Prime Minister's Science, Engineering and Innovation Council

Tsunamis: does anybody have to die?

REPORT OF THE WORKING GROUP ON TSUNAMIS TO THE PRIME MINISTER'S SCIENCE, ENGINEERING AND INNOVATION COUNCIL

2 DECEMBER 2005

This paper was prepared by an independent working group for the Prime Minister's Science, Engineering and Innovation Council (PMSEIC). The views expressed in the paper are those of the Working Group, not necessarily those of the Australian Government.

Cover photo provided by Emergency Management Australia.

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CASE STUDIES, FIGURES AND TABLES

Terms of reference for the Working Group on Tsunamis

The Working Group on Tsunamis will prepare a paper and presentation for the Prime Minister's Science, Engineering and Innovation Council to:

1. identify the impact on Australia and the Asian region of the recent tsunami and the likelihood of similar disasters in the future
2. compare the extent and reliability of tsunami alert and effective warning systems in the Indian and Pacific Oceans
3. outline Australia's research capability in the prediction, modelling, identification and risk management of tsunamis
4. discuss emergency management, particularly coordination and cooperation between relevant agencies that will provide effective public alerts about tsunamis and similar disasters and manage the national response, and
5. examine ways to build Australia's scientific profile and role globally to collaborate and assist the Australasian region in natural disaster management.

MEMBERS OF THE WORKING GROUP [1]

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[1] For biographical notes on the members of the Working Group on Tsunamis, see Appendix A.

ACKNOWLEDGMENTS

The Working Group would like to thank Mr Peter Arnold (Emergency Management Australia), Ms Zena Armstrong (Department of Foreign Affairs and Trade), Dr Sean Tobin (Department of Health and Ageing), Federal Agent Karl Kent (Australian Federal Police), Dr Dale Dominey-Howes (Macquarie University), Professor Beverly Raphael (University of Western Sydney), Commander Michael Beard (Royal Australian Navy), Ms Anita Dwyer (Geoscience Australia), Mr Trevor Dhu (Geoscience Australia), Dr Phil Cummins (Geoscience Australia) and Mr Andrew Coghlan (Emergency Management Australia) for the invaluable information and assistance that they provided to the group.

Executive Summary

Australia's response to the Indian Ocean tsunami was timely and generous, reflecting our commitment to the Asia-Pacific region. The tsunami severely impacted communities in Indonesia, India, Thailand, Sri Lanka and the Maldives and to a lesser extent in the Seychelles and on the eastern coast of Africa.

What is not widely known is that the tsunami also reached Australia. Significant sea-level surges were recorded around Australia and boats were ripped from their moorings. In Western Australia, North West Shelf operations were curtailed and a dozen swimmers swept away. Fortunately there were no casualties. However, a differently generated tsunami, perhaps closer to the Australian coast, could have been catastrophic. On Boxing Day, crowds of holiday-makers, possibly numbering in the hundreds of thousands, would be on beaches around Australia.

The Australian Tsunami Warning System, with funding of $68.9 million over four years, partly responds to this risk. However, there is no facility for coordinating Australia's existing scientific expertise to fully manage and mitigate the risk.

Our vision is to:

> **minimise the loss of life and reduce the cost to Australia from future tsunamis by developing tsunami science that informs strategic management of the risk; and**

> **build resilience in Australian and regional communities to best manage tsunamis and other hazards.**

To this end, we recommend establishing a Regional Centre of Excellence for Tsunamis, ensuring support for the Australian Tsunami Warning System is sustained, and creating formal pathways to better apply Australian science and innovation to emergency management planning and decision-making. The Working Group strongly believes that a more cohesive Australian effort on tsunamis, using the proposed Regional Centre of Excellence as the focal point, will best equip Australia to understand and mitigate the risk of tsunamis. The centre will also link closely with regional and international tsunami initiatives and continue Australia's regional leadership role.

We further propose that a working group be established to guide the formation of the Regional Centre of Excellence for Tsunamis, and report to the Prime Minister's Science, Engineering and Innovation Council (PMSEIC) in December 2006 on progress made.

Implementing the following recommendations will provide the framework needed to enable Australian and regional scientists to work more closely with policy decision-makers in an effective and collaborative manner. This will substantially reduce the number of lives lost and the social and economic costs from the next major tsunami to impact Australia and the region.

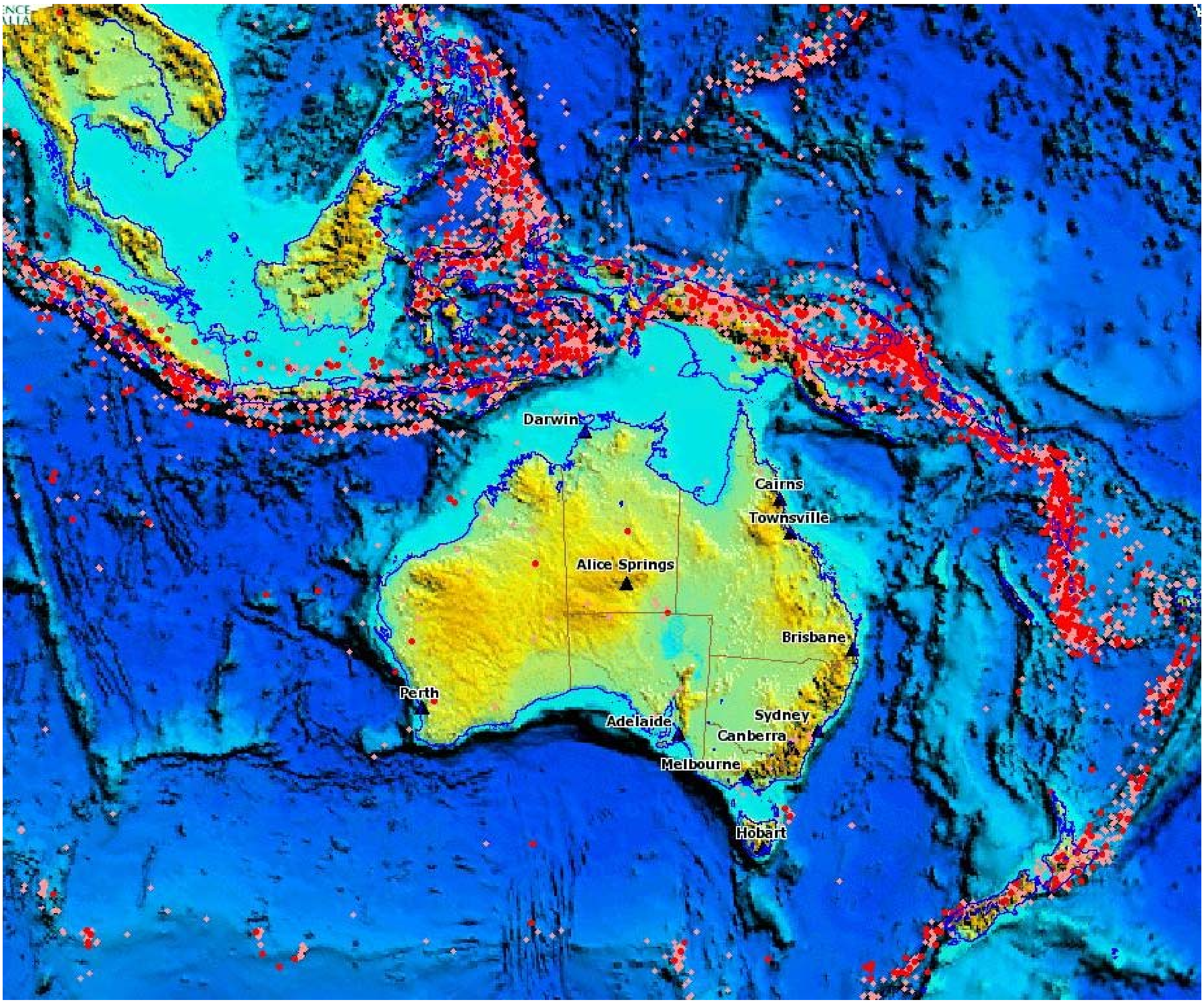
> Recommendation 1: **Establish a Regional Centre of Excellence for Tsunamis to focus Australian and international science/research and collaboration on the challenge of understanding tsunamis and mitigating their consequences.**

> Recommendation 2: **Consolidate the Australian Government decision to establish an Australian Tsunami Warning System through a long-term government commitment to ensure a sustainable and effective national tsunami warning system beyond the current four-year initiative.**

> Recommendation 3: **That PMSEIC requests that the Australian Government, through the Australian Emergency Management Committee, develops an effective pathway to incorporate hazard science into emergency management policy.**

THE TSUNAMI THREAT TO AUSTRALIA AND THE REGION

THE EARTHQUAKES (SHOWN AS RED AND PINK DOTS) OCCURRING ON THE TECTONIC PLATE BOUNDARIES SURROUNDING AUSTRALIA ACCOUNT FOR 30% OF THE WORLD'S ANNUAL SEISMICITY



Source: Geoscience Australia.

1 The Indian Ocean tsunami

The Indian Ocean tsunami on 26 December 2004 was triggered by a massive earthquake off northern Sumatra, where the Australian tectonic plate is being subducted under the Indonesian tectonic plate. The earthquake was one of the largest ever recorded (magnitude 9.3). It lifted the sea floor by up to 10 metres along a zone extending over 1200 kilometres from the Andaman Islands in the Bay of Bengal to northern Sumatra. This movement of the sea floor displaced a huge volume of water that subsequently spread outward as a large tsunami that impacted the entire Indian Ocean basin and caused sea-level surges across the world. Wave heights reached 20–30 metres in Sumatra, 5–10 metres in Thailand, Sri Lanka and India, and 1–3 metres along the African and Australian coasts.

The tsunami caused over 180 000 confirmed deaths. In addition, 45 000 people are still missing, and more than 1 500 000 people were displaced. These figures make the tsunami one of the most devastating in recorded history and rank it among the most lethal natural disasters in human history. While most of the fatalities occurred in Indonesia itself, thousands were killed in India, Sri Lanka and Thailand, and countries as far away as Africa were seriously affected (176 deaths in Somalia). The fatalities

The impact of the Indian Ocean tsunami. Photos: Australian Government included thousands of European tourists, as well as 26 Australians who died in Thailand and Sri Lanka. The immediate effects in Australia were relatively small – curtailment of North West Shelf operations, minor flooding, boats torn from moorings, and a dozen bathers swept out to sea (all subsequently rescued).

The immense scale of the tragedy triggered a massive international relief effort, in which Australia's role was paramount. The Australian Defence Force was among the first to respond, immediately dispatching 1000 personnel to Sumatra, along with helicopters, transport aircraft, a military field hospital and a water purification plant.

This quickly expanded into a relief effort that was the largest peacetime operation Australia has ever launched overseas and the biggest disaster relief operation since Cyclone Tracy. The Australian Agency for International Development (AusAID) and Emergency Management Australia, working in close partnership with relevant state and territory counterparts, were at the forefront of those immediate relief efforts, mobilising police, forensic, engineering and medical teams at short notice.

Australian response to the Indian Ocean Tsunami. Photos: Australian Government

Australia plays a strong leadership role in the Asia-Pacific region, reflecting our stability, prosperity and commitment to regional engagement (see Appendix B, 'Australia's role in the Asia-Pacific region'). Many in the region looked to Australia for assistance, as demonstrated by the large number of calls on our aid program, emergency managers, medical teams, scientists, engineers and others received from counterparts in the region. In all these fields, our political and diplomatic engagement drew on Australian Government as well as state and territory expertise.

In response to the scale of the Indian Ocean disaster, Australia committed $68 million on immediate emergency relief and established the five-year, $1 billion Australia–Indonesia Partnership for Reconstruction and Development. In addition, the Australian public and private sectors contributed more than $340 million through non-government organisations, and Australian state governments committed over $13 million.

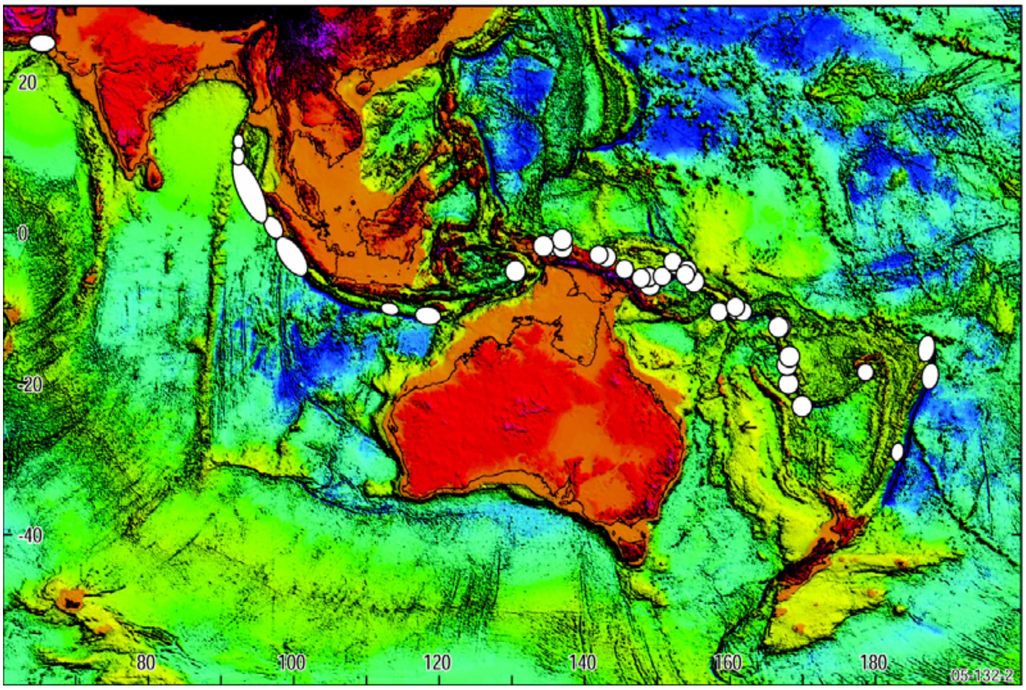
The short-term effects of the Indian Ocean tsunami on Australia were comparable to some natural disasters that have occurred on Australian soil. For example, the 1989 Newcastle earthquake caused 13 Australian deaths and involved an estimated $4.5 billion in cost to Australia, whereas the Indian Ocean tsunami caused 26 Australian deaths and will cost over the $1.4 billion in the direct aid described above. The implications are twofold.

1 Had the tsunami been focused toward Australia, the impacts would have been enormous, with many deaths and major economic consequences.
2 It is important that Australia maintains and strengthens assistance to its neighbours.

THE TSUNAMI RISK TO AUSTRALIA IS REAL

Our current understanding of tsunamis indicates that the tsunami threat to Australia is real (see Appendix C, 'The science of tsunamis'). Australia is surrounded to the north and east by some 8000 kilometres of active tectonic plate boundaries capable of generating tsunamis (Figure 1) that would reach Australia within two to four hours. The lack of major historical events along these boundaries is no reason for complacency and is not an indication of the absence of tsunami danger. The Indian Ocean tsunami should be regarded as a warning that strain energy is accumulating in preparation for one or more massive earthquakes producing large tsunamis that would impact the coast of Australia. Australia's coastal communities and infrastructure are particularly vulnerable to inundation from large tsunamis due to our narrow continental shelf and lack of protective islands.

FIGURE 1 EARTHQUAKES (1861–PRESENT) THAT HAVE CAUSED DAMAGING TSUNAMIS IN THE AUSTRALIAN REGION



Source: Geoscience Australia

The earthquake on 26 December 2004, which ruptured the northern quarter of the 4000 kilometre Sunda Arc, clearly resulted in increased stress on the plate boundary immediately south-east of Banda Aceh and almost certainly triggered the large Nias Island earthquake on 28 March 2005. These earthquakes could be the beginning of a sequence of massive earthquakes similar to that in the northern Pacific between 1950 and 1965. Tsunamis triggered by massive earthquakes along the rest of the active boundary to the north, north-east and east of Australia would be focused towards Australia and have much greater impact on our coast than the Indian Ocean tsunami had.

In recognition of this risk, the Australian Government announced on 10 May 2005 the establishment of the Australian Tsunami Warning System at a cost to government of $68.9 million over the initial four years (Case Study 1). The Working Group welcomes this pro-active initiative, which positions Australia to better safeguard its communities and continue Australian leadership in the region.

CASE STUDY 1 THE AUSTRALIAN TSUNAMI WARNING SYSTEM

The Australian Government is establishing the Australian Tsunami Warning System at a cost to Government of $68.9 million. The System is primarily focused on saving lives in Australia by providing warnings of impending tsunamis. The majority of the expenditure will be on instrumentation and the development of real-time systems to acquire and interpret data, and rapidly communicate warnings to the states and territories.

With anticipated cooperation and input from the states and territories, detailed tsunami inundation and risk maps of vulnerable communities can be developed. The states and territories are also responsible for developing effective tools for warning communities. Most of the work in developing the Australian Tsunami Warning System will depend on the application of existing national and international knowledge of scientists and technicians within the Bureau of Meteorology and Geoscience Australia.

Australia is playing a key leadership role in developing the Indian Ocean Tsunami Warning System, a coordinated network of national warning systems under the auspices of the Intergovernmental Oceanographic Commission of UNESCO. The Australian Tsunami Warning System will be a vital and central component of the Indian Ocean Tsunami Warning System. Australia is also driving improvements to the existing Pacific Tsunami Warning System.

Effective tsunami warning systems for the Indian Ocean and the Pacific Ocean depend on four essential components:

1. public awareness of the possible threat and appropriate response procedures;
2. seismic data and analysis to detect an undersea earthquake or other geophysical event that could initiate a tsunami;
3. sea-level data and oceanographic modelling to determine the magnitude and likely timing of tsunami impacts; and
4. an emergency management and public warning capability to transmit the warning and respond at the local level.

The warning capability in the Indian and Pacific Oceans are compared using these four components in Appendix D, 'Pacific and Indian Ocean tsunami warning systems'.

EARLIER APPLICATION OF SCIENCE COULD HAVE DRAMATICALLY REDUCED THE IMPACT OF THE INDIAN OCEAN TSUNAMI

No Indian Ocean tsunami warning system was in place prior to the Indian Ocean disaster on 26 December 2004, as there was little appreciation of the tsunami threat at either the community or political level. Had a system similar to the Pacific Tsunami Warning System been in operation, with emergency managers alerted and communities mobilised, many thousands of lives would have been saved. While the Australian relief effort was effective, well coordinated and generous, it must be recognised that this effort was responsive in nature.

The merit in moving from a focus on responsive disaster management to strategic management of risk and mitigation measures is well recognised. The Council of Australian Governments' report *Natural disasters in Australia: Reforming mitigation, relief and recovery* noted the need for a 'fundamental shift in focus towards cost-effective and evidence-based disaster mitigation' and that this shift 'represents an historic move beyond disaster response and reaction, towards anticipation and mitigation'.[2] Science has an indispensable role to play by providing the evidence and knowledge needed to enable this significant shift.

Our vision is to:

> minimise the loss of life and reduce the cost to Australia from future tsunamis by developing tsunami science that informs strategic management of the risk, and

> build resilience in Australian and regional communities to best manage tsunamis and other hazards.

To this end, the Working Group makes the following recommendations.

> **Recommendation 1: Establish a Regional Centre of Excellence for Tsunamis to focus Australian and international science/research and collaboration on the challenge of understanding tsunamis and mitigating their consequences.**

The risk of tsunamis to Australia is real but not well appreciated. Recognising the need to improve our understanding of this risk, the Working Group has identified the need for government to attach priority to tsunami science. We advocate a holistic approach that requires fundamental work in such fields as physical sciences (geology and oceanography), mathematics and numerical modelling, the engineering sciences, the biological and medical sciences (coastal ecosystems, forensic science) and the social sciences (economics, sociology).

There are serious gaps in our understanding of tsunamis. The elements needed to fill these gaps already exist within Australia and the region, but they need

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2 Natural Disasters in Australia: Reforming mitigation, relief and recovery arrangements. Council of Australian Governments, 2004, pg vi.

refocusing. Given the far-reaching nature of tsunamis, it is essential to engage the region's scientific community and focus scientific efforts to truly understand tsunami behaviour. A Regional Centre of Excellence would allow Australia and its neighbours to share scientific approaches and findings, facilitate education and community awareness, build relevant capability within the region and ensure sustainable and effective regional partnerships.

A working group is proposed to develop the Regional Centre of Excellence and suggested terms of reference for this working group are in Appendix E, 'Development of a Regional Centre of Excellence'.

> **Recommendation 2: Consolidate the Australian Government decision to establish the Australian Tsunami Warning System through a long-term government commitment to ensure a sustainable and effective national tsunami warning system beyond the current four-year initiative.**

The Regional Centre of Excellence will be inextricably linked with the Australian Tsunami Warning System. The warning system will provide accurate and effective warning information as well as communication systems and education programs for disseminating and responding to tsunami warnings. The warning system will provide the first line of defence for saving lives. Better scientific research and analysis will broaden and complement the warning system by informing other mitigation measures – from land-use planning and building codes to improved disaster response and recovery. Given the ongoing risk of tsunamis to Australia, the Australian Tsunami Warning System program must be continued beyond the four-year establishment period.

> **Recommendation 3: That PMSEIC requests that the Australian Government, through the Australian Emergency Management Committee, develops an effective pathway to incorporate hazard science into emergency management policy.**

Australia's emergency management arrangements are recognised internationally for their quality, but would be significantly improved if better informed through the scientific process. The Working Group has identified a need for the Australian Government to develop an effective, formal pathway to incorporate hazard science into emergency management policy.

Implementing these recommendations will provide the framework needed for Australian and regional scientists to work with policy decision-makers in a more effective and collaborative manner. This collaborative approach will substantially reduce lives lost, and reduce the social and economic costs from any major tsunami that strikes Australia and the region.

2 Emergency management and the tsunami hazard

Australia has a strong tradition in emergency management, and our response and relief capacities are recognised internationally for their excellence.

Each year many Australian communities are affected by natural hazards such as floods, cyclones, bushfires and severe windstorms. Communities and government work together to understand and live with many of these frequent natural hazards (Appendix F, 'Background to emergency management in Australia'). However, as our population grows, our vulnerability to extreme and rare events increases.

To better assess and respond to the potentially catastrophic risk of tsunamis to Australia and our neighbours, we need a better understanding of the behaviour of tsunamis. This requires a greater focus within the scientific community on tsunami science, as well as formal pathways to integrate scientific findings into emergency management decision-making. Strategically applying tsunami science to Australia's emergency management arrangements will improve the safety of communities in Australia and the region, and protect our critical coastal infrastructure.

MOVING TOWARDS MITIGATION

Reducing the impact of natural disasters requires a greater focus on mitigation. This is the clear and consistent finding drawn from current high-level government reports, lessons learnt from recent disasters, and international trends in emergency management. The Council of Australian Governments' report *Natural disasters in Australia: reforming mitigation, relief and recovery* acknowledged that it is critical for all levels of government to shift towards mitigation. This shift represents a holistic approach to managing natural disasters and is further supported by lessons learnt from recent events in our region involving significant Australian resources.

Mitigation refers to the measures taken in advance of a disaster aimed at reducing the impact of future disasters on society and the environment (Case Study 2). While steps have been taken in Australia to move towards mitigation, a further commitment to strategically using science in decision-making will improve the safety of communities in Australia and in our region.

CASE STUDY 2 SHIFT IN US POLICY TO IMPROVE VOLCANO DISASTER MITIGATION

Prior to the 1980s, foreign disaster assistance provided by the US Government to other countries was generally reactive, providing response and relief assistance after a diaster had occurred.

This policy changed after 20 000 people were killed in a mudflow associated with the eruption of Nevado del Ruiz volcano in Colombia in 1985. When the volcano first showed signs of increasing activity, the Colombian Government appealed to donors, chief among them the United States, for assistance in assessing the hazard. In part because US Geological Survey vulcanologists were still committed to monitoring activities on Mt St Helens, the United States provided only minimal support.

On 13 November 1985 an eruption triggered a huge *lahar* (the Indonesian word vulcanologists use to denote a volcanic mudflow) that buried the entire town of Armero under 3–6 metres of mud. Scientists later agreed that the hazard to Armero should have been recognised and the loss of life drastically reduced through appropriate pre-eruption mitigation measures. The US Government had to deal not only with a huge cost in humanitarian aid, but also with the perception that it had ignored Colombia's pleas for help.

Following the Ruiz disaster, the policy of the US Office of Foreign Disaster Assistance shifted to include a stronger focus on pre-disaster mitigation. This policy bore fruit when Mt Pinatubo in the Philippines erupted on 15 June 1991. Vulcanologists sent to monitor the volcano successfully forecast the eruption, saving an estimated 5000 lives and at least US$250 million in property damage. The cost of saving these lives and property was estimated at US$56 million, of which the cost of the monitoring operation itself was US$1.5 million.

Following Australia's recent emergency response and relief efforts and the aid committed to affected countries in our region, intergovernmental debriefs identified key areas for improvement, including a need for data and information to support decision-making and a focus on improving government coordination.[3] Furthermore, a need for greater coordination of mitigation activities has been recognised.[4] Case Study 3 demonstrates that natural disasters can be anticipated, but in the absence of a formal pathway to get findings and advice from scientists to decision-makers the current mechanisms are inadequate for science to be effective.

3 Management Advisory Committee, *Connecting government: whole of government responses to Australia's priority challenges*, Australian Public Service Commission, Canberra, 2004; Emergency Management Australia, *Initial review of response and coordination arrangements following the Bali bombing*, Attorney-General's Department, Canberra, 2002.

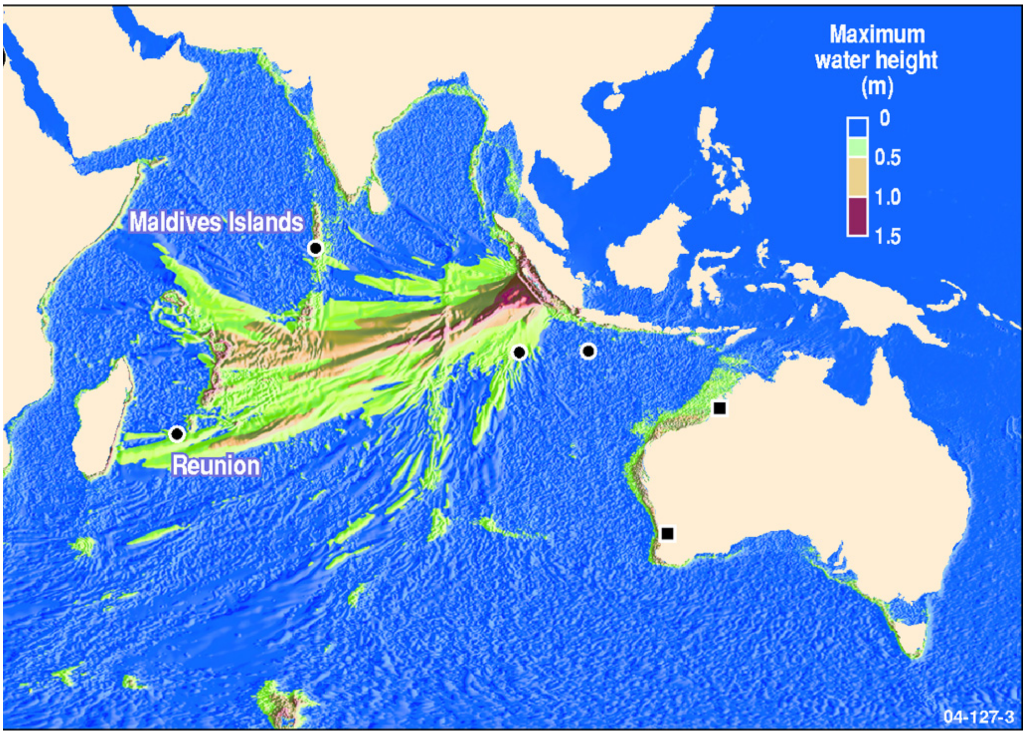
4 Emergency Management Australia, *Lessons learnt from Tsunami Assist*, 2004–05, Attorney-General's Department, Canberra, 2005.

CASE STUDY 3 THE INDIAN OCEAN TSUNAMI – IT WAS ANTICIPATED

Scientists had been aware of the potential for great earthquakes off Sumatra prior to the Indian Ocean tsunami. In 1987 US researchers published their analysis of historical records from the Dutch colonial period in Indonesia, indicating that earthquakes as large as magnitude 8.8 had occurred off Sumatra. In 1999 another US group found that the annual growth rings of Sumatran corals record submergence and uplift associated with earthquakes. This work suggested that an 1833 earthquake that occurred off Sumatra had a magnitude of 9.2, as large as those that have triggered large trans-Pacific tsunamis. In 2004 Australian researchers modelled the tsunami that might have been generated by this earthquake and suggested it could affect the entire Indian Ocean (Figure 2).

While there was an emerging picture of possible tsunami risk within the scientific community there was no formal framework available to absorb and apply this science to mitigate the potential risk.

FIGURE 2 MODELLED EXTENT OF THE 1833 SUMATRAN TSUNAMI, SHOWING OPEN-OCEAN WAVE HEIGHTS



Source: Geoscience Australia

While science has the capacity to contribute to the reduction of risk posed by natural disasters, including tsunamis, it is only by strategically using scientific findings that this potential will be realised. The responsibility for effectively applying science is shared by scientists, emergency managers and planners, and policy decision-makers within all

CASE STUDY 4 SHARING THE RESPONSIBILITY: SCIENTISTS, EMERGENCY MANAGERS AND PLANNERS, AND GOVERNMENT

The Fire and Emergency Services Authority (FESA) of the West Australian Government signed a memorandum of understanding with Geoscience Australia in August 2005. The memorandum supports the development of tools and methodologies to help emergency managers as well as state and local governments to plan for and respond to tsunami events.

Following the Indian Ocean tsunami, Geoscience Australia and FESA recognised the vulnerable nature of the West Australian coast and the need to understand more about the risk posed to communities and infrastructure. To this end, Geoscience Australia has modelled potential tsunami-genic events and is undertaking further modelling to assess the risk to specific communities along the coast. This will assist emergency managers to make better-informed decisions on the tsunami threat to the West Australian coastline.

Geoscience Australia, the Bureau of Meteorology, and Emergency Management Australia work closely with state emergency organisations before, during and after disaster events. However, the agencies are grappling with how best to integrate any scientific findings from their agencies or other researchers and engineers into emergency management practices. A formal pathway for integrating scientific findings into emergency management is needed to maximise the outcomes of the collaboration, providing greater capacity for FESA and potentially all state and territory governments to fulfil their responsibility to protect communities from tsunami impacts.

levels of government as well as the private sector. As shown in Case Study 4, some steps to recognise and address this responsibility are taking place on an ad hoc basis.

Although science does currently inform emergency management policy and practice through informal processes, the Working Group has identified a critical need for a formal link to ensure that emergency management is better informed by science. To this end, a scientific advisory body should be initiated and a formal pathway to link hazard science to emergency management policy should be developed.

> **Recommendation 3: That PMSEIC requests that the Australian Government, through the Australian Emergency Management Committee, develops an effective pathway to incorporate hazard science into emergency management policy.**

3 Science and the tsunami hazard

It took the catastrophic events of the Indian Ocean tsunami to alert Australia to the potential for a tsunami tragedy on our own shores. The Working Group has identified a critical need to improve our understanding of the tsunami hazard and its potential to devastate Australia. However, our current lack of knowledge about the tsunami hazard means that we cannot yet answer crucial questions such as:

> What is the chance of a tsunami impacting Sydney or Perth?

> If a tsunami occurs, which areas are most vulnerable?

> How much protection do environmental features such as the Great Barrier Reef provide to cities such as Cairns?

Answering these, and other, important questions will require a comprehensive understanding of the behaviour of tsunamis.

At the strategic level, policy decision-makers, planners and emergency managers need answers to the following questions in order to develop the most appropriate and cost-effective measures to mitigate the tsunami threat.

1. What is the likelihood of a tsunami affecting Australia and the region?
2. What is the likely impact?
3. How can we reduce loss of life?
4. How can we reduce the cost?
5. How can we best respond to and recover from a tsunami?

Acquiring the knowledge needed to answer these questions will require significant focused and coordinated scientific effort. As with most research the range of science required is not yet known. However, the Working Group has identified some priority areas where the coordination, development and application of science can improve our understanding of the behaviour of tsunamis and make a vital contribution to the safety of Australia and the region.

> Understanding the buildup of stress along the tectonic plate boundaries provides information about the most likely location and the likelihood of an imminent event. This will require active monitoring of the geodynamic processes at these boundaries, in particular the deformation of tectonic plates and the associated buildup of energy.

> Historic and prehistoric evidence of the frequency of tsunamis is critical to understanding how often tsunamis may occur in the future. Australia's geological record contains evidence of tsunamis hundreds and even thousands of years ago. Similarly, evidence of these events will also be found in changes in coral growth

patterns. Case Study 5 demonstrates that this knowledge can give a better appreciation of the risk and identify the need for mitigation strategies.

CASE STUDY 5 SCIENCE ALTERS THE PERCEIVED EARTHQUAKE–TSUNAMI RISK FOR CASCADIA

Earthquake hazard in the Cascadia region of North America's Pacific coast was thought to be only moderate until the scientific basis for this assessment was re-examined in the 1990s. Although there is no historical record of great earthquakes in Cascadia, the geological setting was similar to areas that had experienced them, and the existence of an Indian legend describing severe shaking followed by a flood suggested such events predated the historical record.

Geologists subsequently discovered a thick sand layer buried in coastal marshes (Figure 3) that may have been deposited by a large tsunami. It was then recognised that previously unexplained stands of dead trees may have been killed when coastal lowlands were submerged after a great earthquake. Eventually, Japanese researchers found a historical record of a tsunami reaching Japan for which no earthquake had been felt, whose date was consistent with the tree-ring dating of the Cascadia tree deaths. These discoveries led to the realisation that the likelihood of a massive earthquake and tsunami in Cascadia, for which there is no historical precedent, is very high. Long-term mitigation measures are now being taken to address the hazard.

FIGURE 3 SAND LAYER THOUGHT TO HAVE BEEN DEPOSITED BY THE 1700 CASCADIA TSUNAMI

Photo: National Oceanographic and Atmospheric Administration (NOAA), U.S.A.

> Enhancing our ability to model the flow of a tsunami onshore and its interaction with structures and debris will allow us to determine which parts of our coastline will be affected by a given tsunami scenario and, more importantly, how far onshore the tsunami will come. These scenarios can form the basis for training and capacity-testing exercises as well as the development of robust emergency management response plans (Case Study 6). The reliability of these models is largely determined by the quality of input datasets describing the shape and elevation of the sea floor and onshore terrain. In many cases the data are incomplete or inaccessible. Consequently, there is a critical need to acquire and collate these data in a whole-of-government approach.

CASE STUDY 6 TSUNAMI MODELLING ALLOWS AUSTRALIA TO PREPARE FOR IMPACT

In late 2004 and early 2005, the Australian Emergency Management Committee conducted a series of 'table top' exercises to test Australia's capacity to respond to catastrophic disasters such as the Indian Ocean tsunami. These exercises were underpinned by theoretical scenarios that describe the impact of five different catastrophic events including a hypothetical tsunami striking the Wollongong region of New South Wales. Detailed impact modelling produced a series of maps and animations that demonstrated the potential effect of this tsunami (Figure 4). This modelling required high-resolution datasets describing the region's bathymetry and topography as well as a comprehensive understanding of the number of structures and people exposed to the incoming wave. This tsunami could devastate the Wollongong region, potentially taking thousands of lives and causing an estimated direct economic cost of $10 billion.

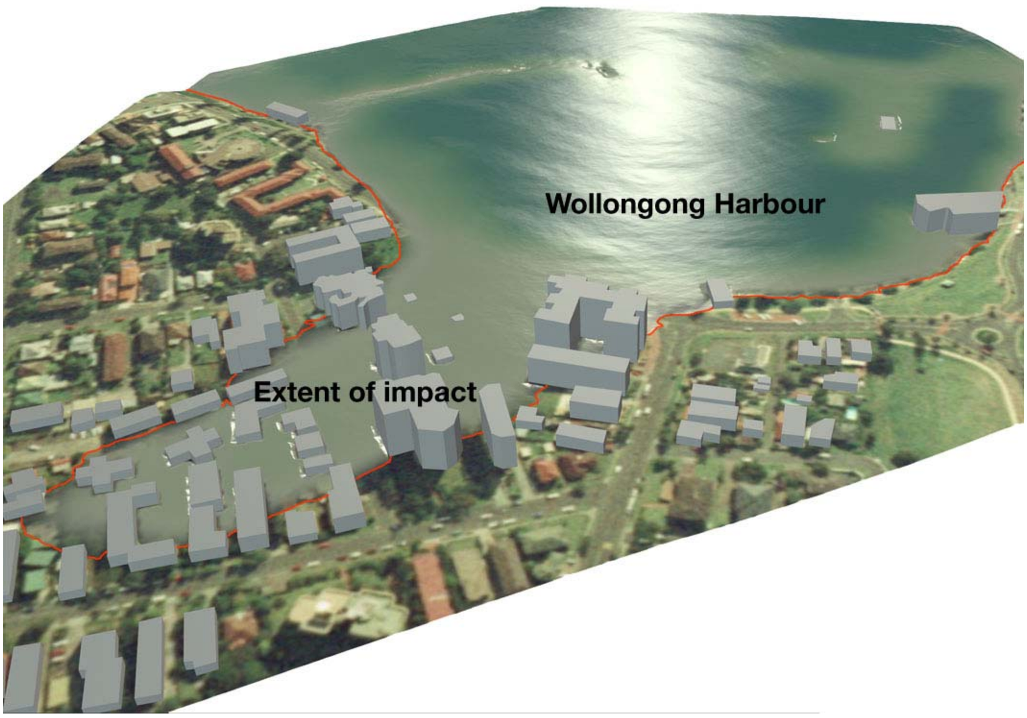
The results of this work have allowed Australian emergency managers and planners to take steps to reduce the scale of such a catastrophe. The project has highlighted the fact that science is the major contributor to the development of scenarios against which risk can be measured and emergency response and recovery protocols can be developed.

> Engineering models can be developed to describe how buildings and infrastructure will perform following the impact of a tsunami. This will inform us about which buildings should be used as evacuation points during a tsunami and what infrastructure is most vulnerable. Moreover, such models can be used to refine and improve Australia's building codes to ensure that Australian structures will withstand a tsunami. Figure 5 demonstrates that well-constructed buildings were able to survive the Indian Ocean tsunami in regions where all other buildings were destroyed.

FIGURE 4 RESULTS OF MODELLING INUNDATION AT WOLLONGONG HARBOUR FROM A 6 METRE WAVE SIMULATED FOR THE AUSTRALIAN EMERGENCY MANAGEMENT COMMITTEE'S CATASTROPHIC DISASTERS WORKING GROUP

THE INCOMING WAVE

THE RESULTANT INUNDATION



Source: Geoscience Australia

FIGURE 5 WELL-CONSTRUCTED BUILDINGS SURVIVED THE INDIAN OCEAN TSUNAMI

Photos: Australian Government

> Adapting microeconomic and macroeconomic models to incorporate the impacts associated with tsunamis will allow Australia to predict the cost of potential tsunamis in terms of the built infrastructure, economy, ecology and environment as well as community wellbeing. These tools will not only enable us to better understand the true cost of tsunamis, but also clearly demonstrate the benefits of mitigation strategies, such as building code improvements.

> The detection of tsunamis by the Australian Tsunami Warning System will require a combination of seismic and sea-level monitoring equipment. The detection of tsunamis is highly dependent on the placement of sensors in areas where earthquakes are most likely to occur and where tsunamis are most likely to travel. In particular, the most advanced type of tsunami detectors are Deep ocean Assessment and Reporting of Tsunamis (DART) buoys (Figure 6), which must be deployed in the deep ocean and involve sophisticated and expensive electronics to transmit signals from the ocean floor to satellites and back to earth. In future, it may be possible to develop systems that are able to detect tsunamis more simply and effectively through satellites or other means that we have not yet imagined.

FIGURE 6 DART BUOY BEING PREPARED FOR DEPLOYMENT

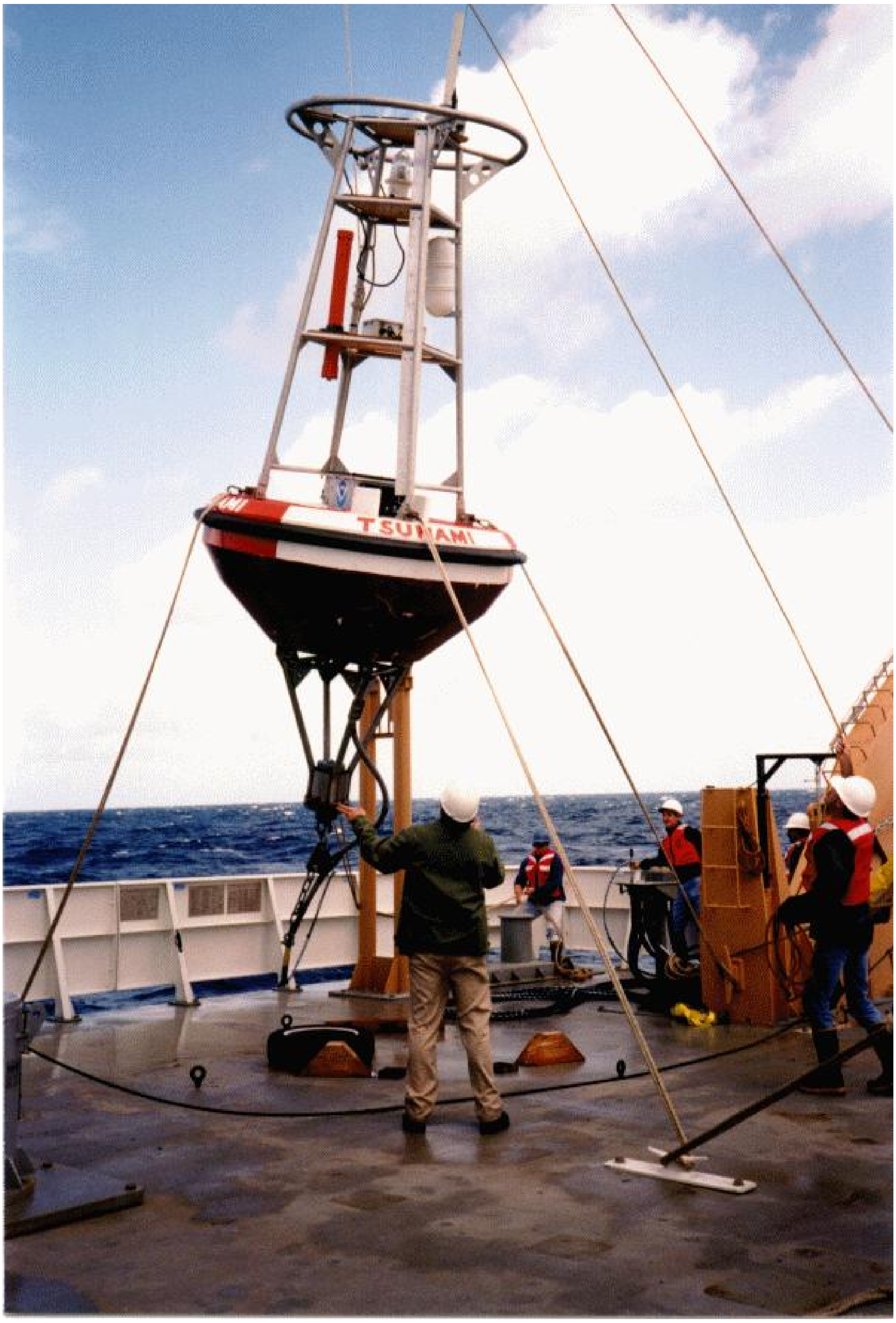


Photo: National Oceanographic and Atmospheric Administration (NOAA), U.S.A.

> The Australian Tsunami Warning System will be complemented by further scientific advances. For example, the current system is predicated on quickly and accurately detecting and locating large tsunami-genic earthquakes. However, Case Study 7 demonstrates that science is not yet able to quickly determine the magnitude of a massive earthquake. Similarly, improvements need to be made in our ability to disseminate alerts to the public. Radio broadcasts and sirens are useful but provide no guarantee that the message will be received and understood. Innovative use of mobile phone technology, coupled with the GPS (global positioning system), may allow warnings to be issued to phones in specific locations in the future. The true value of the Australian Tsunami Warning System will be realised once it incorporates an appropriate, effective and timely method of providing warnings and advice to the community when a tsunami is detected.

CASE STUDY 7 INDIAN OCEAN TSUNAMI REVEALS PROBLEMS IN ALERTING FOR MASSIVE EARTHQUAKES

While seismology has standard procedures for estimating the size of most earthquakes, it is not yet able to reliably and rapidly assess the size of massive earthquakes such as that which triggered the Indian Ocean tsunami. The Pacific Tsunami Warning Center detected the 26 December 2004 earthquake and issued a notification about 10 minutes after it occurred. The initial estimate of the earthquake's magnitude, however, was 8.0 – large enough to cause a local tsunami but not one that might impact an entire ocean basin. One hour after the earthquake the magnitude estimate was revised to 8.5, which caused concern that the impact area might be wider than first envisaged. Much later, estimates became available indicating the magnitude of this earthquake was greater than 9, much larger than the initial estimate and one of the three largest earthquakes ever recorded instrumentally. (A single unit of magnitude corresponds to a factor of 30 in energy. That is, magnitude 9 has 30 times the energy of magnitude 8.) Because this information was not available sooner, news reports were the first confirmation seismologists had that the earthquake was massive enough to generate a tsunami so large as to affect the entire Indian Ocean.

When a subsequent earthquake happened farther south-east along the Sumatra subduction zone on 28 March 2005, its magnitude was rapidly and accurately estimated as 8.7. A tsunami warning was issued and thousands of people fled low-lying coastal areas. In this case no large tsunami was generated, so the alarm was false. While a magnitude 8.7 earthquake would normally generate a large tsunami, it turned out that most of the fault slip associated with this earthquake was concentrated near the base of the fault plane. There was little deformation of the sea floor, and only a local tsunami was generated. This demonstrates that magnitude, the standard measure of earthquake size, does not always provide enough information to accurately assess tsunami-genic potential.

- Research in the social and psychological sciences, drawing on the expertise of anthropologists, psychologists and psychiatrists, economists, sociologists, geographers, historians and political scientists, has focused on developing an understanding of the vulnerability and resilience of individuals and communities impacted by natural disasters and how to enhance recovery. Social and economic attributes contribute greatly to a community's capacity to recover from devastating events. However, we need to understand more clearly the relationship between these attributes and the ability of communities to prepare for and recover from tsunamis. Central to such understanding is recognising that the vulnerability of people and communities is a result of the social relations embedded in broader economic and political systems.
- A community's recovery following a tsunami is strongly affected by its access to critical infrastructure such as electricity, water, telecommunications and transport. The robustness of infrastructure networks needs ongoing research to provide an understanding of network dependencies and key points of failure (Figure 7). Such understanding will allow the development of appropriate mitigation options as well as strategies for rapidly restoring critical infrastructure following a tsunami.
- Forensic science plays a major role in identifying disaster victims. The identification of victims, often extremely difficult overseas and in tourist areas, can be substantially enhanced through research in forensic odontology and through improved fingerprint ridge and DNA analysis. These forensic tools need to be complemented by the development of mobile mortuaries to reduce the spread of disease when dealing with large numbers of deceased.

FIGURE 7 THE TSUNAMI DESTROYED TRANSPORT INFRASTRUCTURE IN SRI LANKA

Tsunami Sri Lanka Victims Assist. Photo: Australian Government

- One of the most serious long-term environmental effects of tsunamis is the contamination of soils and underground water reserves with salt. In some cases this problem is so acute that communities have to depend on outside aid for food and water for years to come. We need to understand the long-term economic consequences of such damage for coastal communities, as well as learn how we can rehabilitate the environment in a cost-effective and environmentally sensitive manner.
- Environmental science can be used to support and enhance natural mechanisms that mitigate the effects of tsunami impacts. For instance, mangroves and coconut palms can provide an effective buffer to waves inundating the coast (Figure 8). By preserving healthy environments for coral reefs we also provide natural barriers that dampen tsunami waves, thereby lessening their impact on the coast.

The Australian scientific community includes research groups with world-class expertise in virtually all of the required fields (Appendix G, 'Australian tsunami research institutions'). The Working Group believes that the Australian Government must clearly signal a new research priority if Australian researchers are to refocus their programs towards tsunami-related research. Moreover, an enabling framework to coordinate such research and ensure its uptake by the emergency management community will guarantee a lasting contribution to Australia's tsunami mitigation capability. This will also allow Australia to take a leading scientific role in the region.

To this end, the Working Group makes the following recommendation:

- **Recommendation 1: Establish a Regional Centre of Excellence for Tsunamis to focus Australian and international science/research and collaboration on the challenge of understanding tsunamis and mitigating their consequences.**

The Working Group has identified the need for an interagency and cross-institutional working group to progress this recommendation. Suggested terms of reference for the group are in Appendix E, 'Development of a Regional Centre of Excellence'. Such a working group will report to PMSEIC in December 2006 on progress made and further proposals for the Regional Centre of Excellence for Tsunamis.

This Regional Centre of Excellence must be linked to the Australian Tsunami Warning System for either to be fully effective. Furthermore, given the ongoing risk of tsunamis to Australia the Australian Tsunami Warning System must be continued beyond the four-year establishment period.

- **Recommendation 2: Consolidate the Australian Government decision to establish an Australian Tsunami Warning System through a long-term government commitment to ensure a sustainable and effective national tsunami warning system beyond the current four-year initiative.**

FIGURE 8 THE COCONUT PALMS NEAR THE SHORE STOPPED A 10 METRE HIGH TSUNAMI FROM PENETRATING MORE THAN A FEW HUNDRED METRES INLAND AT AITAPE, PAPUA NEW GUINEA IN 1998

Photo: Hugh Davies, University of Papua New Guinea.

A Details on members of the Working Group on Tsunamis

Name & affiliation(s)	Biography
Professor Fiona Stanley, AC Director, Telethon Institute for Child Health Research Executive Director, Australian Research Alliance for Children and Youth Professor, School of Paediatrics and Child Health, University of Western Australia	Professor Stanley is the founding Director of the Telethon Institute for Child Health Research that was established in Perth in 1990. The Institute is multi-disciplinary and researches prevention of major childhood illnesses. It currently has nearly 400 employees and students. Prof Stanley's career has focussed on the importance of using population data and research to provide significant health, social and economic benefits to the community. Her research work involves conducting and supervising studies in maternal and child health. Main areas include • record linkage and analysis of population data for epidemiological and public health research • collaborations to link research, policy and practice • strategies to enhance health and well-being in populations including Aboriginal populations. Prof Stanley is a Member of the Editorial Board of three international journals. She has more than 200 published papers in refereed journals, 3 books, 25 book chapters and 40 major reports or monographs. She was also named Australian of the Year in 2003 and is a fellow of the Australia Academies of both Science and Social Science.
Dr Phil McFadden Chief Scientist, Geoscience Australia	During his career in Geoscience Australia and its predecessors Dr McFadden has been responsible for the Geospatial and Earth Monitoring Division, the Geophysical Observatories and Mapping Division, the Geophysics Division, and the Geoscience Computing and Database Branch. His research interests have spanned paleomagnetism, electronics, geomagnetism, mathematical statistics (mainly of vector data and of interlinked sequences), deep earth processes, earth conductivity, airborne magnetics and radiometrics data analysis, and earthquakes. He has published a large number of papers and has co-authored two books. He has been the editor for two international journals. He is a fellow of the Australian Academy of Science and currently serves on the academy's Executive. He recently worked on the Cabinet submission on the 2004 tsunami and presented a report on this topic to the April Coordinating Committee on Science and Technology meeting.
Dr John Schneider Leader, Risk Research Group, Geoscience Australia	As Leader of the Risk Research Group, Dr Schneider is responsible for a team of about 40 hazard scientists, engineers, mathematicians, social scientists and economists that is developing sudden-impact risk models for a wide range of hazards in Australia, including earthquake, tsunami, flood and severe wind. As technical advisors to the Department of Transport and Regional Services, the Risk Research Group is leading the development a national framework for natural hazard risk assessment. Prior to his arrival in Australia in 2000, Dr Schneider worked in private industry and academia, developing earthquake hazard and risk models for a variety risk management applications including corporate risk and public safety issues. From 1995 to 2000 he was Chief Scientist at Aon-Impact Forecasting, a catastrophe risk modelling company based in Chicago, Illinois, USA; and from 1987 to 1994 he was Project Manager for Earthquake Hazard Research at the Electric Power Research Institute in Palo Alto, California, USA. Dr Schneider has an MS (1981) and PhD (1984) in Geophysics from the University of Wisconsin, Madison.
Dr Ray Canterford Branch Head, Weather and Ocean Services, Bureau of Meteorology	Dr Canterford has program and policy responsibility for providing the following services: aviation weather, disaster mitigation, public weather, defence weather, cost recovery, marine weather and oceanography. He has a PhD in Physics (1974) and postgraduate qualifications in meteorology and is a CPEng. His postdoctoral work was undertaken in the US National Oceanographic and Atmospheric Administration (NOAA) under a Fulbright Scholarship. He is the Acting President of the UN World Meteorological Organization (WMO) Commission for Instruments and Methods of Observation.

(Continued on next page)

Name & affiliation	Biography
Associate Professor Ted Bryant Associate Dean, Faculty of Science, University of Wollongong	Associate Professor Bryant is one of Australia's leading experts on tsunamis. His expertise was called on by news outlets around the world after the 2004 tsunami, when he also discussed the possibility of Australia suffering a similar catastrophe.
Professor Peter Mora Department of Earth Sciences, University of Queensland	Professor Mora is the Director of Earth Systems Science Computational Centre at The University of Queensland, Science Chair of the Australian Computational Earth Systems Simulator Major National Research Facility, and Executive Director of the APEC Cooperation for Earthquake Simulation. He is the founding CEO of the Australian Computational Earth Systems Simulator Major National Research Facility. His research on computational earthquake science aims to develop an understanding of the underlying physics of faults and fault systems. Professor Mora is the Australian representative on the OECD's Global Science Forum Steering Committee for Earthquake Science, and is a member of the earthquake source commission of the International Association for Seismology and Physics of the Earth's Interior (IASPEI).
Dr George R Walker Senior Risk Analyst – Aon Re Asia Pacific	Dr Walker has worked with natural hazards since 1966. After four years working as a civil engineer in New Zealand and the United Kingdom, he joined the then University College of Townsville, now James Cook University, in 1968 as a Senior Lecturer in Civil Engineering, becoming an Associate Professor in 1976. In 1989 he was appointed an Assistant Chief of the CSIRO Division of Building Construction and Engineering in charge of the division's Sydney Laboratory, and in 1994 joined Alexander Howden Reinsurance Brokers, now Aon Re Australia, as Head of Strategic Development. He led the investigation of the damage to Darwin from Cyclone Tracy undertaken by the Commonwealth Government, and authored the report that became the basis for reconstructing Darwin and subsequently changed the way houses are structurally designed for wind in the whole of Australia. He is currently a member of the Australian Government's Technical Risk Assessment Advisory Committee and chairs an ISO subcommittee developing international performance standards for housing.
Mr Alan March Humanitarian Coordinator, AusAID	Mr March is AusAID's Humanitarian Coordinator. He led AusAID's Indian Ocean Tsunami Taskforce and was responsible for overseeing Australia's $60 million humanitarian assistance for tsunami-affected countries. He manages AusAID's emergency and humanitarian assistance programs, including responses to cyclones and natural disasters in South-East Asia and the Pacific.
Associate Professor Bob Pokrant Department of Social Sciences, Faculty of Media, Society and Culture, Division of Humanities, Curtin University of Technology	Associate Professor Pokrant is an anthropologist who has worked on coastal communities in Bangladesh for the last ten years. He has published on the history and contemporary development of fisher communities and the growth of export-oriented shrimp production in West Bengal, India and Bangladesh. More recently he has worked on the 2004 Tsunami and its impact on coastal fishing communities and aquaculture in South Asia. He is organising a conference on community adaptation to climate change to be held at Curtin University in 2006. His main research interests are: Global food industry and developing countries; Climate change, community adaptation and development; coastal development and environmental transformation in India and Bangladesh; Fisheries and aquaculture in India and Bangladesh.

(Continued on next page)

Name & affiliation	Biography
Mr Tony Pearce Director, Emergency Management and Security, Office of the Emergency Services Commissioner, Department of Justice, Victoria	Mr Pearce has spent 25 years in the intelligence and emergency management arena. He spent 9 years as an Intelligence (Imagery) Analyst in the Royal Australian Air Force (RAAF) before commencing with the emergency services. After leaving the RAAF he spent 12 years with Ambulance Service Victoria in senior operations management positions responsible for emergency management and major incident response planning. He is a qualified paramedic. Two years in the position of Deputy Director of the Victoria State Emergency Service preceded his move to his current role of Director of Emergency Management and Security in the Office of the Emergency Services Commissioner. In Nov/Dec 2000 Tony and a peer spent four weeks visiting Los Angeles, New York City, Washington DC, London and Belfast to benchmark Victoria's Chemical, Biological and Radiological (CBR) response capacity against environments in which terrorist attacks are commonplace. While in New York City both professional and personal relationships were developed with senior members of the Mayors Office of Emergency Management (OEM) that assisted with his second visit to New York City and Washington DC In May 2002, where hosted by OEM among others he and two peers carried out a two week review of the US multi agency response to the 9/11 terrorist attacks on behalf of the Victorian State Government, as part of Victoria’s emergency management arrangements review to ensure the States ability to respond to similar events.
Mr David Templeman Director General, Emergency Management Australia	Emergency Management Australia (EMA) is the Australian Government agency responsible for reducing the impact of natural, technological and human caused disasters on the Australian community. Since his appointment as Director General in June 2000, Mr Templeman’s particular challenges have included dealing with the re-entry of the Mir Space Station in early 2001, contributing to enhanced security arrangements in Australia since the terrorist attacks on 11 September 2001 and the Bali bombings in 2002, and liaising on national health issues such as the Severe Acute Respiratory Syndrome epidemic in 2003. He also led the coordination of Australian Government assistance in response to major bushfires in eastern Australia in 2002–03 and severe tropical cyclones that affected Fiji, Tonga, Samoa, Niue, Vanuatu and Solomon Islands. A major challenge was managing Emergency Management Australia’s’s role in Operation Tsunami Assist following the earthquake off Sumatra on 26 December 2004.
Mr Robert (Bob) Mitchell Chief Executive Officer, Fire and Emergency Services Authority of Western Australia (FESA)	Mr Mitchell was appointed Chief Executive Officer of the Fire and Rescue Service in 1996 and in 1999 was appointed the inaugural Chief Executive Officer of the Fire and Emergency Services Authority of Western Australia (FESA). FESA is comprised of the Fire and Rescue Service, the Bush Fire Service, the State Emergency Service and the Volunteer Marine Rescue Service, and has responsibility for the emergency management arrangements in Western Australia. Mr Mitchell is Chairman of the State Mitigation Committee, which was established to provide strategic guidance to all those involved in natural hazard mitigation activities within Western Australia. He is responsible for ensuring a whole-of-government approach to reduce risk in the state. He is also Deputy Chairman of the peak State Emergency Management Committee and has been responsible for overseeing the response to and the recovery from a range of major disasters in recent years including cyclones Vance and Elaine, the Moora floods and the 2005 Perth Hills fire. As the CEO of FESA Mr Mitchell has overarching responsibility for matters pertaining to building fires, bush fires, hazardous materials emergencies, motor vehicle accident rescue, floods, cyclones, storms, tsunamis, cliff and high angle rescues, landslides and earthquakes.

B Australia's role in the Asia-Pacific region

Australia's leadership in the Asia-Pacific region reflects our stability, prosperity and commitment to regional engagement. We have an ongoing involvement in developing national capacities for managing emergencies and responding to disaster events. This occurs on a number of levels:

> by responding immediately to a disaster;

> by building the capacities of emergency management organisations to enable them to mitigate risk; and

> by participating in regional forums to develop strategic planning and coordination documents at a regional level.

Australia is increasingly called on to provide assistance in response to disasters in this region. Our response is often a combination of official aid provided through the Australian aid program managed by Australian Agency for International Development (AusAID), and activation of the Australian Government Overseas Disaster Assistance Plan (AUSASSISTPLAN). The plan is prepared and maintained by Emergency Management Australia in conjunction with AusAID. It is a contingency plan to meet requests from developing countries for Australian physical and technical assistance. Activities undertaken under the plan are funded through AusAID and may call on any Australian Government assets. The plan is activated following consultation between the Minister for Foreign Affairs and the Attorney-General.

In practice the main assets called on are the transport, medical, engineering and communication skills of the Australian Defence Force and the medical teams sourced, with the guidance of the Department of Health and Ageing, from the Australian state and territory medical systems. The plan supports and works closely with whole-of-government coordination and tasking through the Department of Prime Minister and Cabinet and/or the Department of Foreign Affairs chaired Inter-Departmental Emergency Task Force. This task force brings together a range of government agencies that have a role in the managing and responding to the crisis. A crisis centre in Canberra may be activated to support this role.

Australia works with other donors in the region to coordinate disaster relief, particularly with France and New Zealand under the FRANZ arrangements for disasters affecting other countries. Pursuant to these arrangements, the three countries share information on preparedness for, and response to, Pacific disasters (in most cases, cyclones), coordinate their assets and undertake regular desktop planning and response exercises. The FRANZ arrangements have made a significant contribution to response effectiveness following cyclones such as Ivy in Vanuatu in 2004, and could be useful in the event of a Pacific tsunami.

The monitoring of events such as cyclones, earthquakes and political situations by relevant Australian agencies and their linking through formal and informal protocols promotes Australia's preparedness for mitigation and response activities. Both AusAID and Emergency Management Australia hold standing stores of relief supplies such as tarpaulins, water containers and purification tablets so that they can be deployed at short notice. Both have personnel available within 24 hours for deployment.

Australia is also involved in a number of activities to build the capacity of national and regional emergency management offices to manage the whole cycle of disaster preparedness, prevention, response and recovery, particularly in Solomon Islands, Papua New Guinea and Indonesia. Smaller activities have been undertaken across the Pacific in, for example, Tuvalu, Cook Islands, Vanuatu and Fiji to provide assistance in establishing Emergency Operations Centres, improving communications during a disaster, public awareness raising and exercise management.

Under the $1 billion Australia Indonesia Partnership for Reconstruction and Development, announced after the Indian Ocean Tsunami, Emergency Management Australia is currently developing a long-term partnership with its Indonesian counterpart agency, BAKORNAS. The partnership is likely to include staff exchanges, joint exercises, training and technical assistance.

Representatives of Australian agencies (primarily Emergency Management Australia, AusAID, the Department of Foreign Affairs and Trade, the Department of Defence, the Australian Bureau of Meteorology and Geoscience Australia) participate in regional meetings to develop strategic disaster mitigation plans and to address emerging regional issues. Recently Australia worked with Pacific island countries to put together the framework for action that will guide the development of emergency management responsibilities across Pacific island government departments. Australia was also active at the United Nations World Conference on Disaster Reduction in Kobe, Japan, in January 2005, which was a major international forum to address disaster-related issues, releasing a document providing guidelines for governments to achieve strong emergency management structures and processes.

Australia's role in providing relief and technical assistance to the region is increasing. While the capabilities of the relevant agencies are finite, the systems in place, together with regular exercising of our planning and response capacity and hard-won experience, equip Australia well to continue its leadership role in the region.

C

The science of tsunamis

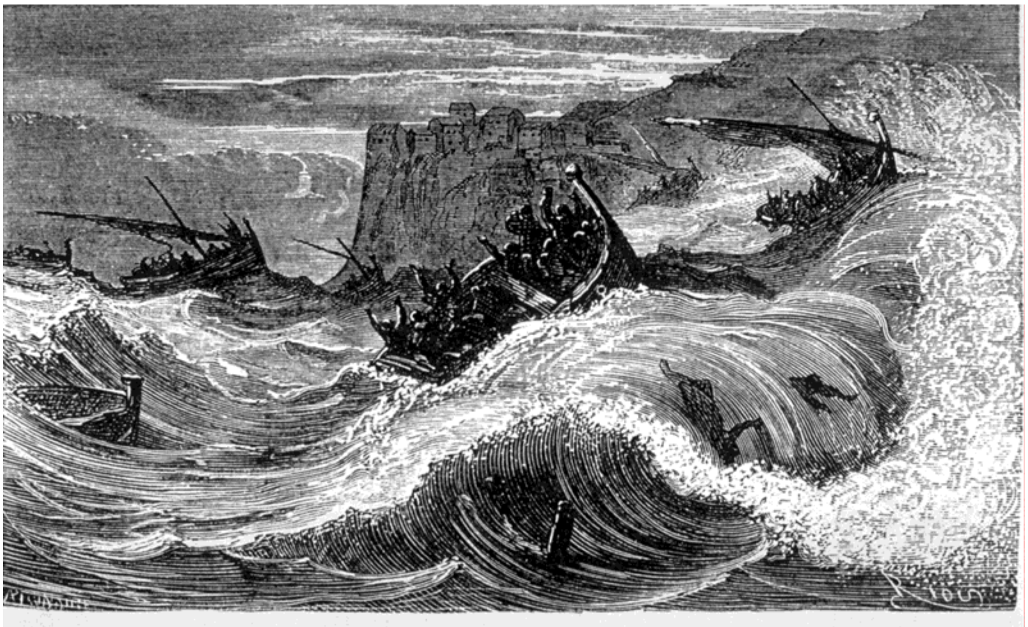


Fig. 55.—INCIDENT DURING THE EARTHQUAKE AT SUMATRA (1861).

Source: Zurcher, F. and E. Margolle, Volcanoes and Earthquakes. Philadelphia: J.B. Lippincott, 1869.

WHAT IS A TSUNAMI?

Tsunami is a Japanese word – *tsu* (津) meaning 'harbour' and *nami* (波 or 浪) meaning 'wave'. It refers to a wave generated by sudden movement of the sea floor, most often by undersea earthquakes. While Japan has the most complete historical record of tsunamis, human history includes many encounters with tsunamis, and these are not exclusive to the Pacific Ocean. The eruption of Santorini in the 1600s created a large tsunami in the Mediterranean Sea, and the arrival of Vasco da Gama's fleet in India in 1524 coincided with a violent seaquake and tsunami.

A tsunami is very different from the wind-generated waves we consider to be normal ocean waves. Wind-generated waves cause movement of water only near the sea surface and have wave lengths measured in metres. In contrast, tsunamis involve water movement to the sea floor (3 kilometres in the deep ocean), with wave lengths of 100 kilometres or more. That is, they involve movement of much larger masses of water. In the deep ocean they rarely have a height greater than 0.5 metres. However, as they approach shallow water they slow down and increase dramatically in height in water depths of less than 20 metres. Waves during the Indian Ocean tsunami of 26 December 2004 were about 0.6 metres high in the open ocean but reached heights of 10 metres along many coasts, even those thousands of kilometres from the earthquake.

THE SOURCES OF TSUNAMI IN THE AUSTRALIAN REGION

Tsunamis are ocean waves generated by sudden movement of the ocean due to earthquakes, landslides on the sea floor, land slumping into the ocean, major volcanic eruptions or large meteor or asteroid impacts.

The vast majority of tsunamis are caused by large earthquakes under the sea floor, when large slabs of rock are forced to move past each other suddenly. Vertical movement of the sea floor in this manner causes the overlying water to move upwards and spread outwards from the earthquake centre as a tsunami. Submarine landslides also cause tsunamis when sediment on steep slopes such as those around volcanic islands or along the edge of continental shelves becomes unstable and fails under gravity. Less common are tsunamis initiated by volcanic eruptions, which are caused by the explosion or collapse of a volcano. Asteroids and meteors also cause sudden impacts on the earth and, if they fall in the ocean, can generate tsunamis. Although such impacts are rare, there is evidence that tsunamis generated by this mechanism have reached Australian shores in prehistoric times. More detail follows about the potential for earthquakes, volcanoes, submarine landslides and asteroids or meteors to generate tsunamis in the Australian region.

EARTHQUAKES

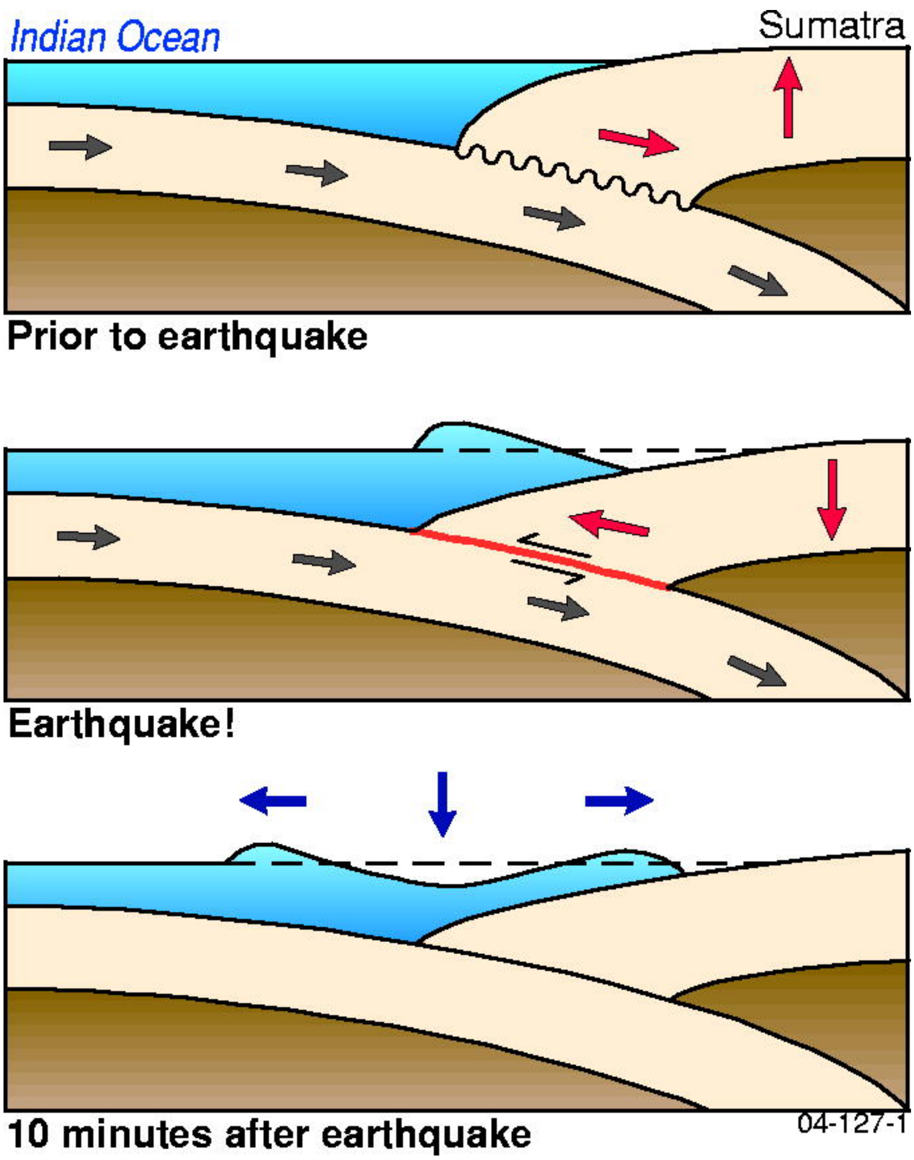
The most frequent sources of large tsunamis are earthquakes that occur in subduction zones, where two of the rigid plates comprising the earth's surface converge and one slides beneath the other. As the plates 'rub' past each other, friction along their contact pulls the upper plate downward, causing stress to increase on the interplate contact. An earthquake occurs when the stress exceeds the frictional strength and the upper plate 'pops' back upward, vertically displacing a large mass of water (Figure C1). The stress builds up continuously along the 8000 kilometre system of subduction zones that surrounds Australia to the north and east.

Subduction zones have the potential to produce the largest earthquakes in the world. Of the 12 largest earthquakes that have occurred since 1900, all but one occurred in subduction zones and produced large tsunamis. To assess tsunami risk to Australia, we need to cast this earthquake threat in terms of the probability of events as a function of their magnitudes and locations, as well as their potential to generate tsunamis. While there is still insufficient information to perform such an assessment for most of the subduction zones facing Australia, some general conclusions can be drawn from the information available.

EARTHQUAKES IN INDONESIA

We now know with certainty that the subduction zone off Sumatra can produce magnitude 9 earthquakes, large enough to generate massive tsunamis that will affect the whole Indian Ocean basin. Such earthquakes have occurred there in both modern and historical times, and there is no question that they will do so again. The recurrence rate in any section of the Sumatra subduction zone can be roughly estimated by dividing the average slip across the fault by the relative rate of convergent motion between the plates. For a plate convergence rate of 5 cm per year, it takes 100–200 years to accumulate 5-10 metres of strain or slip potential, which is the average fault slip in magnitude 9 earthquake. For example, the 28 March 2005 Nias Island earthquake ruptured a section of the Sumatra subduction zone that last ruptured in 1861, a recurrence time of 144 years, which is consistent with our rough estimate.

FIGURE C1 HOW A TSUNAMI IS GENERATED BY A SUBDUCTION ZONE EARTHQUAKE



Note: *Top:* Prior to the earthquake the lower subducting plate drags against the upper plate, causing flexure. *Centre:* Stress on the plate boundary causes the upper plate to rebound to its initial, unflexed position, displacing the sea surface – the earthquake. *Bottom:* The displaced sea surface propagates outward as a tsunami. The blue arrows indicate the direction in which the water will travel.

Source: Geoscience Australia

While we might expect the sections of the Sumatra subduction zone that ruptured on 26 December 2004 and 28 March 2005 not to rupture again for another 100–200 years, there is good reason to believe the section off central Sumatra may rupture much sooner. This section last ruptured in a single, massive (magnitude 9) earthquake in 1833. If it were to rupture again now the recurrence time of 172 years would also be consistent with our rough estimate.

A recurrence of the 1833 tsunami would have a much smaller effect on Thailand and Sri Lanka than the December 2004 event did, but it should have an effect on other Indian Ocean countries, including Australia, similar to that of the 2004 event. The effects in Sumatra, however, may be considerably worse. The Boxing Day tsunami razed entire villages along the north coast of Sumatra and devastated the city of Banda Aceh, causing over 160 000 deaths. In the event of an 1833-like earthquake, a wave of similar size is likely to strike the coast of Sumatra but in this case the cities of Padang and Bengkulu would lie in its path. The total population affected would be 950 000, almost double that of Banda Aceh (400 000 pre-tsunami).

We do not know whether earthquakes off Java, to the east of Sumatra, can be as large as magnitude 9, but we do know that earthquakes as large as magnitude 8.5 have occurred and that such earthquakes can generate large tsunamis. In 1977 a magnitude 8.3 earthquake occurred off Java, which caused a tsunami with an observed maximum height on Australia's north-western coast of 6 metres. Similar tsunamis, which may reach several metres in height at some locations, can be expected to occur along the north-west coast of Australia every few decades. Such tsunamis would be much more lethal in Indonesia itself, where the numbers of fatalities could be in the tens of thousands.

Further east, consideration of the potential for tsunamis from the Timor Trough and the Banda Sea raises more questions than it answers. Subduction in the Timor Trough, for example, ceased about 5 million years ago, but geodetic measurements suggest that Timor and Australia are still moving towards one another. Does this mean that strain energy is building up in the Timor Trough? If so, how large might the resulting earthquake be, and what might be the effect on Australia's northern coast? We do know that magnitude 8.5 earthquakes can occur in the Banda Sea adjacent to Timor, but the only historical case directed little energy towards Australia. Understanding the likelihood and probable effects of a Timor Trough or Banda Sea tsunami is critical for Darwin, which lies in its direct path.

EARTHQUAKES IN THE SOUTH-WEST PACIFIC

The subduction zone along the north coast of Irian Jaya and Papua New Guinea generates many earthquakes of magnitude 7–8, and these can cause large local tsunamis (such as the 1998 Aitape tsunami, which killed 2200 people). The evidence to date is that the direct impact on Australia has been nil because of the intervening landmass.

The subduction zones in the south-west Pacific that do present a direct threat to Australia are the New Hebrides Trench off Vanuatu, the Tonga-Kermadec Trench north of New Zealand, and the Puysegur Trench south of New Zealand. For the New Hebrides Trench, examination of the tectonic uplift preserved in coral growth bands suggests only moderate earthquakes occur along short segments of the subduction zone. However, the potential for these segments of the Vanuatu subduction zone to rupture together in a single large earthquake should not be discounted. A large tsunami generated in this manner could pose a significant hazard to Australia's north-east coast.

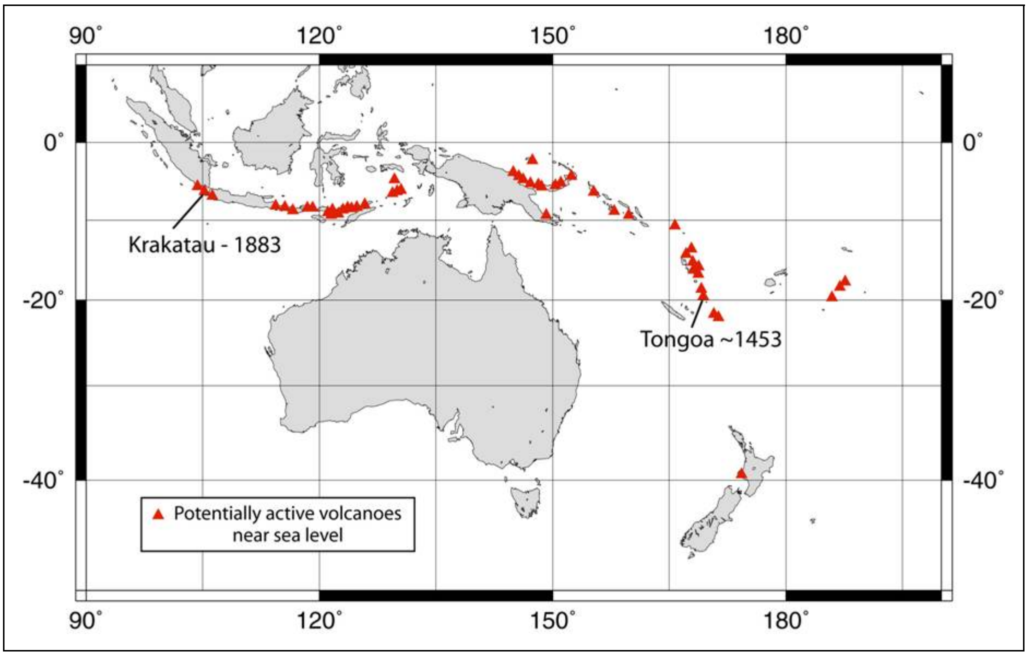
The Tonga-Kermadec Trench, stretching from the Tonga Islands to New Zealand, has historically experienced earthquakes of magnitude 8.0–8.3, and these have generated only local tsunamis. Recent work on an earthquake that occurred in 1865, however, suggests that the potential for the generation of far-field tsunamis in the Tonga-Kermadec Trench may have been underestimated. If so, large earthquakes occurring in the central part of this subduction zone have the potential to direct considerable tsunami energy towards Australia's eastern coast.

South of New Zealand, much of the relative plate motion is horizontal. So even when large earthquakes occur they typically generate only small tsunamis. There is, however, a section of plate boundary just to the south of New Zealand known as the Puysegur Trench, along which subduction has been occurring for the past 7 million years, a very short time in geologic terms. Subduction zones with such short histories are rare and their potential to produce large earthquakes and tsunamis is unknown. No earthquake has occurred on this trench in the historic past, which would suggest either that subduction is aseismic and no large earthquakes will occur; or that the subduction zone has been accumulating strain energy for over 200 years and has the potential to rupture in a major earthquake. If an earthquake were to rupture the entire 500 kilometres of the Puysegur Trench, it could generate a very large tsunami, and the coast of Tasmania would lie directly in its path.

VOLCANOES

There are over 30 active volcanoes capable of generating a tsunami that could affect Australia (Figure C2). Seventeen of these are located in the south-west Pacific and up to 20 are located in Indonesia. The Krakatau eruption of 26–27 August 1883 is the only documented eruption to affect Australia. It caused 36 000 deaths in Indonesia and generated a tsunami in the Indian Ocean that was more extensive than the 2004 Boxing Day event. Within four hours of the final eruption, a four-metre high tsunami arrived at Northwest Cape, Western Australia. The wave swept through gaps in the

FIGURE C2 LOCATION OF VOLCANOES IN THE AUSTRALIAN REGION THAT WERE ACTIVE IN THE 20TH CENTURY OR THAT ARE DORMANT BUT COULD RE-ERUPT



Note: Only volcanoes near sea level and having the capacity to generate tsunami are plotted. Some volcanoes may be missing.
Data source: Geoscience Australia

Ningaloo Reef and penetrated one kilometre inland through sand dunes. Around AD 1453, the volcanic eruption of Tongoa, Vanuatu, which was 3–4 times bigger than Krakatau, produced a tsunami 30 metres high. It is not known if this tsunami reached the east coast of Australia.

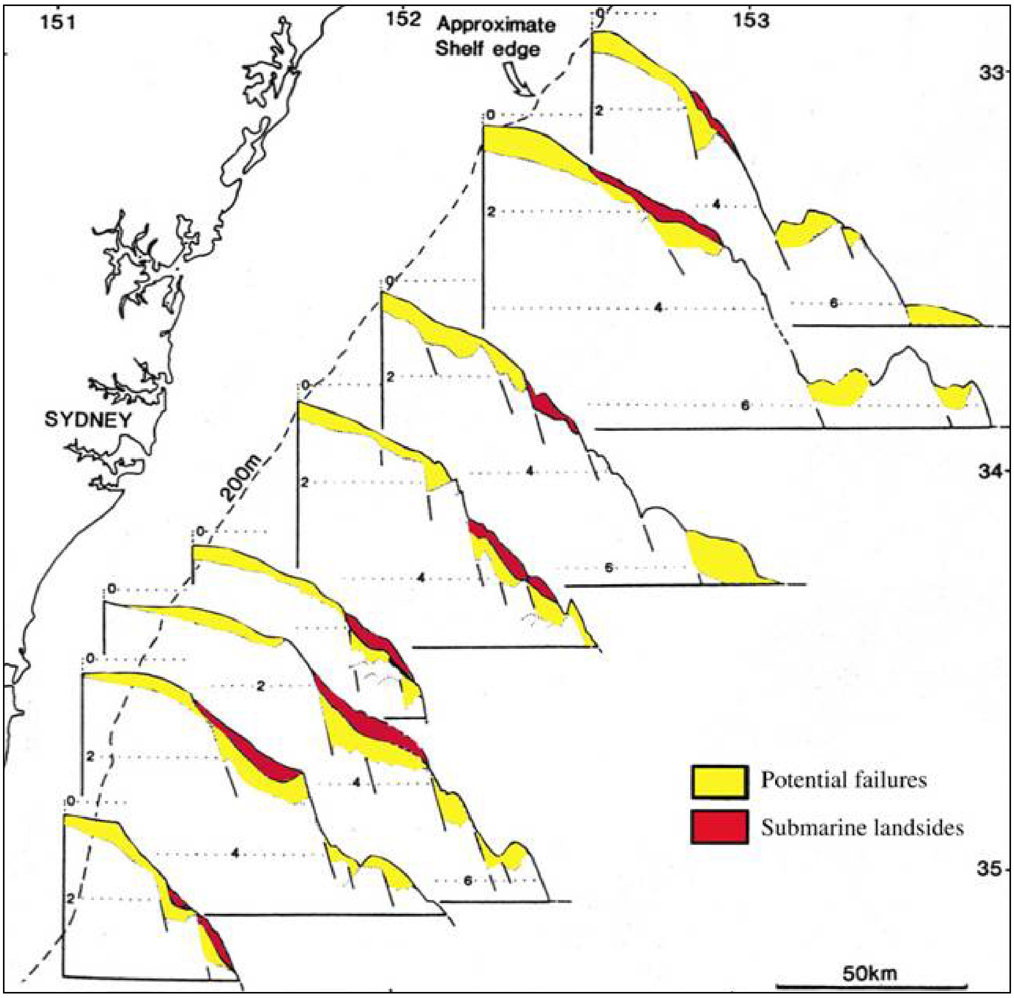
SUBMARINE LANDSLIDES

Less is known about the effect of submarine landslides, although the steep continental shelf edge around the eastern and southern portions of Australia are potential sources of such failures. One hundred and seventy landslide scars exist along the coast of New South Wales, with several significant ones lying adjacent to Sydney (Figure C3). One of the largest landslides occurred off Bulli and was 10 kilometres wide and 20 kilometres long – large enough to have generated a significant local tsunami.

Anecdotal evidence also exists at Wollongong, Venus Bay and Albany of freak waves having swamped the coast on clear, calm days. The event known as ‘Black Sunday’, which occurred on 6 February 1938 at Bondi Beach, also falls into this category. This event was characterised by three successive waves that piled water on the beach and returned as backwash sweeping swimmers out to sea. The waves were not restricted to Bondi Beach, being reported on adjacent beaches and as far north as Newcastle.

Five people drowned at Bondi. These freak wave events may represent tsunamis generated by small, localised, submarine landslides.

FIGURE C3 BATHYMETRIC PROFILES OFFSHORE IN THE SYDNEY REGION SHOWING THE THICKNESS OF SEDIMENTS PRONE TO SLIPPAGE AND ACTUAL SLIDES



Data source: Based on CJ Jenkins and JB Keene, 'Submarine slope failures of the southeast Australian continental slope: a thinly sedimented margin', *Deep-Sea Research*, vol. 39, no. 2, pp. 121–36 (with permission from Elsevier).

ASTEROIDS OR METEORS

Meteors and asteroids on near-earth orbits are ultimately the source of the most spectacular and life-threatening impacts. We now know that major extinction events marking the transitions between geologic eras, such as between the Cretaceous and Tertiary periods 65 million years ago, are the result of the massive impacts of meteors or asteroids of about 10 kilometre in diameter. Objects capable of causing worldwide catastrophes are most certainly associated with massive tsunamis, with wave amplitudes far exceeding any tsunami in historic times.

Fortunately, major asteroid or meteor impact events are rare. For example, objects 10 kilometres in diameter, responsible for the extinction of the dinosaurs, occur but once in 100 million years. Objects of greater interest are those with diameters between 100 metres and 1 kilometre, which can cause severe damage, including tsunamis, and have about a 1 per cent chance of striking this century. While the likelihood is small, it is not speculative.

There is considerable uncertainty about the generation and propagation of tsunami waves from intermediate-sized objects with diameters in the range 100 metres to 1 kilometre. Larger objects are clearly capable of penetrating to the ocean floor and generating long-period waves that travel across the ocean with little loss of energy. Smaller objects almost certainly do not generate tsunamis. Scientists are modelling the tsunami potential of these intermediate-sized objects to better understand the asteroid or meteor tsunami threat.

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D Pacific and Indian Ocean tsunami warning systems

Any tsunami warning system works on the premise that the event that generates the tsunami (most often an earthquake) will also generate seismic waves. Since seismic waves travel much faster than tsunamis, data from seismographic stations distributed around a tsunami source area and transmitted in real time for analysis can be used to rapidly detect a potentially tsunami-genic event. Once this detection has been made, data from stations measuring sea level close to the source and transmitted in real time can be used to determine whether a tsunami has been generated and, if so, a warning can be issued.

For areas close to the tsunami source, a rapid warning would have to be issued solely on the basis of seismic data, which accepts a higher risk that the alarm is false. It has long been recognised, however, that the detection of a tsunami and the issuance of a warning are ineffective unless there is a means to transmit this warning to communities, and the communities know the appropriate action to take when a warning is received. An effective tsunami warning system therefore relies on four essential components:

> seismic data and their analysis to determine the source of an undersea earthquake or other geophysical event that could initiate a tsunami;

> sea-level data to confirm the generation of a tsunami, and modelling to estimate the magnitude and likely timing of its arrival in affected areas;

> an emergency management and public warning capability to transmit the warning and respond at the local level; and

> public awareness of the possible threat, response procedures, and prior community and infrastructure risk assessment.

The capabilities of the tsunami warning systems for the Pacific Ocean and the Indian Ocean (pre- and post-Indian Ocean tsunami) are considered in this appendix in terms of the essential components of such systems (see table D1).

PACIFIC OCEAN

Because it is ringed by active geologic plate boundaries that generate large tsunamis, the Pacific Ocean has experienced tsunamis more frequently than any other ocean, and therefore has the world's most sophisticated tsunami warning systems. These systems have been driven mainly by the United States, whose focus has been on protecting Hawaii and the US Pacific coast. The main operational facility, the Pacific Tsunami Warning Center (PTWC) is located in Hawaii. The PTWC was established in

1949, three years after an earthquake in the Aleutian Islands generated a tsunami that killed 165 people in Hawaii. It is a US National Oceanographic and Atmospheric Administration (NOAA) facility whose objective is to locate large earthquakes in the Pacific, determine whether they have generated tsunamis, and issue warnings.

Further development of the Pacific Ocean's tsunami warning system was spurred by other large earthquakes and tsunamis in the Pacific in the 1950s and 1960s. The International Tsunami Information Centre, also based in Hawaii and staffed by NOAA, was established in 1965. UNESCO, through the Intergovernmental Oceanographic Commission, established the International Coordination Group for the Tsunami Warning System in the Pacific in 1968. Its purpose is to ensure that tsunami warnings are disseminated throughout the Pacific. These latter developments were a response to the recognition that the technical means to detect an earthquake and tsunami did not constitute an effective warning system unless they were accompanied by adequate means to transmit the warnings to affected populations, as well as assessment of the tsunami hazard and public awareness of the threat.

While it provides warning for long-range, trans-Pacific tsunamis, the PTWC is not resourced to protect coastal areas near tsunami-source regions, except for Hawaii itself. For this reason several local or national tsunami warning systems have been established in the Pacific for French Polynesia, Japan, Russia, Chile, US Alaska and west coast, US Hawaii, and Canada. These systems place special emphasis on rapid data handling and communication in order to provide some warning within the first hour of tsunami generation to populations in areas adjacent to the tsunami source. Such systems currently do not exist, however, in the south-west Pacific for Australia, New Zealand, Papua New Guinea or Pacific island countries.

The Australian Government's decision in 2005 to establish the Australian Tsunami Warning System (see 'Indian Ocean' below) will provide Australia with warnings of tsunamis generated in the south-west Pacific. It will also provide greatly improved instrumentation of the south-west Pacific. The data gathered will be shared with the PTWC to allow it to provide Pacific island countries with enhanced coverage of events occurring in their region, although this will still not be sufficient to provide reasonable lead times of local tsunamis for these countries. To address this problem, the Australian technical agencies (Geoscience Australia, the Bureau of Meteorology, and Emergency Management Australia) and AusAID are working with the South Pacific Applied Geoscience Commission (SOPAC) to build public awareness and tsunami warning capacity in the region.

INDIAN OCEAN

Unlike the Pacific, until the 2004 Indian Ocean tsunami it was not widely appreciated that the Indian Ocean was at risk from ocean-wide tsunamis. Consequently, there was no formal warning system operational in the Indian Ocean at the time the tsunami occurred. National efforts at earthquake and sea-level monitoring were not focused on tsunami warning. The only real-time earthquake monitoring networks were run by Australia, India and Malaysia, designed solely for monitoring earthquakes within their respective borders. Although the earthquake that caused the tsunami was detected, the sparse seismographic coverage of the Indian Ocean contributed to a severe underestimation of its size, and the lack of real-time sea-level data made it impossible for the tsunami to be verified before it had already impacted the countries most severely affected. Finally, no communication networks had been established to disseminate a warning to Indian Ocean communities, and because no public education had been conducted these communities were unable to recognise the natural indicators of an approaching tsunami (for example, sudden recession in the sea level) where they were evident.

Since the tsunami, the Intergovernmental Oceanographic Commission, the World Meteorological Organization, the International Strategy for Disaster Reduction and the Indian Ocean countries have moved rapidly to develop a tsunami warning system for the Indian Ocean. The Australian Government has played a fundamental role, both in coordinating the development of an international warning system via the Intergovernmental Oceanographic Commission, and in establishing the Australian Tsunami Warning System. The latter will provide Australia with warning of Indian Ocean tsunamis as well as contribute to a warning system for the Indian Ocean as a whole. In contrast to the Pacific Ocean, where the United States was the prime driver behind establishing a warning system, 27 countries are contributing to the establishment of the Indian Ocean tsunami warning system. These countries will work to establish national systems that will be linked in an international 'system of systems', with the establishment of the latter coordinated by the Intergovernmental Oceanographic Commission. Donor countries, including Australia, are involved in public awareness and capacity-building efforts directed at developing countries in the region.

The Australian Tsunami Warning System will form one essential component of the Indian Ocean tsunami warning system, especially since some of Australia's island territories (Christmas and Cocos Islands) are well placed to provide warning of tsunamis initiating off Indonesia. Operation of the Australian system will be the joint responsibility of:

> Geoscience Australia, which will operate and analyse data from a network of real-time seismographic stations;

> the Bureau of Meteorology, which will operate and analyse data from a network of real-time sea-level stations as well as disseminate warnings; and

> Emergency Management Australia, which will be responsible for public awareness and the coordination of national assistance to state and territory responses to a tsunami disaster.

All of these organisations will work with AusAID to engage developing countries in the region in capacity-building efforts aimed at improving tsunami warning capability throughout the region.

TABLE D1 A COMPARISON OF TSUNAMI WARNING CAPABILITY IN THE PACIFIC AND INDIAN OCEANS

<table>
<tr><th></th><th>Pacific Ocean</th><th>Indian Ocean (pre-tsunami)</th><th>Indian Ocean (post -tsunami)</th></tr>
<tr><td>Public awareness</td><td>Intergovernmental Oceanographic Commission and national agencies</td><td>Non-existent</td><td>Intergovernmental Oceanographic Commission and national agencies (eg Emergency Management Australia [a]</td></tr>
<tr><td>Seismographic data</td><td>150 real-time stations</td><td>Several Pacific Tsunami Warning Center stations plus Indian, Malaysian & Australian national networks [b]</td><td rowspan="2">Extensive networks planned as conglomeration of national networks [a]</td></tr>
<tr><td>Sea level data</td><td>100 real-time stations</td><td>1 station at Cocos Island with data accessible hourly</td></tr>
<tr><td>Funding & operational responsibility</td><td>Single national agency (US National Oceanographic and Atmospheric Administration)</td><td>No agency with formal responsibility</td><td>Multiple national agencies [a]</td></tr>
</table>

[a] In Australia, the components of the Australian Tsunami Warning System will be operated by Geoscience Australia (seismographic data), the Bureau of Meteorology (sea-level data and warning dissemination), and Emergency Management Australia (public awareness). [b] National networks did not share data and this severely limited their coverage of offshore events.

E Development of a Regional Centre of Excellence

Options for establishing a Regional Centre of Excellence for Tsunamis range from a virtual link-up of existing disparate scientific and response activities to the commissioning of a new multi-institutional centre involving the relevant national agencies, research facility and research institutions. It is proposed that in the first instance an interagency and cross-institutional working group from, among others, AusAID, the Bureau of Meteorology, the Department of Foreign Affairs and Trade, Emergency Management Australia, Geoscience Australia, the Department of the Prime Minister and Cabinet, and universities and other institutions with relevant research programs, be formed to:

- explore current Australian and regional capacities that can be developed and applied in the short term;
- review existing tsunami-related research under way in Australia and the region; and
- investigate the optimal approach and framework required to develop a Regional Centre of Excellence.

The working group would identify ready synergies from within existing Australian and regional resources to immediately support Australian tsunami preparedness and response – to build on, focus and expand existing Australian and international research and collaboration to address the challenge of understanding the threat of tsunamis and developing cost-effective mitigation.

The working group would also identify any significant gaps in Australia's capability and determine priorities for scientific and response activities. This may include consideration of the appropriateness of making hazard science a national research priority.

Finally, the working group would explore and scope options for formalising a Regional Centre of Excellence for Tsunamis, including but not limited to a mandate, a location, programs of national and regional activities, and draft costings.

It is further proposed that the working group report back to the Prime Minister's Science, Engineering and Innovation Council in December 2006 with an overview of activities undertaken, analysis of unmet needs and a long-term plan for the formation of the Regional Centre of Excellence for Tsunamis.

F Background to emergency management in Australia

The Australian Constitution does not address matters relating to the protection of life and property. Consequently states and territories have primary responsibility for such matters. The Australian Government has a broad responsibility to support the jurisdictions in developing emergency management capabilities. The Australian Government emergency management responsibility lies with the Attorney-General's Department, as detailed in the Administrative Arrangements Orders. A Commonwealth policy statement was last issued in 1998.

In pursuing their emergency management responsibilities, states and territories work in conjunction with agencies in all tiers of government, and relevant non-government and private sector organisations, to effectively manage risks to communities. Emergency Management Australia is also a partner to provide leadership in ensuring national emergency management policy and development.

All jurisdictions adhere to a nationally consistent doctrine underpinning this policy and delivery function: comprehensive, all hazards, emergency management incorporating prevention, preparedness, response and recovery in a risk management framework.

An aware, informed and prepared community is a key element in reducing risk and managing the consequences of disasters. An integral part of community preparedness is an effective warning and information dissemination system. All states and territories have integrated information and warning systems for communicating with the public on hazards likely to impact within their jurisdiction. These systems aim not only to provide a warning of hazard impact, but also to educate the public in advance of an incident about appropriate actions to protect themselves and their property.

Effective and well-tested procedures and plans exist for cross-border operations. However, there are varying degrees of coordination of community education and warning between jurisdictions. The development of the Australian Tsunami Warning System will address this issue for the tsunami hazard.

For more detail, see Emergency Management Australia, *Emergency management in Australia: concepts and principles*, Australian Emergency Manual Series, Manual Number 1, Attorney-General's Department, Canberra, 2004 <www.ema.gov.au>.

G Australian tsunami research institutions

BUREAU OF METEOROLOGY	
Bureau of Meteorology Research Centre	Research ocean modelling in the domains of global, regional and local events. Ocean observing systems, including those for tsunamis. Storm surge research and prediction modelling and analysis for meteorological and oceanographic natural hazards.
Bureau of Meteorology National Tidal Centre	Tsunami modelling, sea-level instrumentation and analysis. Applied studies and real-time monitoring and prediction of tsunamis.
Bureau of Meteorology Weather and Ocean Services	Disaster mitigation and multihazard warning systems. Real-time ocean modelling.
CURTIN UNIVERSITY	
South Asia Research Unit	Coastal development, fisheries and aquaculture in South Asia, particularly India and Bangladesh. Local cultures of disaster management (tsunami, cyclone, storm surge, flooding).
GEOSCIENCE AUSTRALIA	
Risk Research Group	Sudden onset hazards, including earthquakes, tsunamis and landslides. Engineering, social and economic research into the impact of natural hazards on communities and infrastructure. Risk assessment methods, models and tools for emergency managers and planners, and private industry.
Earth Monitoring Group	Earthquake and geodetic monitoring. National datasets for earthquake hazard assessments, land surveying and national maps. Seismic monitoring and analysis for the Australian Tsunami Warning System and the associated 24/7 operations centre.
National Mapping and Information Group	National topographic maps and integration of existing data in the coastal zone for tsunami inundation modelling.
Petroleum and Marine Division	Seismic surveys of the sea floor for use in tsunami propagation modelling and information on submarine landslides.
JAMES COOK UNIVERSITY	
Geology	Field studies of prehistoric tsunamis in Australia and South-East Asia. Post-tsunami field studies.
Centre for Disaster Studies	Field studies of the impact of tsunamis on human settlements.
Tropical Environment Studies & Geography	Identification and characterisation of coastal deposits on shorelines and mid-ocean reefs arising from tsunamis in Pacific and Indian Ocean region. Socioeconomic impact of tsunamis on tourism and small island nations.

MACQUARIE UNIVERSITY	
Physical Geography	Extensive research on historical tsunamis based on field studies and historical records, management of tsunami risk, tsunami vulnerability and risk assessment.
Risk Frontiers	Field studies following tsunamis and implications for insurance. Mapping of probabilistic tsunami hazard analysis and GIS mapping of tsunami vulnerability.
MONASH UNIVERSITY	
Civil Engineering	Reduction of vulnerability to tsunamis through engineering design and land use planning. Development of international guidelines on tsunami-resilient construction in coastal areas.
UNIVERSITY OF MELBOURNE	
Civil Engineering	Effect of tsunamis on critical infrastructure.
UNIVERSITY OF QUEENSLAND	
Earth Systems Science Computational Centre	Numerical modelling of earthquake and tsunami generation, and tsunami propagation.
Australian Computational Earth Systems Simulator	Major National Research Facility providing computational infrastructure for simulating earth phenomena including earthquakes and tsunamis.
Civil Engineering	Overland flow of tsunami surges, including effect debris entrainment, and impact on obstacles such as buildings. Interaction of tsunami waves with shoreline.
UNIVERSITY OF WOLLONGONG	
Geology	Field studies of prehistoric tsunamis in Australia.
UNIVERSITY OF WESTERN SYDNEY	
Health Sciences	Impact of tsunamis on mental health.
OTHERS	
Insurance Industry	Historical records of tsunamis around Australian coastline. Post-tsunami field studies. Insurance aspects of tsunami damage. Structural design to reduce damage from tsunamis. Insurability of tsunami losses.
Centre for Earthquake Research in Australia	Tsunami risk studies based on historical records in Australia, Pacific and South-East Asia, and management of tsunami risk.