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Geological and historical records of tsunami in Australia

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Abstract

The Indian Ocean tsunami (IOT) of 2004 has resulted in significant interest within Australia about the record of tsunami for the continent because an understanding of tsunami hazard begins with a catalogue of past events. Here, a preliminary catalogue of tsunami affecting Australia is presented. The catalogue contains entries for 57 tsunami events. The oldest event is dated at 3.47 Ga, the most recent is the July 17th 2006. Forty-four tsunami were recorded on the New South Wales coast although the NW coast of Western Australia records a significant number of events. Forty-seven events have affected Australia since AD1858. Maximum run-up for an historic event is +6 m asl whilst the maximum run-up for a palaeotsunami event is reported at an elevation of at least +100 m asl. Twenty-three percent of historic Australian tsunami were generated by unknown causes and Papua New Guinea, the Solomon Islands and Indonesia collectively represent the most important source area of historic tsunami for Australia. Geological records for palaeo and historic tsunami are identified and summarised. The geological record of tsunami represents a potentially important source of information for Australian tsunami. However, at the present time, the geological record is both limited and controversial and future research should seek to re-examine proposed geological evidence of tsunami. From an analysis of this preliminary catalogue of Australian tsunami, a series of key research priorities have been identified to guide future research in the region.

Keywords: Tsunami; Australia; Geological; Historical records; Future research questions

1. Introduction and aims

The Great Sumatra–Andaman Indian Ocean Tsunami (IOT) of 26th December 2004 was the most lethal tsunami disaster the modern world has known. It has prompted an unparalleled international scientific and intergovernmental response with several foci including the development and deployment of tsunami warning systems in at risk areas, detailed hazard, risk and vulnerability assessment and tsunami education and disaster planning. The 2004 IOT was something of a wake up call for Australia since prior to this event few had seriously considered the possible threat that tsunami might pose to Australia. This is in spite of the fact that Australia's coasts have been affected by modern tsunami (Rynn, 1994) and geological records suggest that palaeotsunami orders of magnitude larger than those recorded in modern times have occurred on numerous occasions during the Holocene (Bryant et al., 1992; Young et al., 1996; Nott, 1997; Bryant, 2001; Bryant and Nott, 2001). While the IOT has demonstrated that large, widely destructive teletsunami are not confined to the Pacific, our understanding of how often such events may occur and what areas they may impact is still very limited — especially in Australia. Together with the establishment of an Australian Tsunami Warning System (ATWS) (Geoscience Australia, 2005), there is now a clear and urgent need to fully understand the hazard

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(Geist et al., 2006). This is important because it can be seen from Fig. 1a that Australia is surrounded by crustal plate boundaries at which active crustal subduction, high seismicity and volcanic activity are all occurring. In Australia, little work has been undertaken to catalogue tsunami (a first step towards a proper understanding of hazard) through an analysis of its geological and historical record. Consequently, the aims of this paper are to:

1. present a preliminary catalogue of tsunami reported to have affected the continental mainland of Australia;
2. provide a summary of the geological and geomorphological record and characteristics of tsunami in Australia; and to
3. outline a series of key research questions to help define future research priorities within Australia.

To achieve these aims, first, a description of how the catalogue was constructed is provided. The attributes of each tsunami are outlined and a 'validity score' and 'tsunami intensity score' are given to each event. Second, a discussion of selected tsunami and their geological records and effects are provided in order to characterise and compare these records (signatures) with tsunami elsewhere and to explore how the geological record may help to improve our understanding of tsunami in Australia. Lastly, the significance of the Australian tsunami record is discussed and issues identified that might direct future research priorities in the region. Whilst this work cannot be considered complete, the purpose of presenting it at this stage is to stimulate further scientific research to refine and improve our understanding of tsunami in Australia and to enrich the emerging ATWS with data.

2. Construction of the catalogue

Information about tsunami that have impacted Australia *is* already available. However, much of this information is fragmentary, variable in quality and extent, is spread between (and within) numerous datasets — some unpublished and is known to only a few. Here, an attempt is made to draw together different information sets on tsunami reported for Australia for the benefit of the wider scientific and disaster management communities. The principle data sets used are the Geoscience Australia — Australian Tsunami Database (unpublished), NOAA/NGDC Tsunami Event Database, Rynn (1994), the Sydney Morning Herald (1858–present), Australian regional newspapers (various dates), various unpublished government reports and additional unpublished data held within the Risk Frontiers *Compactus* at Macquarie University, Sydney. The catalogue includes tsunami that affected the mainland continental coastline, the state of Tasmania and Lord Howe and Norfolk Islands only (Fig. 1b). It does not include the Australian Antarctic territories, the Australian dependencies and former Australian territorial lands. Tsunami that affected these later regions are excluded from this study because: Antarctica requires special consideration and a unique approach to determining its tsunami history; territorial dependencies may more readily, conveniently and sensibly be treated as part of other geographic areas (e.g., Micronesia) or because specific locations are now their own autonomous federal states and as such, deserve their own catalogues (e.g., Papua New Guinea).

For each event, the catalogue supplies: the corresponding ID (event) number, the date of occurrence (year, month and day), the source region of the tsunami, the tsunamigenic cause, the region of impact in Australia, the maximum (max (H)) wave height and/or distance of inundation data, a comment description, an indication of the tsunami intensity (TI) of each event based upon the 12 point (I–XII) tsunami intensity scale of Papadopoulos and Imamura (2001) (TI: I = not felt, II = scarcely felt, III = weak, IV = largely observed, V = strong, VI = slightly damaging, VII = damaging, VIII = heavily damaging, IX = destructive, X = very destructive, XI = devastating and, XII = completely devastating) and an indication of the validity of the tsunami event (based upon the NOAA/NGDC Tsunami Event Database classification: 0 = erroneously listed event, 1 = very doubtful tsunami, 2 = questionable tsunami, 3 = probable tsunami, 4 = definite tsunami). Lastly, the original sources for each event are listed. This format follows the NOAA National Geophysical Data Center "Tsunami Event Database" catalogue (see: http://www.ngdc.noaa.gov/seg/hazard/tsevsrch_idb.shtml for further details). This is the first time that such a detailed and publicly available, tsunami catalogue for Australia has been collated. Of particular importance, the present author applies a 'validity score' to each event based upon an evaluation of the evidence (published or otherwise) used to identify the tsunami by the original reporting author/organisation. Some events have been listed with a 'validity score' of zero (0) meaning that an event has been erroneously listed. I choose to retain these events within the catalogue to show readers that a careful cross-check of the original sources for these events has been completed. This will allow readers to be confident that I have considered such events rather than over-looking any that may have been listed elsewhere. Also, for the first time for Australian tsunami, a tsunami

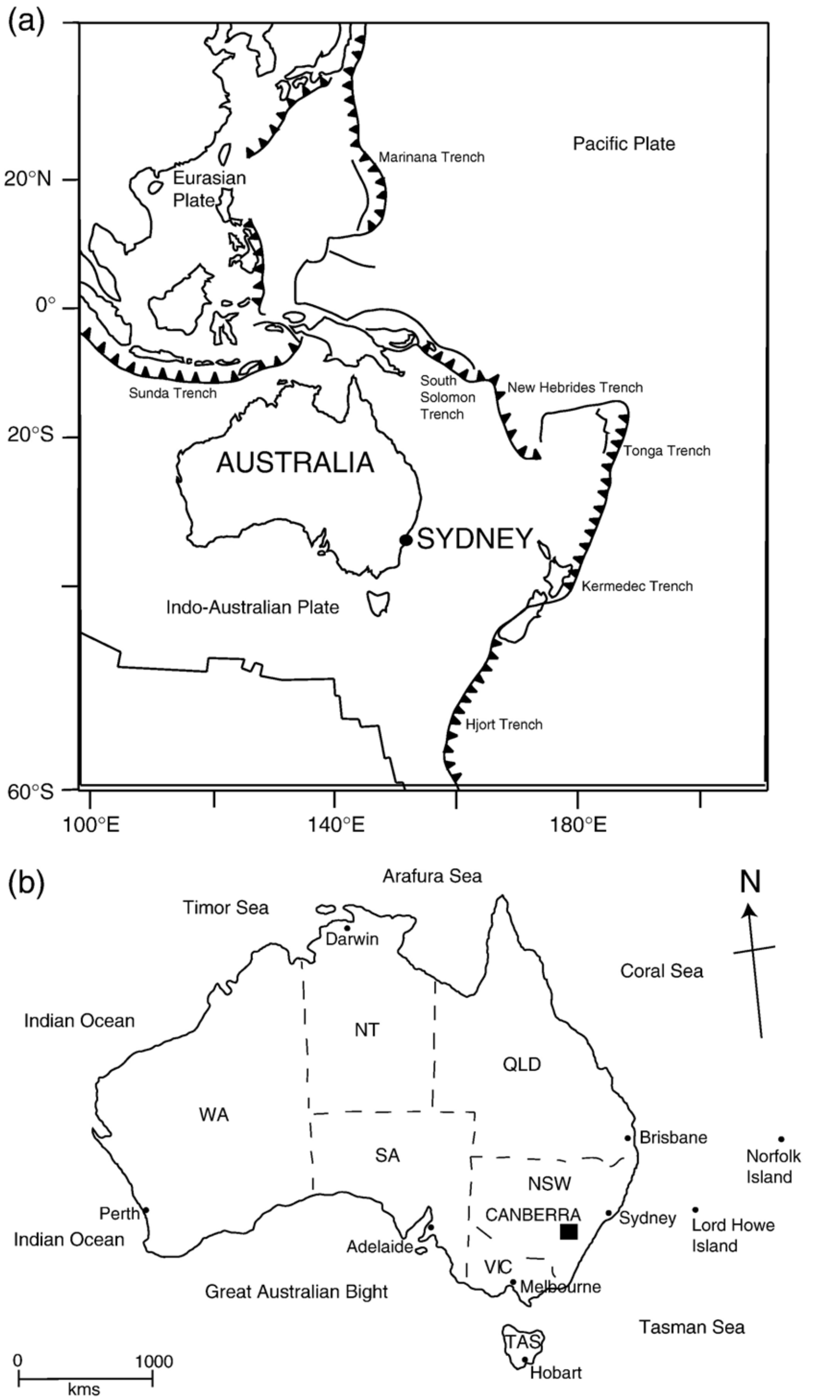


Fig. 1. a) Simplified map of the geo-tectonic setting of Australia, SE Asia and the SW Pacific region. Active crustal subduction (including high seismicity and volcanic activity) occurs to the north, east and southeast of Australia and is indicated by the hatched trench lines. The main continental area sits within the Indo-Australian plate. b) The continent island of Australia. The states and territories are: New South Wales (NSW); the Northern Territory (NT); Queensland (QLD); South Australia (SA); Tasmania (TAS); Victoria (VIC) and Western Australia (WA). The State capitals are indicated in lower case and the Federal capital in upper case. Lord Howe and Norfolk Islands (both administratively part of NSW) are also indicated off the eastern seaboard in the Tasman Sea.

intensity (TI) score is given to each event permitting direct comparison with other events in the Austro–Asia, Asia–Pacific region (e.g., 1998 Papua New Guinea tsunami). A TI value is provided rather than the more common 'run-up' because run-ups on the Australian coast are difficult to determine where there have been no post-event surveys or eye witness observations. Also, detail exists within the documentary accounts that may be used to broadly determine intensity.

3. Results

The results are presented in distinct subsections. First, the full list of tsunami identified in this study is presented and particular details of general interest are noted. Next, detail concerning the palaeo and historic tsunami records respectively, are provided. These events have been separated out in order to provide a more realistic understanding of hazard since it will be seen that the palaeo record is dominated by a trend of low-frequency high-magnitude events and the historic record is characterised by the reverse. Lastly, the geological record and geomorphological effects of tsunami on the natural environment are described and their characteristics noted.

3.1. The catalogue of Australian tsunami

There are 57 individual tsunami identified within this study. Table 1 provides a quick look summary of the events. The full catalogue is presented in Appendix A. The date of the oldest event is 3.47 Ga years before present. The most recent event is dated the 17th July 2006. Australia preserves a geological record of tsunami that stretches back over 3.5 billion years. Two billion years separate the two oldest events in the catalogue from the next event. The palaeotsunami record is comprised of ten events and 47 events make up the historic record.

The catalogue contains interesting data regarding the number of events recorded by state. New South Wales (NSW) records 44 events (77% of all events); the Northern Territory (NT) records none (0); Queensland (QLD) records nine events; South Australia (SA) records five events; Tasmania (TAS) records ten events; Victoria (VIC) records five and Western Australia (WA) records twelve events (Fig. 2a). It should be noted that the total number of events recorded by all states is greater than the total number of events within the catalogue because an individual tsunami may have inundated the coast of more than one state. NW Western Australia records a significant number of tsunami observations — twelve out of 57 (or 21%). Thirty-five events (or 61.4%) were generated as a consequence of earthquake; two events (or 3.5%) were caused by volcanic eruptions; three events (or 5.3%) were generated by asteroid impact; one event (or 1.75%) was generated by a submarine landslide and significantly, sixteen events (or 28.1%) were generated by unknown causes.

3.1.1. The Australian palaeotsunami record

The Quick Look Table (Table 1) and Appendix A indicate that geological evidence for ten tsunami have been identified for the period prior to European occupation of Australia. In this study, the 'palaeo' record is that which occurred prior to European occupation although it is recognised that Australia has been occupied by indigenous people for more than 40,000 years (O'Connell and Allen, 2004). These ten events represent 17.5% of the *total* number of events reported within the catalogue. The two oldest events are dated 3.47 Ga and 2.47–2.6 Ga respectively. Approximately 1.9 billion years separate these two from the next. No geological evidence has been reported for palaeotsunami between the third event at 570 Ma and the fourth event at 105 ka. This indicates that a significant hiatus exists within the palaeotsunami record. Another significant break exists between the fourth event dated at 105 ka and the remaining six events which all occurred within the Holocene period.

The three oldest tsunami events reported were triggered by asteroid impact and generated distinctive tsunami deposited sediments that have become components of the Australian geological record. The reason that these events are included is to illustrate that tsunami have impacted Australia for a very long time. The fourth event dated at 105 ka is thought to have been generated by submarine sediment slides off Lanai, Hawai'i (Young et al., 1992, 1993, 1996). The causes of the other six events are unknown.

The maximum run-up for a palaeotsunami is +100 m above sea level (m asl) — possibly as much as +130 m asl (event ID number 5 in Appendix A) which is recorded at Steamers Beach, Jervis Bay, New South Wales (see Fig. 3 for location). This event occurred at *circa* 8700–9000 BP. It is not known what process generated this tsunami, nor where it came from. A tsunami that is reported to have occurred at *circa* 6500 BP may have inundated to a distance of 10 km inland across the Shoalhaven delta area of New South Wales. Again, no information is available about the cause or origin location of this event.

Fig. 2b shows the distribution of palaeotsunami by state and New South Wales (NSW) preserves evidence for seven (or 70%) of all reported palaeotsunami events.

Table 1
Quick look summary of Australian tsunami (information is summarised from Appendix A)

Number of events listed	Oldest event listed	Most recent event listed	Highest run-up (m asl); greatest inundation	Most common cause	Most common source regions	Geological nature of record; characteristics, diagnostics etc
Palaeotsunami events (i.e., those occurring prior to European occupation of Australia in AD1788)						
10	3.47 Ga	200/250 P	+100 asl; 30 m inland	Unknown −60% Asteroid — 30%	Unknown	2 major types identified: (1) Asteroid tsunami deposits. Descriptions such as: "The megaclasts appear to have been incorporated contemporaneously and/or at a late stage of settling of the microkrystite spherules, and possibly represent exotic tsunami-transported blocks…" (2) Other (more regular ?) tsunami deposit types. Descriptions such as: "Estuarine sandy mud buried under 2.3m of coarse beach sand and pebbles, which in turn is buried by 2.5m of dune sand"
Historic tsunami events (i.e., those occurring after European occupation of Australia)						
47	February AD1858	17th July 2006	+6 m asl	Earthquake — 74%	Unknown (23.4% of historic events) SW Pacific (Papua New Guinea, Solomon Islands and Indonesia) (25.5% of historic tsunami)	Accounts rarely describe geological record/geomorphological impacts Some accounts of modern events provide limited information on environmental effects. Descriptions such as: "….. the most significant impact made on the shoreline occurred near the Northwest Cape. The tsunami inundated the beach and car park at Baudin where the shore is exposed by a gap in the Ningaloo reef. A surge estimated at around 3 to 4 m carried hundreds of fish, as well as crayfish, rocks and coral inland for a distance of 200–300 m"

3.1.2. The Australian historical record

The Quick Look Table (Table 1) and Appendix A indicate that the earliest historic records identified for tsunami occurring in Australia date back to AD1858. The historic period records 47 events since AD1858. These 47 events represent 82.5% of the *total* number of events reported within the catalogue. Seventeen (of the 47) historic events (or 36.17%) occurred within the 19th century and 30 (of the 47) historic events (or 63.83%) were recorded between 1901 and 2006.

The maximum run-up for a historic event is +6 m asl (event ID number 48 in Appendix A) recorded at Cape Leveque in Western Australia on the 19th August AD1977. This tsunami was generated by a magnitude 8 earthquake in the Sunda Islands, Indonesia. The most widely reported tsunami (>20 observations) (event ID number 41 in Appendix 1) was that of 23rd May AD1960 (Fig. 3). Maximum run-up for this event was +1.7 m asl at Eden, New South Wales. Fig. 2c shows the distribution of historic tsunami by state. NSW was affected by 37 of the 47 tsunami (or 78.70%).

Of the 47 historic events, 35 (or 74.47%) were generated by earthquakes, two events (4.25%) were generated by volcanic eruptions, and the remaining ten

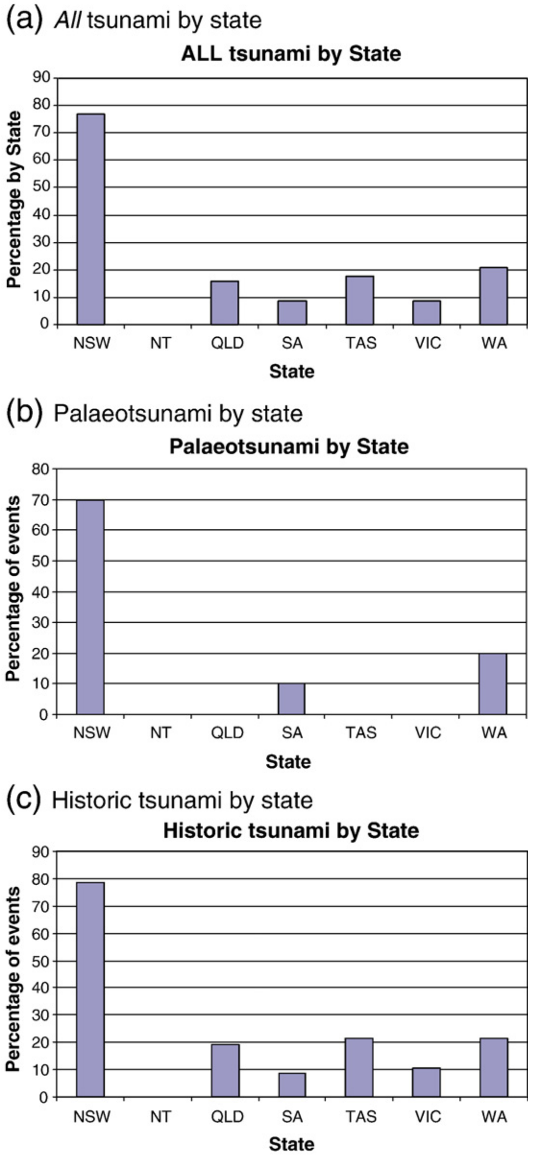


Fig. 2. a) Percentage of *all* tsunami by state. b) Percentage of palaeotsunami by state. c) Percentage of historic tsunami by state.

events (or 21.27%) were generated by unknown causes. No historic events are *known* to have been generated by asteroid or aerial or submarine sediment slides.

3.2. Geological and geomorphological records and effects of tsunami in Australia

We now turn to the geological and geomorphological record and effects of tsunami in Australia. In recent years, an increasing body of work has been published focusing on these records but a significant bias in these descriptions exists towards the palaeotsunami record. Here again, a distinction is made between the geological and geomorphological effects of palaeo and historic tsunami in Australia.

3.2.1. Geology and geomorphology of Australian palaeotsunami

The sedimentological description of Australian palaeotsunami deposits may be divided in to two classes. The first relates to sediments laid down by asteroid generated tsunami and these deposits are extremely old. The second class relates to Holocene palaeotsunami. Consequently, a very substantial hiatus exists in the palaeotsunami record.

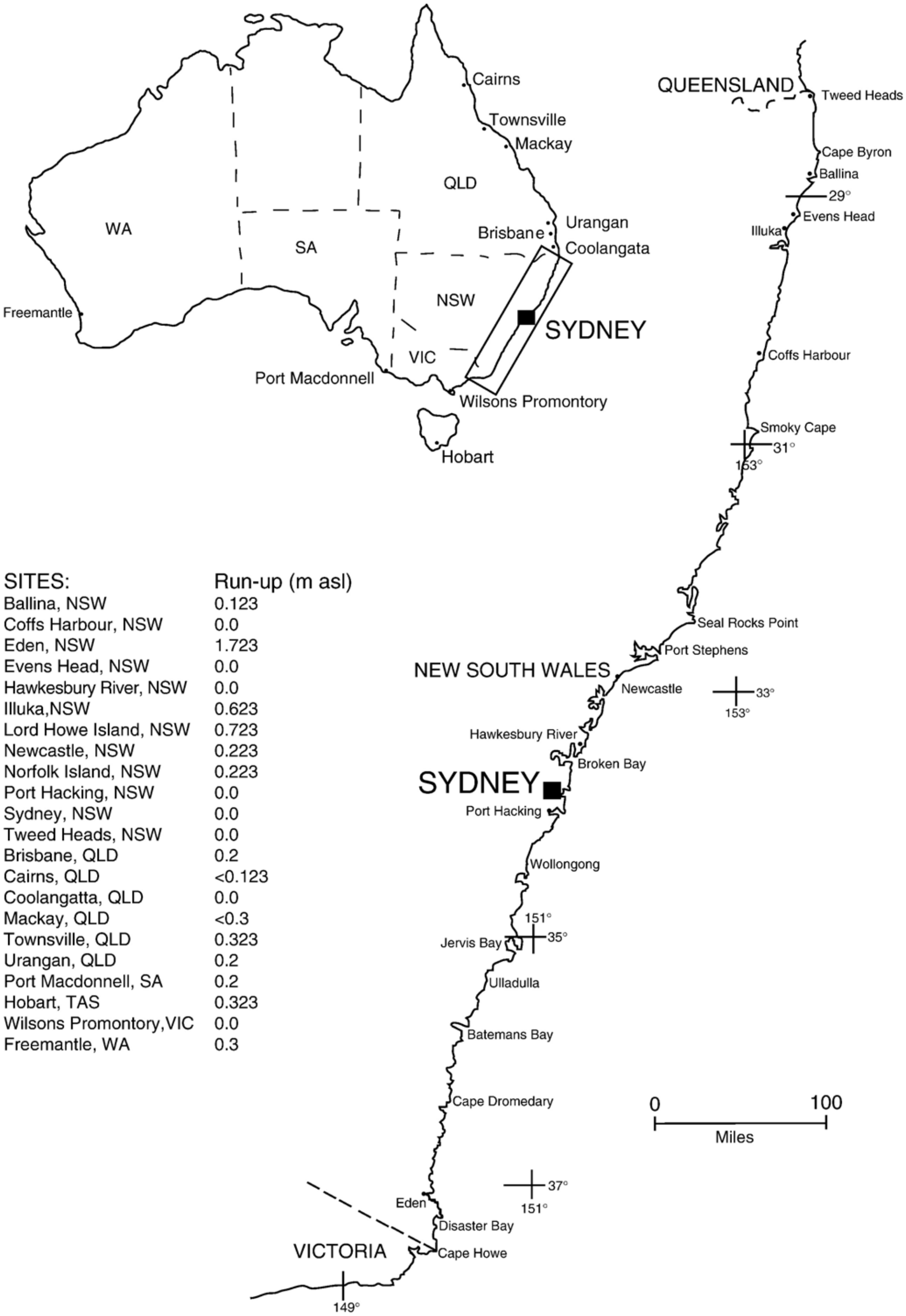
Recent work by Hassler et al., (2000), Glikson and Allen (2004), Glikson (2006) and Glikson et al., (2004) has focused on the impacts, effects and records of asteroid impacts in to the proto-Australian continent. Based upon detailed field reconnaissance and mapping, rock sampling and laboratory analyses, these researchers have come to recognise what they describe as the signatures of tsunami deposited sediments associated with these asteroid impacts in sedimentary sequences. Interested readers are referred to their work for more detail but broadly, their descriptions of these deposits include:

"microkrystite spherule-bearing diamictite, interpreted as tsunami deposit", and "a 0.6–0.8 m thick unit of silicified chert-intraclast conglomerate..... The unit includes <40 cm large subangular to subrounded chert pebbles and cobbles set in a sand to granule-size matrix containing sparse well preserved silicified and matrix-resorbed spherules" (Glikson 2006; Glikson et al., 2004).

Further descriptions include:

"deposit is about 1.5–2.0 m thick…….. larger boulders occur mostly at the top of DGS4, commonly at high angles…… the boulders and fragments commonly overlie spherule-rich stilpnomelane material. Locally the boulders protrude above DGS4, with consequent flexure of overlying layered chert and banded iron formation. The megaclasts appear to have been incorporated contemporaneously and/or at a late stage of settling of the microkrystite spherules, and possibly represent exotic tsunami-transported blocks…." (Hassler et al., 2000; Glikson and Allen 2004; Glikson 2006).

Since the 1980s, much research suggests that the coasts of Australia were repeatedly impacted by tsunami



SITES:	Run-up (m asl)
Ballina, NSW	0.123
Coffs Harbour, NSW	0.0
Eden, NSW	1.723
Evens Head, NSW	0.0
Hawkesbury River, NSW	0.0
Illuka,NSW	0.623
Lord Howe Island, NSW	0.723
Newcastle, NSW	0.223
Norfolk Island, NSW	0.223
Port Hacking, NSW	0.0
Sydney, NSW	0.0
Tweed Heads, NSW	0.0
Brisbane, QLD	0.2
Cairns, QLD	<0.123
Coolangatta, QLD	0.0
Mackay, QLD	<0.3
Townsville, QLD	0.323
Urangan, QLD	0.2
Port Macdonnell, SA	0.2
Hobart, TAS	0.323
Wilsons Promontory,VIC	0.0
Freemantle, WA	0.3

Fig. 3. Sites inundated or affected by the tsunami of 22nd May 1960. This event is associated with the most number of observations for any tsunami affecting Australia.

during the Holocene — some of them very large (Young and Bryant, 1992; Bryant et al., 1992a,b; Young et al., 1995, 1996; Bryant and Young, 1996; Nott, 1997; Bryant, 2001; Bryant and Nott, 2001; Kelletat and Scheffers, 2003; Nott, 2003a,b; Nott, 2004; Switzer et al., 2005). These authors have described a rich and varied geological record of Holocene palaeotsunami. Given the huge distances of inundation (up to 30 km from the coast (Bryant and Nott, 2001, p242)) and enormous flood run-ups (up to +130 m asl) at Steamers Beach (Bryant et al., 1997)) described, at least two (if not more) of the reported palaeotsunami events fall within the category of being classified as 'mega-tsunami'. Consequently, some of this work has lead to what has been referred to as the 'Australian mega-tsunami hypothesis' (Goff et al., 2003; Dominey-Howes et al., 2006).

Bryant (2001) and his co-workers have identified a variety of signatures of Holocene tsunami in Australia (Table 2), which they divide into two major classes: (1) depositional and; (2) erosional. For both of these major classes, examples of either 'sedimentary deposits' and 'geomorphic forms' or just 'geomorphic forms' are provided. Depositional signatures are divided into small scale individual sedimentary deposits such as "sand laminae" or "dump deposits" and large scale geomorphological forms like "carseland" or "coastal barriers". The erosional signatures are divided into small scale features such as "drill holes" or "cavettos" eroded into rock surfaces and large scale features that are individual geomorphological forms like "truncated cliffs" or "arches". For a fuller account of these palaeotsunami signature types, see Bryant (2001) and the references contained therein. The importance of these reported signature forms will be considered in Sections 4.2 and 4.4.

3.2.2. Geology and geomorphology of historic Australian tsunami

Whilst an examination of Appendix A shows that a significant number of tsunami have affected Australia in historic times, documentary accounts were mainly concerned with the effects of these tsunami on settlements, infrastructure and people. However, individual accounts do contain tantalising glimpses of the effects of tsunami on the natural environment. The tsunami that occurred on the 15th August AD1868 is reported to have had a number of effects. For example, at King Georges Sound, WA:

"the sea suddenly rose three feet, lighters were turned around, and old hulks which lay embedded in the sand for years were removed from their places and carried further up on the beach" (Sydney Morning Herald, 7/9/1868).

This quote clearly indicates that the tsunami caused erosion of unconsolidated sandy sediments to such an extent so as to permit objects to be entrained within the tsunami flow and transported further landward. At Currimbene Creek, Jervis Bay, NSW we learn:

"…..the water rushed up [Currimbene Creek, Jervis Bay], with unusual force and velocity, and increased volume; some time after it raced back in a similar manner, sweeping away a large portion of sand that had

Table 2
Australian palaeotsunami signature types (from Bryant, 2001, p60)

Depositional		Erosional		
Sedimentary deposits	Sand laminae	Cavitation features	Impact marks	
	Landward tapering splays		Drill holes	
	Foraminifera and diatoms		Sinuous grooves	
	Boulder floaters in sand			
	Dump deposits			
	Disturbed middens	S-forms	Muschelbrüche, sichelwannen,	
	Ridges, mounds and dunes		V-shaped grooves	
	Smear deposits		Flutes and rock drumlins	
	Imbricated boulder stacks		Facets and cavettos	
	Turbidites		Potholes and hummocky topography	
			Transverse troughs	
Geomorphic forms	Carseland	Geomorphic forms		Ramps
	Coastal barriers			Canyon drainage channels
			Sculptured headlands features	Pools and cascades
				Fluted promontories
				Sea caves, arches
				Inverted keel like stacks
				Whirlpools and plugs
			Landscape features	Truncated cliffs
				Raised platforms
				Toothbrush shaped headlands
				Eroded barrier remnants

impeded navigation" (Sydney Morning Herald, 24/8/1868).

Once again, we learn that an Australian tsunami had sufficient energy to erode unconsolidated sediment. Lastly, a tsunami that occurred on the 3rd June 1994 is reported to have had the following effects at Baudin in WA:

"the most significant impact made on the shoreline occurred near the Northwest Cape. The tsunami inundated the beach and car park at Baudin where the shore is exposed by a gap in the Ningaloo reef. A surge estimated at around 3 to 4 metres carried hundreds of fish, as well as crayfish, rocks and coral inland for a distance of 200–300 m" (Foley, 1994).

Significantly, this account indicates that this tsunami eroded and transported marine rocks and corals from the near-shore *and* deposited them landward.

4. Discussion

The discussion is divided in to three sections. First, the catalogue is discussed generally and then some consideration is given to the palaeotsunami and historic tsunami records respectively. These are considered separately since they are fundamentally different. Second, the geological impacts and effects of Australian tsunami are examined and the similarity and/or difference with tsunami effects elsewhere are noted. Lastly, a series of research priorities are identified in order to provide a better understanding of Australian tsunami.

4.1. Discussion of the (entire) preliminary catalogue

Australia is generally considered as a region where few tsunami occur and consequently, as a place where tsunami risk is relatively low. However, the catalogue indicates that at least 57 events have occurred (of which 47 are listed since AD1858). Relatively speaking, this is a much higher 'rate of occurrence' than many other regions of the globe (Scheffers and Kelletat, 2003).

The geological record of tsunami is much longer than was expected (by this author) stretching back at least 3.47 Ga. It is extremely unlikely that no tsunami affected the coasts of Australia between the second and third or third and fourth events listed. Further research around the Australian coastline (and at the coasts of proto-Australia) should reveal evidence of additional tsunami especially as geologists learn to recognise their signatures and evidence.

Overall, 77% of Australian tsunami were recorded on the coast of NSW. Examination of Fig. 2 indicates that whether we consider the whole, or only the palaeo or historic tsunami records, NSW dominates the list of events. Given the lack of data for the palaeo-record, it is not possible to make any meaningful comments. However, initial inspection of the catalogue suggests that the eastern sea board of Australia is at a significantly greater risk of tsunami impact (recording 44 out of 57 events). Whilst the actual number of tsunami that impacted the east coast may be high, it does not mean that other coasts are at a lower risk. It is not surprising that the east coast records so many events because it is the most heavily populated region of Australia. It may be that the high tsunami observation record, simply reflects population density on the eastern sea board. Alternatively, research may have been concentrated on the eastern side of the continent where coincidentally, most university and research organisations are located.

Almost 30% of the tsunami listed in Appendix A were generated by unknown causes (and most of these were actually in the early historic period). Such a significant percentage of unknown sources might present a challenge to government organisations and scientists concerned with understanding the tsunami hazard for Australia. Over 60% of Australian tsunami were generated by earthquake events suggesting that earthquake sources represent the biggest tsunami source and threat.

4.2. Discussion of the palaeotsunami record identified in the preliminary catalogue

Table 1 shows that ten palaeotsunami events have been reported for Australia. Given the size of the continent, its long geological history and low population density, it is not a surprise that so few palaeotsunami events have been reported. With time, it is anticipated that this record will be extended at least in terms of number of events (if not length of record).

Australia represents a fairly significant target for asteroid strikes (Haines, 2005; Shoemaker and Macdonald, 2005) and as such, the continent preserves geological evidence for asteroid generated tsunami. At the present time, no independent work has validated the reported asteroid palaeotsunami deposits although future work is likely to re-examine (and verify) these deposits and identify further asteroid tsunami deposits.

Tsunami event ID number 4 (Appendix A) dated to *circa* 105 ka by Young et al., (1992, 1993, 1996) was attributed by these authors to a tsunami reported to have been triggered by submarine slumping off Lanai, Hawai'i (Moore and Moore, 1984). Whilst submarine sediment slides of the volume and type of Lanai certainly have the capacity to generate tsunami, the on-shore evidence for the 105 ka tsunami on Lanai itself, has now been challenged calling in to question the occurrence of the reported 105 ka Lanai tsunami (Felton et al., 2000; Keating and Helsley, 2002; Felton et al., 2006). Consequently, the claim of Young et al (ibid) for a 'cause and effect relationship' between their field evidence on the NSW coast and the proposed Lanai slide tsunami should probably now be re-examined. In light of the work of Felton et al., (2000); Keating and Helsley (2002); Felton et al., (2006), tsunami event ID number 4 has been given a 'validity score' of just 2 (indicating that this event is in fact, doubtful).

The reported Holocene palaeotsunami record of Australia (and NSW in particular) is tantalising. Independent validation of the reported record has profound implications for understanding Australian coastal evolutionary processes and for determining coastal vulnerability in the region. This is because the reported palaeotsunami evidence generally points towards the occurrence of high-magnitude (low-frequency) events — potentially orders of magnitude larger than anything observed during historic times. Furthermore, the locations of these reported high-magnitude palaeotsunami deposits coincides with the very high exposure of people and infrastructure along the Newcastle–Sydney–Wollongong coastal corridor. For example, tsunami event ID number 5 is reported to have generated a run-up in excess of +100 m asl and tsunami event ID number 6 may have inundated the coast to distances of 10 km inland. If the field evidence for these events is accepted, it should be a matter of urgency to determine how frequently events of this magnitude occur and from where they originate. However, some authors have begun to question the evidence reported for Australian palaeotsunami (Felton and Crook, 2003; Goff and McFadgen, 2003; Goff et al., 2003; Noormets et al., 2004; Dominey-Howes et al., 2006). The controversy surrounding the reported palaeotsunami record will be discussed in Section 4.4.

4.3. Discussion of the historic tsunami record identified in the preliminary catalogue

Since AD1858 (the date of the first event recorded during the historic period), 47 tsunami have affected Australia. Given the previously noted view that Australia is a place of low tsunami risk, this record of events might be considered rather frequent. The historic record is biased towards events recorded during the 20th and 21st centuries and also to those recorded on the New South Wales coast. Again, this should not be considered a surprise given the high density occupation of the eastern seaboard, the location of major ports and research institutes and marine organisations.

It is possible that for the historic period, the actual number of tsunami that impacted the Australian coasts is likely to be much higher than that recorded. Australia has a very long convoluted coastline (that extends for more than 60,000 km) (Harvey and Caton, 2003) — 90% of which is not occupied or visited regularly. Therefore, there is a high probability that many events have gone unrecorded, particularly on the north eastern, northern and north western coasts close to tectonically active areas such as Papua New Guinea, the Solomon Islands and the Indonesian archipelago. Similar observations were made by Scheffers and Kelletat (2003).

The maximum run-up for a historic event of +6 m asl (tsunami event ID number 48) is interesting. Whilst the largest recorded run-up for a historic event (although surveys of the July 2006 event may indicate larger run-ups (Prendergast., pers. comm.)), it is dwarfed by the maximum palaeo run-up. If the historic record is relied upon to determine risk, it would suggest that the NW coastal region of Australia represents the highest hazard within Australia. However, exposure is relatively low in this region. This trend is the reverse of that indicated by the palaeo record.

Using the tsunamigenic zones of the Pacific region identified by Gusiakov (2005), it is possible to examine from where tsunami affecting Australia originate (at least for the historic period). By far the largest percentage of tsunami affecting Australia (25.5%) since AD1858 originated in the Papua New Guinea, Solomon Islands and Indonesia region and as such, may represent an important future source region. However, caution should be exercised given the limited number of events actually identified in the catalogue. The next most important source region is South America — responsible for 12.8% of Australian tsunami. Thirty-eight percent of tsunami were generated in regions across the Pacific and Southern Oceans and significantly, 23.4% of historic tsunami were generated in unknown source regions. Given the relatively high percentage of Australian tsunami originating in unknown source areas, scientists and authorities should tread carefully when thinking about risk.

There are several important issues that arise from an analysis of the recent tsunami history of Australia.

4.3.1. Coverage and extent of reports

There is a remarkable bias in the catalogue towards those events recorded on the eastern sea board as already mentioned and the present author is highly likely to have missed records for other events affecting the continent.

4.3.2. Types of information recorded

The vast majority of information recorded for tsunami observed during the modern period relates to the effects tsunami had on human systems. For example, accounts restrict themselves to observations of unusual tidal fluctuations and their relationship to moored boats and operating ships in harbours and ports. Information is usually provided about the number of waves within each tsunami wave train and more rarely, the wave period. Infrequent reports describe the grounding of boats due to water draw down within harbours. Rarely, accounts mention impacts on the natural environment — for example, the erosion and transport of sediments.

4.3.3. Exaggerations

Insufficient data exists to determine whether any of the reports of historical tsunami have been exaggerated. Actually, the opposite may be the case and that reports are accurate. This may be due to the fact that most reports come from Tidal Facilities and Harbour Master Stations. Typically, personnel that work at such locations are familiar with ocean and tidal cycles and appear to have kept observational notes that are factual (almost scientific) rather than filled with elaborate descriptions as was common in Victorian, Edwardian and early 20th century writing.

4.4. Discussion of the geological record of tsunami in Australia

4.4.1. Palaeotsunami

In Section 4.2, reference was made to the 'controversy' surrounding the reported palaeotsunami record in Australia. This controversy is based upon two issues: (1) the nature and type of evidence proposed for palaeotsunami and (2) the accuracy of the evidence and the possibility of erroneous interpretation. In order to understand and resolve this controversy, it is necessary to compare the nature of the Australian palaeotsunami record with that reported globally and to re-examine proposed evidence for palaeotsunami in light of new data and understanding. In the remainder of this section, the variety of geological deposits and signatures that tsunami imprint upon the coastal landscape are summarised and compared to those reported in Australia and outlined in Table 2. Similarities and differences can then be discussed and their bearing in relation to the palaeotsunami record of Australia explored.

Based upon numerous post-tsunami field surveys following recent events (e.g., 1992 Nicaragua (Satake et al., 1993); 1992 Flores Island (Shi et al., 1995); 1994 Java (Dawson et al., 1996); 1998 Papua New Guinea (Goldsmith et al., 1999; Kawata et al., 1999) and 2004 Maldives (Keating et al., 2005) and palaeotsunami studies, a variety of tsunami signatures and effects have been recorded. From these studies, it would appear that modern and palaeotsunami leave similar signatures imprinted within the coastal landscape and these are listed in Table 3.

Tsunami sediments are frequently deposited as continuous and discontinuous 'sediment sheets' which may comprise silts, clays, sands and boulders; these sheets mantle the underlying surface which may have been affected by wave erosion (though not always); rise in altitude and taper landward; are often sharply bounded at the top and bottom; are moderately to well sorted; are fine to massively bedded; have particle size distributions that fine upward and landward; include rip-up intraclasts within the body of the tsunami sediment unit and have microfossil assemblages which suggest landward transport of species from different water environments (or from the marine environment in to a terrestrial environmental setting) and the shells of which may be crushed or broken (see references cited in Table 3). Recently, boulder and mega-clast deposits together with their imbrication and orientation have been presented as evidence of tsunami (Bryant, 2001; Bryant and Nott, 2001; Scheffers, 2004; Mastronuzzi and Sansò, 2004). However, some authors contest this claim (Williams and Hall, 2004) whilst others remain to be convinced (Saintilan and Rogers, 2005). Deposition and preservation of tsunami sediments is dependent upon an adequate sediment supply, processes of reworking during backwash and subsequent tsunami inundation and post-depositional environmental processes (Dawson and Shi, 2000; Dominey-Howes, 2002). Authors usually present a 'suite' of these signatures in their analyses to argue the tsunami provenance of specific units.

From a careful analysis of the studies listed in Table 3, it is apparent that not all tsunami result in the deposition of all of the signature forms. In fact at best, only a selection of these signature forms may be present in any specific tsunami facies. This is potentially rather problematic. Consequently, whilst it is inappropriate to refute a tsunami origin for an individual sediment facies simply because it does not contain any (or all) of the reported signature types, it is the reporting authors responsibility to unequivocally demonstrate that a particular sedimentary facies owes its origins to a tsunami

Table 3
Modern and palaeotsunami signature types

Signature type	Description of the signature	Site locations for signature type	References
Basal unconformity	Lower contact between base of tsunami deposit unit and underlying sediment may be unconformable or erosional	(1) Scotland; (2) Hawai'i; (3) Japan	(1) Dawson et al. (1988); (2) Moore and Moore (1988); (3) Fujiwara et al. (2000)
Intraclasts	Lower/basal tsunami unit may contain "rip-up" or intraclasts or reworked or underlying material	(1) Scotland; (2) Hawai'i;	(1) Dawson (1994); (3) New Zealand; (2) Moore et al. (1994); (3) Goff et al. (2001)
Basal load structures	Lower/basal tsunami unit contains loading structures	(1) SW England; (2) Japan	(1) Foster et al. (1991); (2) Minoura and Nakaya (1991)
Fining upward sequence	Tsunami sediment horizons fine upwards	(1) SW England; (2) Scotland; (3) Flores Indonesia; (4) New Zealand; (5) Japan; Dawson and Smith (2000); (6) Papua New Guinea	(1) Foster et al. (1991); (2) Dawson (1994) and (3) Shi (1995) and Shi et al. (1995); (4) Chagué-Goff et al. (2002) and Goff et al. (2001); (5) Fujiwara et al. (2000); Nanayama et al. (2000); (6) McSaveney et al. (2000)
Landward fining sequence	Particle size of tsunami sediments fine landward from the shore	(1) SW England; (2) Scotland; (3) Flores Indonesia; (4) Russia; (5) Japan	(1) Foster et al. (1991); (2) Dawson (1994); (3) Shi (1995) and Shi et al. (1993); (4) Minoura et al. (1996); (5) Sawai (2002)
Distinctive layering	Separate waves in the tsunami wave train may deposit individual layers and/or individual layers may contain distinctive sub-units associated with deposition during run-up	(1) Hawai'i; (2) Scotland; (3) Indonesia; (4) Japan; (5) Portugal	(1) Moore and Moore (1988); (2) Smith et al. (2004); (3) Dawson et al. (1996); (4) Nanayama et al. (2000); (5) Hindson and Andraede (1999)
Cross bedding	Landward and seaward currents shown by imbrication of shells and/or low-angle wedged shaped lamination and/or cross bedding	(1) Japan; (2) Italy; (3) Argentina; (4) Tanzania	(1) Fujiwara et al., (2000); (2) Massari and D'Alessandro (2000); (3) Scasso et al. (2005); (4) Bussert and Aberhan (2004)
Imbricated boulders	Stacks or lines or accumulations of imbricated boulders at the coast	(1) Australia; (2) Caribbean; (3) Italy; (4) Cyprus	(1) Nott (1997); (2) Scheffers (2004); (3) Mastronuzzi and Sansò (2004); Kelletat and Schellmann (2002)
Biostratigraphy	Microfossil assemblages of diatoms and foraminifera. May be pelagic and/or benthic species in shallow water environments. Tests/frustules may be crushed and broken in significant percentages	(1) Greece; (2) United States; (3) Scotland	(1) Dominey-Howes et al. (1998); (2) Hemphill-Haley (1995, 1996); Williams and Hutchinson (2000); (3) Smith et al. (2004)

based upon other lines of evidence such as geomorphological data, eye witness accounts and so forth.

This brings us to the first of the controversies with regard to the proposed Australian palaeotsunami record. That is, it is apparent that the reported Australian tsunami signature types (see Table 2) often differ to those described elsewhere (see Table 3) and that many of the Australian types are seemingly unique. Several possibilities exist to explain these observations including that tsunami impacting on the Australian coastline are somehow different, or that researchers in Australia have evolved different explanations for the same evidence, or that errors in interpretation have occurred. There is no quick or ready solution to this paradox other than to acknowledge that such a difference exists and to seek ways of identifying the different signatures as well as re-examining the published evidence.

The second controversy in relation to the Australian palaeotsunami record — and perhaps the more significant, concerns possible errors in interpretation of the reported field data. Recent work by Felton and Crook (2003); Goff and McFadgen (2003); Goff et al., (2003) and Noormets et al., (2004) have all demonstrated that previously reported field evidence for palaeotsunami in Australia was misinterpreted and may be explained by non-tsunami processes. Most recently, Dominey-Howes et al., (2006) demonstrated that for one of the key sites for a palaeo-mega-tsunami deposit, the proposed marine (tsunami) deposited sediments were in fact, an *in situ* soil horizon. Collectively, these issues make it difficult at the present time to say anything meaningful about the nature and extent of the geological record of palaeotsunami in Australia — at least not until these controversies are resolved.

4.4.2. Historic tsunami

Whilst very limited in nature, a few accounts do indicate that modern Australian tsunami have been able to erode, transport and deposit marine sediments within the coastal landscape and have resulted in small scale geomorphological changes. These descriptions suggest that historic tsunami do the same 'type' of work within the coastal landscape of Australia as elsewhere in the world.

4.5. Future research priorities

One of the most significant lessons from the tsunami of 26 December 2004 and 17 July 2006 to the Australasian geological community is that Australia *is* at risk from tsunami flooding. These events did inundate coastal areas of Western Australia although no systematic field surveys have been reported that quantify the extent, nature and record of this flooding (Cummings pers. comm., 2005). Consequently, there exists a great need to better understand the tsunami record of Australia and to dismiss entirely the reported palaeotsunami evidence as some authors have, is both unwise and unfair.

It is possible to use the results and discussion presented in this paper to outline a series of key research priorities for the future.

4.5.1. Improving the record of tsunami events

The catalogue of events presented here is preliminary. Further work should be undertaken to refine those events listed and provide extra data. For example, the data needs correcting so that arrival times are provided in universal standard time. This would facilitate analysis of travel times around the continent for individual waves such as that of the 22nd May 1960 (see Fig. 3). Also, work should be undertaken to try and identify further events not currently listed in the catalogue. Such efforts should focus on both documentary and archival searches for modern events as well as upon geological studies within coastal landscape areas for evidence of palaeotsunami. There is also a strong need to undertake this work in areas that are not densely occupied and where exposure is low to try and improve the record. This is because a fuller understanding of the record (for example on the western seaboard) will help to improve our understanding of tsunami risk in the Indian Ocean region as well as in Australia *per se*.

4.5.2. Re-examining the geological record of Australian tsunami

The published palaeotsunami record for Australia is limited and has sparked some debate within the scientific community, especially around the mega-tsunami hypothesis of eastern Australia. New work by Dominey-Howes et al., (2006) has demonstrated that previously reported palaeomega-tsunami deposits are in fact, *in situ* soil horizons. Such findings imply that further work is necessary to better characterise and understand the nature and extent of tsunami deposits in Australia and to determine their similarity or difference to tsunami deposits elsewhere. Furthermore, research should attempt to resolve such questions as, "what 'work' do Australian tsunami do as they inundate coastlines; might other environmental processes offer an alternative explanation for the apparent 'tsunami deposited sediments' reported in many locations; and, is the 'mega-tsunami' hypothesis of Bryant and co-workers tenable given what we know?"

Consequently, it is recommended that post-event surveys should be carried out in Australia following tsunami inundation and the impacts and geological record of these tsunami reported. Concurrently, a re-examination of the reported palaeotsunami deposits should be undertaken and compared and contrasted with palaeotsunami deposits elsewhere. This work is vital if the controversy surrounding the reported palaeotsunami evidence is to be resolved and the potential value of such records may be realised.

Reconnaissance field work designed to investigate geological records of tsunami should be focused on coastal areas in Australia adjacent to tsunamigenic regions such as Indonesia and Papua New Guinea given the likely importance of these regions as source zones. Geological work should also be undertaken to identify further evidence for asteroid generated tsunami and to compare and contrast these deposits with similar asteroid tsunami deposits elsewhere.

4.5.3. Characterisation of Australian tsunami sources

The main source areas for historic tsunami that have affected Australia have been identified to some extent. Work should focus on characterising the likely sources of possible future tsunami events (i.e., a Probabilistic Tsunami Hazard Assessment) to gain an improved insight in to likely magnitudes and intensities of tsunami along different sections of Australia's coasts. This is very important because at the present time we are uncertain about which source areas are likely to be the most significant in the future. Furthermore, work should seek to understand what effect the continental rise and width of the continental shelf have on inundation distances and maximum run-up for different source events? Lastly, urgent work is needed to better understand local source areas for tsunami. For example, an interesting paper by Jenkins and Keene (1992) identified abundant, geologically recent submarine slumps on the continental rise off-shore of the area between Newcastle and Eden (NSW). At the present time these slumps remain undated and have not been mapped and studied in detail. There exists the possibility that these slump features could represent important local tsunamigenic sources/mechanisms and might have the capacity to generate locally large magnitude tsunami.

4.5.4. Risk and vulnerability assessment

Not all of Australia's coasts are equally vulnerable to tsunami inundation. Work should focus on determining which sections of coast represent the highest risk and contain the greatest exposure. From these assessments, probable maximum loss calculations for human life, homes, businesses and infrastructure should be undertaken.

4.5.5. Public understanding of tsunami risk and risk mitigation strategies

The development and implementation of the Australian Tsunami Warning System is a vital component in helping to make Australia safe from the impact of tsunami. However, of equal or greater importance, is the public understanding of tsunami risk and the development of risk mitigation efforts. Recent work by Bird and Dominey-Howes (2006) has shown that in spite of the enormity of the 2004 Indian Ocean Tsunami, the Australian general public has a confused understanding of the tsunami risk to Australia. Their findings suggest that the development of risk mitigation strategies will have to be carefully considered.

5. Conclusions

The Indian Ocean tsunami (IOT) of 2004, the most catastrophic tsunami to date, has prompted international efforts to better understand tsunami hazard and risk globally. The IOT event has resulted in significant interest within Australia about regional records of tsunami, the relative risk and future likely impact of tsunami. An understanding of tsunami hazard begins with detailed records of events within specific areas. Here, a preliminary catalogue of tsunami affecting Australia has been presented. The catalogue contains entries for 57 tsunami events. The oldest event is dated at 3.47 Ga, the most recent is the July 17th 2006. Forty-four tsunami were recorded on the New South Wales coast although the NW coast of Western Australia records a significant number of tsunami events. Forty-seven events have affected Australia since AD1858. Maximum run-up for an historic event is +6 m asl whilst the maximum run-up for a palaeotsunami event is reported at an elevation of at least +100 m asl. Twenty-three percent of historic Australian tsunami were generated by unknown causes and Papua New Guinea, the Solomon Islands and Indonesia collectively represent the most important source area of historic tsunami for Australia. Geological records for palaeo and historic tsunami have been identified and summarised. The geological record of tsunami represents a potentially important source of information for Australian tsunami. However, at the present time, the geological record is both limited and controversial and future research should seek to re-examine proposed geological evidence of tsunami. From an analysis of this preliminary catalogue of Australian tsunami, a series of key research priorities have been identified to guide future tsunami research in the region.

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Appendix A. Preliminary catalogue of Australian tsunami

ID number	Date			Source region	Cause	Region of impact in Australia	Max (*H*) (run-up); distance of inundation	Comments and descriptions	TI	V	Information sources/references
	Year	M	D								
Palaeotsunami events (i.e., those occurring prior to European occupation of Australia in AD1788)											
1	3.47 Ga				Asteroid	WA	No data available	"microkrystite spherule-bearing diamictite, interpreted as tsunami deposit" NOTE: there may be more than two individual asteroid (and tsunami) deposits at this location. Further work is needed.	XII	3	Glikson 2006); Glikson et al. (2004)
2	2.47–2.6 Ga				Asteroid	WA	Modelled amplitude *c.* 200 m. Deposit is laterally extensive for at least 40 km east-west and nearly 150 km north-south	"possibly represent exotic tsunami-transported blocks…."	XII	3	Hassler et al. (2000); Glikson (2006); Glikson and Allen (2004)
3	570 Ma				Asteroid	SA	No data available	"completely reworked by impact-induced tsunamis"	XII	3	McKirdy et al. (2006); Williams and Wallace (2003); Williams and Gostin (2005); Wallace et al. (1996)
4	105 ka			Hawai'i	Submarine volcano landslide	NSW	*c.* 15–25 (?) m asl	"Traces of erosional features observed on ramps"	XII	2	Bryant (2001); Bryant and Nott (2001); Young et al. (1992, 1993, 1996)
5	~ 8700–9000 BP			Unknown	Unknown	NSW	Run-up at Steamers Beach reported at elevation of at least +100 m asl	"[at Kiola] Estuarine sandy mud buried under 2.3 m of coarse beach sand and pebbles, which in turn is buried by 2.5 m of dune sand"	?	2	Bryant (2001); Young et al. (1996, 1997);

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Appendix A (*continued*)

ID number	Date			Source region	Cause	Region of impact in Australia	Max (*H*) (run-up); distance of inundation	Comments and descriptions	TI	V	Information sources/references
	Year	M	D								
6	~ 6500 BP			Unknown	Unknown	NSW	Inundation up to 10 km inland at Shoalhaven Delta	"[at Callala] sand ridge overlying estuarine deposit"	?	2	Bryant (2001); Young et al. (1993, 1997)
7	~3000 BP			Unknown	Unknown	NSW	Run-up *c.* +1.5 m asl, inundation approximately 1.5 km inland	"innermost sand ridges..... The shells in this deposit are from very mixed origins, including estuarine, rocky shoreline, open beach and continental shelf environments"	?	2	Bryant (2001); Bryant and Nott (2001); Bryant et al. (1992); Young et al. (1997)
8	~1600–1900 BP			Unknown	Unknown	NSW	Minimum run-up for this event is +5.7 m asl; deposits located along 240 km stretch of coastline	"[at Mystery Bay] mound of cobble and shell..... eroded remnant of another, almost identical deposit..... also consists of cobbles and shell, but the cobbles are significantly larger…."	?	2	Bryant (2001); Bryant et al. (1992a); Young et al. (1997)
9	~500–900 BP			Unknown	Unknown	NSW	Run-up to > 40 m asl at Atcheson Rock; deposits located along 120 km stretch of coastline	"[at Cullendulla] ridges of sand containing shell overlying estuarine sediments"	?	2	Bryant (2001); Bryant et al. (1992); Young et al. (1997)
10	~200–250 BP			Unknown	Unknown	NSW	*c.* +5 m asl	"[at Haycock Point] blocks plucked from shore platform and deposited up to +5 m asl"	?	2	Bryant (2001); Bryant et al. (1992);Young et al. (1997)
Historic tsunami events (i.e., those occurring after European occupation of Australia in AD1788)											
11	1858	2	6	Unknown	Unknown	TAS	0.0 m asl	"Tidal phenomenon. There was (says the Courier) a most extraordinary flow and ebb of the tide on Saturday [6/2/1858], in New Town Bay"	III	2/3	SMH(12/2/1858)
12	1866	8	9	Unknown	Unknown	NSW	0.0 m asl	According to Rynn (1994), tsunami was registered on the "tide gauge"	II	1	Rynn (1994)

13	1866	8	15th–21st	Unknown	Unknown	NSW	0.0 m asl	According to Rynn (1994), tsunami was registered on the “tide gauge”	II	1	Rynn (1994)
14	1867	8	5th–13th	Unknown	Unknown	NSW	0.0 m asl	According to Rynn (1994), tsunami was registered on the “tide gauge”	II	1	Rynn (1994)
15	1868	8	15	North Chile	Earthquake in Chile on 14/8/1868. Tsunami takes day to reach Australia	NSW, QLD, SA, TAS, WA	1.2 m asl	“A remarkable phenomenon was observed in Sydney Harbour on the 15th August. It was high water about 5 o’clock on that morning, and the tide was ebbing at a constant velocity about 8 am, when it suddenly turned, and the waters, as if impelled by some extraordinary influence, returned up the harbour with great force…..”	V	4	SMH (17/8, 18/8, 19/8, 20/8, 21/8/1868); SMH (22/8, 24/8,31/8, 2/9, 5/9, 7/9, 9/9/1868); SMH (5/11/1868); Fort Denison Tidal Register, May 1866–December 1882; NOAA/NGDC (2006); Rynn (1994)
16	1868	10	16	Central Chile	Earthquake	NSW, QLD	0.0 m asl	“disturbances were observed at this location”, and; “there were five tides during the day and there was erratic water movement”	III	3	SMH (19/10/1868); NOAA/NGDC (2006)
17	1868	12	24	Unknown	Unknown	VIC	0.5–1.2 m asl	“A tidal wave. The *Banner of Belfast* thus reports a phenomenon, which does not appear to have been observed at any other of the Victorian seaports: “Another tidal wave!”	IV	2	SMH (8/1/1869)
18	1869	8	11	Unknown	Unknown	NSW	0.0 m asl	According to Rynn (1994), tsunami was registered on the “tide gauge”	I	1	NOAA/NGDC (2006); Rynn (1994)
19	1870	8	12	Unknown	Unknown	NSW	0.0 m asl	According to Rynn (1994), tsunami was registered on the “tide gauge”	I	0	NOAA/NGDC (2006); Rynn (1994)
20	1874	10	13	Unknown	Unknown	TAS	0.0 m asl	“on the morning of the 13th a tidal wave occurred at Port Davey; and in the afternoon there was a severe earthquake which shook the houses distinctly, and was felt on vessels some distance from shore”	II	2	SMH (29/10/1874)

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Appendix A (*continued*)

ID number	Date			Source region	Cause	Region of impact in Australia	Max (*H*) (run-up); distance of inundation	Comments and descriptions	TI	V	Information sources/references
	Year	M	D								
21	1877	5	10	North Chile	Earthquake on 10th May. Tsunami takes day to reach Australia	NSW, QLD	0.8 m asl	"the first indication in Sydney occurred on Friday at 5:20 am, when the tide gauge at Fort Denison recorded the first series of waves "	V	4	Maitland Mercury (15/5/1877); SMH (12/5, 15/5/1877); NOAA/ NGDC (2006); Rynn (1994); Journal of Assistant Harbour Master of Newcastle, 26 June 1873–28 January 1881
22	1879	5	15	Unknown	Unknown	NSW	0.05 m asl	"on the afternoon of May 15th, the tide gauge at Fort Denison recorded a series of periodic waves usually called tidal waves"	II	4	SMH (20/5/1879)
23	1880	9	21	Chile	Earthquake	NSW	0.0 m asl	Fort Denison Tidal Register states "tide oscillating several inches"	II	2	Fort Denison Tidal Register May 1866 –December 1882; Rynn (1994)
24	1883	8	27	South Java Sea — Krakatoa	Volcanic eruption	WA	1.8 m asl	"On the 27th the tide [at Geraldton] rose to eight feet at 8 pm and again at 8:30 pm"	V	4	NOAA/NGDC (2006); Rynn (1994); Hunt (1929)
25	1883	8	28	South Java Sea — Krakatoa	Volcanic eruption	NSW, WA, TAS	1.5 m asl	"Krakatoa tsunami waves recorded from 28/8/1883 until 31/8/1883"	V	4	NOAA/NGDC (2006); Rynn (1994); Hunt (1929); Berninghausen (1966, 1969); Fort Denison Tidal Register January 1883–December 1892; Journal of the Assistant Harbour Master, Newcastle 28 May 1883–31 December 1885; Daily Mirror (12/7/1977)
26	1885	1	6	Unknown	Earthquake	WA	0.0 m asl	Rynn (1994) states that there were "observations at this location"	II	0	Rynn (1994); NOAA/ NGDC (2006)
27	1895	2	2	Unknown	Unknown	NSW	0.33 m asl	"At 5:10 pm on the 2nd at Newcastle, there was a tidal wave of thirteen inches on the sheet causing ships in the harbour to drag their anchors"	IV	3	Fort Denison Tidal Register December 1892– December 1898

28	1922	11	11	North Chile	Earthquake	NSW	0.2 m asl	“Erratic operation of tidal gauge pen at Fort Denison was that of an earthquake in Chile”	IV	4	NOAA/NGDC (2006); Rynn (1994); Hart (1931); Port of Sydney Journal (1946); Daily Mail (18/11/1922); Acting Deputy Superintendant Department of Navigation, Newcastle (1922)
29	1924	6	26	Macquarie Island	Earthquake	NSW	0.0 m asl	“Macquarie Island Earthquake 26th June 1924…..first tidal effect [at Fort Denison Tidal Register, Sydney] at 3:30 pm on 26 June….. tidal wave appears 464 mph”	II	4	NOAA/NGDC (2006); Rynn (1994); Fort Denison Tidal Register, December 1922–February 1928
30	1929	6	17	New Zealand	Earthquake	NSW	0.0 m asl	“New Zealand earthquake (Sydney time 08:52) 1st tidal effects felt at Fort Denison”	II	4	Hart (1931); Rynn (1994); NOAA/NGDC (2006); Fort Denison Tidal Register, March 1928–May 1933
31	1931	2	3	New Zealand	Earthquake	NSW	0.0 m asl	Rynn (1994) states “observation registered on tide gauge”	I	4	Rynn (1994)
32	1931	2	13	New Zealand	Earthquake	NSW	0.0 m asl	“reported tsunami attributed to earthquake in New Zealand”	II	4	Hart (1931); NOAA/NGDC (2006); Rynn (1994)
33	1933	3	2	Japan	Earthquake	NSW	0.0 m asl	“the full effect of the catastrophe did not manifest itself on the tide register at Sydney until some 54 h afterwards”	II	4	NOAA/NGDC (2006); Port of Sydney Journal (1946)
34	1946	4	1	Aleutian Islands	Earthquake on 1st April. Tsunami takes day to reach Australia	NSW	0.08 m asl	“after a shock in the same area (Aleutian Islands) on April 1st 1946, a tidal wave of three inches high reached Sydney in 46 h”	II	4	NOAA/NGDC (2006); SMH (11/3/1957); Fort Denison Tidal Register, July 1944–August 1950
35	1948	9	9	Tonga Trench	Earthquake	NSW	0.0 m asl	“Niaufu tidal wave recorded”	II	4	NOAA/NGDC (2006); Fort Denison Tidal Register, July 1944–August 1950
36	1951	8	24	Formosa, Taiwan	Earthquake (?)	NSW	0.0 m asl	“disturbance indicated on tide trace reckoned to be the results of earthquake in Formosa”	II	3	Fort Denison Tidal Register, September 1950–July 1956
37	1952	11	4	Kamchatka, Russia	Earthquake	NSW	0.0 m asl	“effects of an earthquake in far north Pacific noted on gauge”	II	4	Fort Denison Tidal Register, September 1950–July 1956; NOAA/NGDC (2006)

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Appendix A (*continued*)

ID number	Date			Source region	Cause	Region of impact in Australia	Max (*H*) (run-up); distance of inundation	Comments and descriptions	TI	V	Information sources/references
	Year	M	D								
38	1953	11	4	Solomon Islands	Earthquake	NSW	0.0 m asl	"severe earthquake near the Solomons. Recorded at 4 pm EST 26 h after earthquake at Fort Denison on gauge"	II	4	Fort Denison Tidal Register, September 1950–July 1956
39	1957	3	11	Central Aleutians	Earthquake	NSW	0.0 m asl	"In Sydney, the effect of the tidal wave was felt on Sunday afternoon [11/3/1957] when it raised the normal tide two to three inches"	IV	4	SMH (11/3, 12/3/1957); NOAA/NGDC (2006); Fort Denison Tidal Register, August 1956–October 1962; Camp Cove Tidal Register, June 1954–August 1960
40	1958	11	8	South Kuril Islands	Earthquake	NSW	0.0 m asl	"Main shockwave from severe earthquake off Japanese coast recorded at [Fort Denison] tide gauge at 11:45 pm 39 h after initial disturbance"	II	4	NOAA/NGDC (2006); Fort Denison Tidal Register, August 1956–October 1962; Camp Cove Tidal Register, June 1954–August 1960
41	1960	5	23	Central Chile	Earthquake on 22nd. Tsunami takes day to reach Australia	NSW, QLD, SA, TAS, VIC, WA	1.723 m asl	"First Chilean shockwaves recorded at Riverview at 8:15 pm on 21/5/1960….. first seismic ocean waves recorded by tide gauge [at Fort Denison] at 9:35 pm on 23/5….. severe seismic ocean waves recorded cessation at 3:15 am 28/5"	V	4	NOAA/NGDC (2006); Rynn (1994); Courier Mail (25/5/1960); Fort Denison Tidal Register, August 1956–October 1962; Camp Cove Tidal Register, June 1954–August 1960
42	1964	3	29	Alaska	Earthquake on 28th March. Tsunami takes day to reach Australia	NSW, TAS	1.0 m asl	"drastic alterations in the motion of the tides were noted"	I	4	Braddock (1969); SMH (30/3/1964)
43	1971	7	26	Bismark Sea, New Guinea	Earthquake	NE (QLD) and SE (NSW) Australia	0.0 m asl	Hatori (1982) indicates that this tsunami was observed in NE and SE Australia. (Note: this was a definite tsunami (validity 4), but it is unclear that it was actually recorded on an Australian tide gauge)	I	3	Hatori (1982); SMH (27/7 and 28/7/1971)

44	1975	7	20	Solomon Islands	Earthquake	NSW	0.0 m asl	"tsunami wave recorded on Camp Cove tide gauge"	II	4	NOAA/NGDC (2006); Camp Cove Tidal Register, March 1973–December 1979; SMH (22/7/1975)
45	1976	1	14	Kermadec Islands	Earthquake	NSW	0.0 m asl	Fort Denison Tidal Register states that "Earthquake — Pacific Ocean….. First tidal effects at 7:47 EST, 14th January" and, Rynn (1994) states that "observations of the tsunami were made"	II	4	NOAA/NGDC (2006); Rynn (1994); Fort Denison Tidal Register, March 1975–November 1981
46	1977	4	20	Solomon Islands	Earthquake	NSW, QLD	0.0 m asl	Fort Denison Tidal Register states "Solomon earthquake effects recorded in Sydney"	II	4	NOAA/NGDC (2006); SMH (22/4/1977); Fort Denison Tidal Register, March 1975–November 1981
47	1977	4	21	Solomon Islands	Earthquake	QLD	0.0 m asl	Rynn (1994) states "event registered on tide gauge"	II	3	NOAA/NGDC (2006); Rynn (1994); SMH (22/4/1977)
48	1977	8	19	Sunda Islands, Indonesia	Earthquake	WA	6.0 m asl	NOAA states 6 m run-up at Leveque; 4 m at Point Samson, and 2 m at Dampier Harbour all in Western Australia"	IV	4	NOAA/NGDC (2006); Rynn (1994); Gregson *et al.*, (1978)
49	1986	5	8	Aleutian Islands	Earthquake on 7th. Tsunami takes day to reach Australia	NSW	0.0 m asl	Fort Denison Tidal Register notes observation of seismic ocean waves on 8/5/1986	II	4	NOAA/NGDC (2006); Fort Denison Tidal Register 1982–1994
50	1989	5	23	Macquarie Island	Earthquake	NSW, TAS	0.3 m asl	Fort Denison Tidal Register notes observation of tidal disturbances following Macquarie Island earthquake. NOAA indicates run-up of 0.3 m asl on the SE coast of Australia	II	4	NOAA/NGDC (2006); Rynn (1994); Fort Denison Tidal Register 1982–1994
51	1989	10	19	California, USA	Earthquake on 18th. Tsunami takes day to reach Australia	NSW	0.0 m asl	Fort Denison Tidal Register observes tidal disturbances following San Francisco earthquake on 18/10/1989	II	4	NOAA/NGDC (2006); Fort Denison Tidal Register 1982–1994

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Appendix A (*continued*)

ID number	Date			Source region	Cause	Region of impact in Australia	Max (*H*) (run-up); distance of inundation	Comments and descriptions	TI	V	Information sources/references
	Year	M	D								
52	1994	6	3	Java, Indonesia	Earthquake	WA	3.0 m asl	"the most significant impact made on the shoreline occurred near the northwest Cape. The tsunami inundated the beach and car park at Baudin where the shore is exposed by a gap in the Ningaloo reef"	V	4	Rynn (1994); Foley (1994)
53	1995	5	15	Loyalty Islands, New Caledonia	Earthquake	NSW	0.0 m asl	"observed on tide gauge"	II	4	National Tidal Facility/Bureau of Meteorology
54	2004	12	26	Sumatra, Indonesia	Earthquake	NSW, QLD, SA, TAS, VIC, WA	*c*. +1.1 m asl	"observed on tide gauges"; and "inundated coasts of Western Australia"	III	4	National Tidal Facility/Bureau of Meteorology
55	2005	3	28	Nias Island, Indonesia	Earthquake	TAS, VIC, WA	*c*. +0.2 m asl	"observed on tide gauges"	I	4	National Tidal Facility/Bureau of Meteorology
56	2006	5	3	Tonga	Earthquake	NSW, QLD, TAS, VIC	*c*. +0.2 m asl	"observed on tide gauges"	I	4	National Tidal Facility/Bureau of Meteorology
57	2006	7	17	Java, Indonesia	Earthquake	SA, WA	*c*. +0.3 m asl	"observed on tide gauges"	I	4	National Tidal Facility/Bureau of Meteorology

For each event, the catalogue supplies: the corresponding ID (event) number, the date of occurrence (year, month (M), day (D)), the source region of the tsunami, the cause, the region of impact in Australia, the maximum (max (*H*)) wave run-up (metres above sea level) and/or inundation data, a comments description, an indication of the tsunami intensity (TI) of each event based upon the 12 point (I–XII) tsunami intensity scale of Papadopoulos and Imamura (2001) TI I=not felt, II=scarcely felt, III=weak, IV=largely observed, V=strong, VI=slightly damaging, VII=damaging, VIII=heavily damaging, IX=destructive, X=very destructive, XI=devastating and, XII=completely devastating and an indication of the validity (V) of the tsunami event (based upon the NOAA NGDC Tsunami Database classification): 0=erroneously listed event, 1=very doubtful tsunami, 2=questionable tsunami, 3=probable tsunami, 4=definite tsunami). NSW=New South Wales, QLD=Queensland, SA=South Australia, TAS=Tasmania, VIC=Victoria, WA=Western Australia.

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