 tons were transported against gravity 5–7 m above sea level and inland for distances of 50–100 m. The boulders are randomly orientated and not abraded. Vegetation and soil development as well as the lack of sediments indicate that even the strongest storm waves (or those from category 5 cyclone *Vance* in 1999) have never covered this slope or else there would be evidence of coarse sediment deposition. The same is true for Quobba Island (Fig. 6). The small island is scattered with large boulders situated in vegetation and it is clear that the island's surface normally is out of reach of storm waves. Quobba Island is, however, covered with small fragments of coral and *Tridacna* shells with different states of weathering. These fragments may have been transported by exceptionally strong storms, but their weight (several kg) is about a thousand times smaller than that of the boulders. Boring bivalves found in two of the largest boulders resting at +6 m asl, 50 m inland on the east coast of Quobba Island close to the blowholes, yielded conventional ASM radiocarbon ages of 610–1060 yr BP (see Table 1 and Fig. 1).

On the mainland, opposite Quobba Island, dune-like sand ridges exist more than 250–300 m inland from the cliffs. The ridges seem at first sight to be a part of the chevron sand ridges further inland, however they contain — at least up to 400 m inland and 15 m asl — many clasts that include rounded pebbles, cobble, coral fragments, and shells from the rocky shoreline (e.g., *Patella* (*Scutellastra*) *laticostata* and *Coralliophila* sp.). Radiocarbon dating of these shells yielded a conventional age of 5740±40 yr BP (Quobba dune, see Table 1 and Fig. 1). This last age is coincident with the age reported by Nott and Bryant (2003) for sandy hills of the same appearance at Learmonth south of Exmouth on the Cape Range Peninsula. One can assume that the same extensive and extreme tsunami was responsible for dumping marine sediments inland at both sites that are several hundred kilometres apart. The development of soil and vegetation, and nature of weathering of boulders and coral fragments support an old absolute age for the deposits. The limited force of storm waves (because of the shallow foreshore) in contrast to those that have dislocated the boulders on top of the cliffs (i.e., tsunami waves) is evident for a boulder weighing a little less than 10 tons in shallow water in front of the northeast side of Quobba Island. The boulder is a fragment from the island's cliff (eolianite) that now rests about 30 m away from the cliff in the water, most certainly transported to its present place by tsunami wave backwash from Quobba Island as is evident in the attached mini-structures. Rock pool formation on the upper parts and horizontal oyster encrustations along the base both document that it has not been moved for a long time even though it must have been

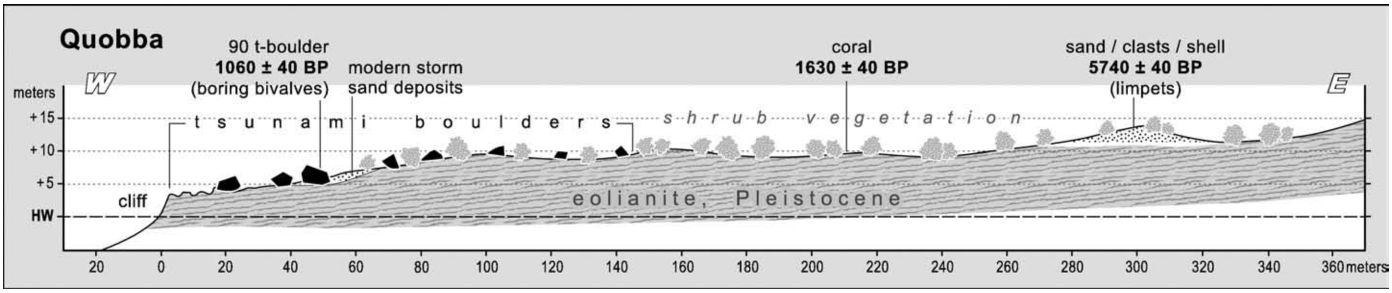

Fig. 5. Profile across the coastline on top of the cliff in the Quobba Blowhole area.

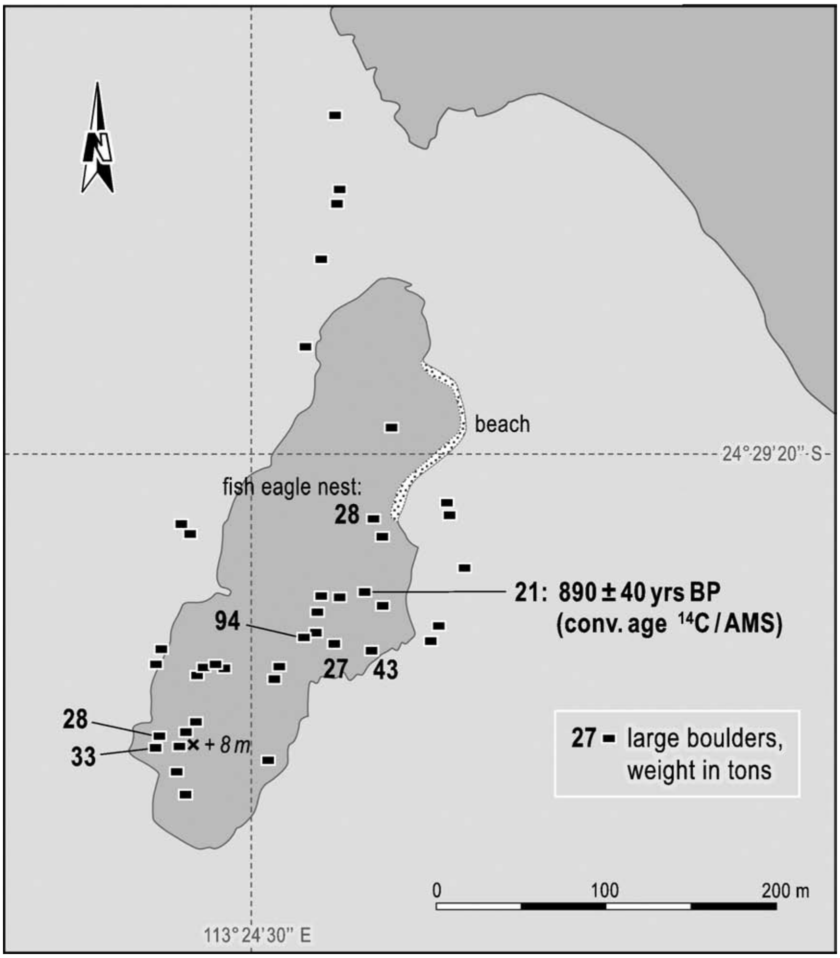

Fig. 6. Sketch of boulder locations at Quobba Island.

exposed to extreme storm waves. Conventional radiocarbon dating yielded event dates from 550 to 5780 yr BP (see Fig. 1 and Table 1).

3.4. Central west coast area: Shark Bay, Kalbarri, and the Abrolhos Islands

The inner parts of Shark Bay are protected from the open sea and thus from direct tsunami impacts. They show, however, widely spaced beach ridges, like the one at Shelly Beach that is 0.8 m high and ~12 m wide. Four to five of these wide ridges are typical of the inner embayments. They are built exclusively of billions of small (<1 cm) bivalves (*Fragrum erugatum*), which found their ecological niche in these hypersaline environments. The highest ridge at Shelly Beach (+3 m above mean High Water) yielded an absolute conventional radiocarbon age of 1760±40 yr BP. The very good preservation of the beach ridges indicates that since 1760 yr BP no strong disturbance (like a tsunami) has reached this protected part of the coastline of Western Australia.

In the Kalbarri region, the coastline consists of high, steep sandstone and limestone cliffs that are interrupted in isolated places by pocket beaches at the mouths of creeks. The spring tide range here is about 3 m, and the water is deep compared with Shark Bay or Quobba. Large well-rounded sandstone boulders weighing up to 10 tons or more exist on the upper parts of the beaches. While it is conceivable that swell and storm waves could transport these large boulders across the surf zone and onto beaches, many may simply have fallen from nearby cliffs and been moved by storm waves alongshore. In a small bay at Eagle Creek, large boulders weighing up to 20 tons can be found lying 7–8 m asl on a rocky ledge surrounded by marine sand and shells. A radiocarbon date from these shells yielded a conventional age of 730±40 yr BP. We cannot unequivocally state that the deposit here is the result of an extreme tsunami event.

The Abrolhos Archipelago with its 122 islands protects the Western Australian coastline over a distance of 170 km between 29° and 27°30′ south. It is still possible for swell and storm waves (from tropical cyclones coming from the north or subantarctic winter storms from the south) to refract around the islands and reach the mainland coastline. Despite being 50–60 km from the mainland, the islands should protect the coast from tsunamis originating from the open Indian Ocean. We collected 150 samples for dating from extensive and well-preserved beach ridges on the Abrolhos Islands. Initial results indicate that the ridge systems span a time period of more than 4500 years For example, on Serventy Island the oldest ridge dated at 5070±60 yr BP while the youngest dated at 700±50 yr BP.

On Post Office Island in the northern part of the Pelsaert group (the southernmost group of the Abrolhos Archipelago) cemented clusters of very fragile platy coral were found. The blocks were imbricated and resting ~80 m from the shoreline, 1.6 m asl on the inner part of the island. It is unlikely that these fragile blocks could survive wave attack or transportation during longer lasting storms. An absolute conventional radiocarbon age for these deposits was 1680±60 yr BP. The site of these deposits is cut off from the open sea by a 3 m high storm ridge dated to 1520±40 yr BP.

3.5. Southwest Australia: Cape Naturaliste to Albany

The southwest corner of Australia from Cape Naturaliste to Albany and further east is composed of crystalline granites and granite–gneisses intruded by diorite dikes. At many places, these rocks are

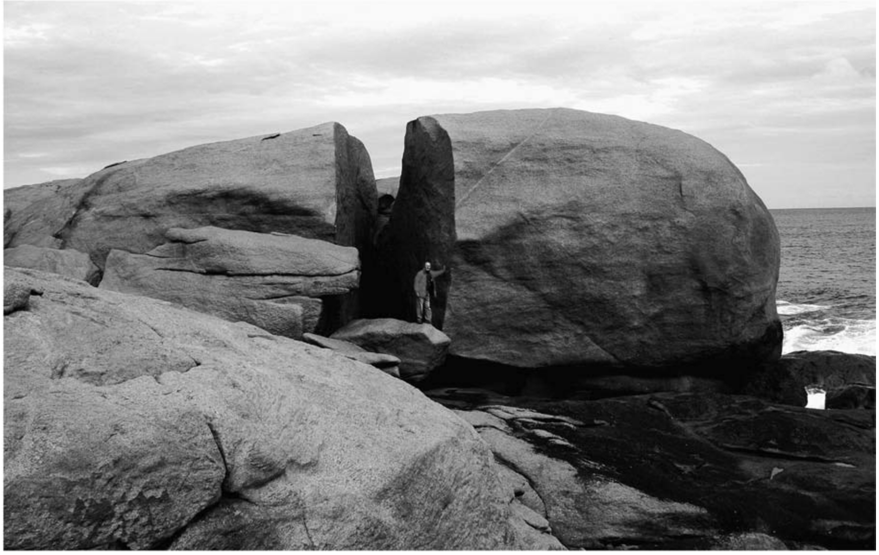

Fig. 7. At Merchant Rock in Naturaliste–Leeuwin National Park, a young fissure in a woolsack boulder of about 700 tons has opened up to 2.6 m.

covered by different generations of eolianite that are mostly Pleistocene in age. Beaches consisting of fine material eroded and abraded from these fossil dunes have developed in between promontories consisting of bare rock surfaces and woolsacks of different size, from small boulders up to thousands of tons in weight. Many of these blocks rest in the surf zone. The foreshore is very shallow for 1–2 km seaward, diminishing waves originating from the southern Indian Ocean (the "roaring forties"). Most of this coastline is festooned with chevron dunes (Scheffers and Kelletat, 2003b). Although they often resemble parabolic coastal dunes, it is highly doubtful that they have an aeolian origin for three reasons: because their axes bend up to 90° in either direction at their landward end; because some are also developed as cliff-top features without a source of sand; and because they can change direction within embayments by up to 100°.

Along the west coast of Cape Naturaliste–Cape Leeuwin National Park, no coastal sediment basins or sediment traps exist. Thus, the sediments here consist of sand and boulders that originated from chemically deep weathering of granites (woolsack formation) and from the eolianite, which itself are a product of former deep weathering. Boulders up to nearly 1 m in diameter and lying up to +8 m asl form pavements over long sections of beaches in embayments. The pavements extend inland where they disappear under dense vegetation. The fragile structure of vermetids on some of the boulders at Merchant Rock was still intact and dated to more than 3100 BCE, illustrating long term stability of the features. Even high waves that cross the shallow foreshore during storm surge conditions have not been able to move these boulders a significant amount.

Several sites contain boulders that have been moved more than 10 m asl and 100 m inland beyond the limits of even the largest subantarctic swells. Here we describe three examples which we believe can be produced only by tsunami. The first occurs at Merchant Rock on the west coast of Naturaliste National Park (Fig. 7) where a block weighing at least 700 tons has been split in two with the smaller part weighing about 300 tons moved 2.6 m to the north. The second example exists at Cave Bay west of Albany (Fig. 8a and b). It was originally described by Bryant and Nott (2001). Here, a large granite boulder more than 5 m long and weighing ~80 tons was moved alongshore for at least 200 m (the nearest granite outcrop is 200 m away) by westerly tsunami waves. This boulder (and others from eolianite nearby) sits balanced on Holocene beachrock. The third example exists at Islet Point near Nanarup east of Albany (dated to 1670 CE). Here, the lower part of a granite promontory has been stripped bare of debris with boulders appearing more than 5 m above sea level. At about 8 m asl, a large platy boulder weighing ~90 tons and with a long axis of more than 7 m was shifted upslope 0.8 m and

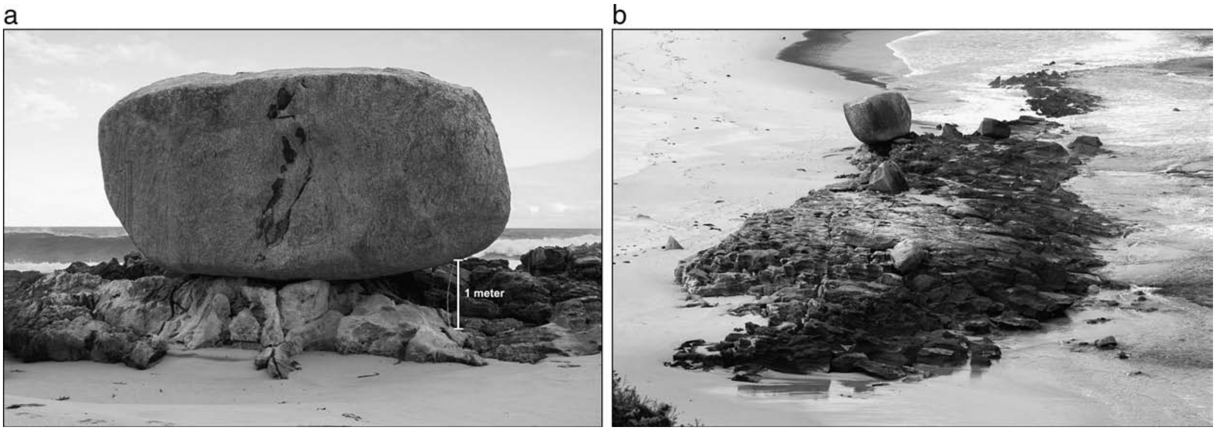

Fig. 8. a) A large granite boulder of approximately 80 tons on beach rock in Cave Bay west of Albany. b) The same boulder looking seaward (see scale).

moved eastward for another 1.6 m. Again, the unweathered nature of the boulder's edges suggests a recent age for the movement. We are convinced that a more detailed investigation along the rocky shorelines of southwest of Australia will lead to better documentation of the dislocation of very large boulders, but because they derive from woolsack weathering in a terrestrial environment, absolute dating will be difficult because of the absence of marine organisms attached to these boulders.

4. Discussion

The new evidence and dating of younger Holocene tsunami impacts along the coastline of West Australia presented in this paper is based mainly on the presence of coarse sediment. In contrast to fine sediment deposits, large boulders better reflect the hydrodynamic force and the extensive run up heights of a tsunami wave. However, the abundance and distribution of large boulders may or may not reflect the run up or the magnitude of the event because their presence depends on the availability of boulders of significant size in the tsunami-affected area. The availability of boulders is controlled by lithology, weathering history, and/or transport processes. Boulder production from coral reefs depends upon the degree of prior disturbance, the structure of the reef and its species composition.

A wide variety of physical parameters control the transport of boulders by tsunami waves, including the velocity of water movement and the inundation height. In this respect, the Indian Ocean tsunami that occurred in December 2004 is very instructive (Kelletat et al., 2007). The wide and shallow shelf areas around Thailand, Malaysia, India, and Kenya caused a relatively slow propagation and approach of the tsunami waves. Therefore, boulder transport by this tsunami was insignificant. The maximum weight of boulders moved by the tsunami in Thailand was only 10–40 tons close to sea level even where the flow depth was 10–12 m (Kelletat et al., 2007). Boulder transport did not reflect the destructive energy of the Indian Ocean tsunami.

4.1. Tsunami wave transported boulders

Tsunami boulder deposits have been described from very different settings, such as:

- incorporated in a sandy matrix as “floating boulders” (i.e., in bimodal sediment units (Bryant (2001), from Australia; Scheffers (2002) and Kelletat and Scheffers (2004) from the Caribbean and the Bahamas))
- boulder ridges or ramparts with a huge amount of clasts found in Australia, the Mediterranean, and the Caribbean (Bryant, 2001; Kelletat and Schellmann, 2002; Scheffers and Kelletat, 2003a; Nott, 1997, 2003b, 2004a; Robinson et al., 2006; Scheffers, 2005, 2000, 2006, Scheffers and Scheffers, 2007)
- boulder clusters including imbrication from Polynesia, Italy, Lebanon, the Intra-American Seas, Venezuela, the Hawaiian Islands, Portugal, and Japan (see Fig. 3.9 in Harmelin-Vivien and Laboute, 1986; Jones and Hunter, 1992; Bryant, 2001; Noormets et al., 2002, 2004; Kelletat et al., 2005a,b; Scheffers and Kelletat, 2005, Scheffers et al., 2005; Mastronuzzi et al., 2006; Monaco et al., 2006, Morhange et al., 2006)
- boulder trains from Australia, Bahamas and Mallorca (Young et al., 1992, 1996; Bryant et al., 1996; Bryant, 2001; Kelletat et al., 2005a,b)
- isolated boulders on the Bahamas, Barbados, Chile and the Ryukyus of Japan (Kato and Kimura, 1983; Taggart et al., 1993; Hearty, 1997; Scheffers and Kelletat, 2006).

4.2. Storm wave transported boulders

The forces of storm waves and their supposed ability to move large boulders on rock platforms are well documented (Bryant, 2001). Under exceptional circumstances waves greater than 16 m have been recorded in the North Atlantic. There is evidence of a single boulder being tossed 25 m above sea level on the island of Surtsey in Iceland by such waves. Waves with a force of 3 tons m^{-2} in the 1800s moved blocks weighing 800 and 2600 tons into the harbour at Wick, Scotland. Williams and Hall (2004) and Noormets et al. (2002) favour the storm hypothesis in the areas they studied. Williams and Hall (2004) argue that the megaclast deposits at more than 30 m asl on Ireland's cliff sites are the result of storms. Noormets et al. (2002) compared the position of onshore megaclasts in Hawaii using a time series of aerial photographs during which three tsunamis as well as strong swell events took place. In some locales, a tsunamigenic or storm-induced origin for the transport of megaclasts is hotly debated. Contentious is the documented appearance of a 200-ton boulder measuring 6.1 m × 4.9 m × 3.0 m on an intertidal rock platform during a storm in 1912 at Bondi Beach, Sydney (Suessmilch, 1912). However Cass and Cass (2003) show that the boulder appears in an 1881 photograph. It has not moved since, even during the great storms of 1876, 1889, 1912 and May, 1974 — the latter judged the worst in a hundred years. It is debatable whether the boulder was ever emplaced by a storm at all.

There is also substantial evidence of powerful storms not even moving small boulders. According to Bryant (2001), many exposed boulders with diameters of 1–2 m were not moved in New South Wales, Australia during the 1974 1:100 year storm with wave heights of 7–10 m in May 1974. On Mallorca (Mediterranean Spain), during a 1:500 year storm in December 2001 with wave heights of 9 m at the beach, the largest boulders transported only weighed 2.5 tons. Older tsunami boulders weighing up to 40 tons were dislocated only a few centimetres during the same event (Kelletat et al., 2005a,b). The coast of New Zealand is affected by some of the greatest wave power in the world (with Tasmania in second place with 40% less wave energy, see Brown, 1990). Here, Goff et al. (2004) reported that the largest boulder transported by storm waves was only 0.7 m in diameter and was moved only 35 m inland. Scheffers and Scheffers (2006) observed a 6-ton boulder on top of a coral reef terrace 5 m asl on Bonaire island (Netherlands Antilles) deposited during Hurricane *Ivan* in September, 2004 by waves reaching 12 m high in the surf zone.

4.3. Storm and tsunami wave height calculation for boulder transport

Nott (1997, 2003a,b) developed wave transport equations that incorporate water density, boulder density, coefficient of drag, coefficient of lift, coefficient of mass, gravitational constant, instantaneous flow acceleration, flow velocity/wave celerity, and the three

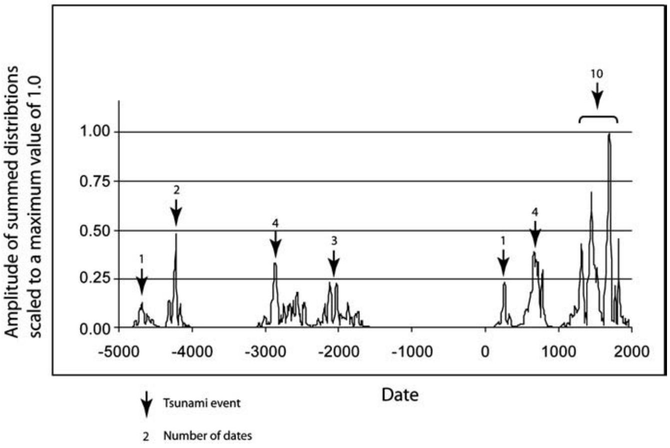

Fig. 9. Frequency distribution of tsunami events over the Holocene based on 25 new event dates.

boulder axes. Moreover, Nott distinguished between three pre-transport settings: submerged, sub-aerial, and joint bounded. We used Nott's equations (Nott, 2003b) to calculate the storm and tsunami wave heights necessary to move the boulders described above. Joint-bound boulders weighing 10 tons with a long axis of 2.7 m and a short axis of 0.6 m need storm wave heights of at least 9 m to be overturned. If these boulders are even platier, then they require wave heights of 13 to 18.5 m to be overturned. It is much easier for storm waves to move boulders with a cubic shape or lying in a submerged position. Storm waves can move boulders similar to the ones we have measured in West Australia weighing up to 20 tons. In contrast, very platy boulders or those weighing more than 20 tons will be barely moved by storm waves and will require tsunami waves to be transported.

Considerably less force is required to move a submerged or sub-aerial boulder lying close to shore. Here, rapid change in momentum, which is related to water depth, initiates boulder movement. However, considerably more force is required to transport boulders against gravity, a land inwards loosing energy by friction. Additionally, the transport capability of tsunami waves can be increased by increasing the density of water by increasing the amount of suspended material.

The movement of boulders by waves depends on a wide variety of parameters. The most important include (in order of importance):

1. *Size, weight, density, and form* i.e. the relation of the three boulder axes. A well-rounded boulder may be moved more easily than a cubic or platy one.
2. *Boulder origin* i.e. submerged (buoyancy larger when submerged in seawater), sub-aerial, and joint bounded (attached to original rock).
3. *Wave characteristics* i.e. height, period and velocity are interdependent, density of water (with or without suspension load), approach angle, breaking or non-breaking wave depending on water depth.
4. *Fabric characteristics* i.e. as a single boulder or one in a packing arrangement; long or short axis parallel to the wave train; on top of the surface or partly immersed in loose or solid ground.
5. *Topography* i.e. gentle or steep slope; continuous or discontinuous slope; convex, concave, or straight; hard or loose surface (e.g., bed of clasts); degree of surface roughness.
6. *Transport characteristics*: with or without air cushion, degree of submergence, influenced by backwash from former wave, nature of turbulence.

4.4. Age dating of extreme hydrodynamic events in WA

Table 1 compiles the results of radiocarbon dating used in this study. Radiocarbon dates do not simply represent a calendar age. Each can be plotted as a frequency distribution over a span of radiocarbon years, which can be converted at 10-year intervals to a calendar age using a calibration table based on marine species (Stuiver et al., 1998). The results of a number of calibrated age distributions can then be summed together over time to show not only the timing of an event, but also how many dates support that event along a coast. The more sites preserving shell as evidence of that event, then the greater the amplitude of the summed distributions. Our new results for Western Australia are plotted in Fig. 9. Unfortunately, the conversion of a radiocarbon frequency distribution does not correspond exactly to a calendar one because radiocarbon production in the atmosphere varies over time. This can lead to age reversals. Age reversals plague the last two millennia. This means that peaks in a calendar frequency distribution sometimes cannot be interpreted as the likely time for an event because age reversals leave gaps that artificially create peaks in a calendar-age distribution (see also Haslett and Bryant, 2007). Fig. 9 uses 25 radiocarbon dates (one of our dates was modern) and illustrates this problem. For example, the distribution plotted between 4000 and 4500 BCE represents a single event. It contains a gap because of an age reversal around 4300 BCE. All of the peaks in the last eight hundred years probably represent a single event. The exact timing of this event is difficult to resolve. If all our dates correspond to the timing of a tsunami, then seven events are shown in Fig. 9. These are centred on 4700 BCE, 4250 BCE, 2850 BCE, 2050 BCE, CE 200, CE 590 and CE 1500. There may be an event around CE 1100 but it is obscured by the last event and age reversals around this time. A more recent event in the last 250 years cannot be ruled out, but is impossible to date using radiocarbon because the ages come out as modern. By far the most extensive event is the one that has occurred within the last 800 years. Its signature is preserved at more than six locations along the coast, from Kalbarri in the south to Cape Leveque in the north — a distance of 1800 km.

Three of the events are noteworthy because they occur at times of other calamities in the region. The event dated as 1500 CE, overlaps with a mega-tsunami event documented in the 15th century along the southeast coast of Australia. This event, named Mahuika, has been attributed to a comet impact approximately 250 km south of the South Island of New Zealand (Abbott et al., 2003; Bryant et al., 2007). Any tsunami generated by this impact would not have affected the west coast of Australia to the degree documented in this paper. The second event dated at 590 CE is close to a catastrophic event triggered in CE 535 by an unknown explosion or eruption in the Indonesian-Northern Australian region (Keyes, 2000). The last event centred on 2850 BCE corresponds to a global catastrophe in 2807 BCE documented by Masse (2007). Finally, an event centred on 2050 BCE may also have a cosmic origin although the evidence is less conclusive. Its timing corresponds with the fall of the Akkadian empire in the Middle East at around 2200 BCE, which has been linked to an impact (Masse, 2007).

5. Conclusions

Despite the increasing knowledge on Holocene paleo-tsunamis in Australia and a rising number of absolute dates, there is a need for further field work to map the extent of contiguous tsunami along the coastline. Much of our work to date has involved identifying coarse grained deposits or bedrock erosion. The mapping of buried deposits in embayments is poorly researched, while the study of the effects of tsunami on the continental shelf, including coral reefs, is at most rudimentary. Moreover, the ongoing scientific debate on the genesis of well-developed and widespread chevron dunes around Australia appears linked to this issue. While this study reinforces the initial work published by Nott and Bryant (2003), unresolved questions remain. For example, the source region and mechanisms of tsunami are either poorly determined or speculative. Because of this, most coastal scientists would prefer to dismiss the field evidence rather than come to terms with the fact that the West Australian coastline is prone to repetitive tsunami, some of which are much larger than any experienced historically.

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