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ECHOES *of ancient tsunamis*

New research will help gauge the tsunami hazard to Australia

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Geological signatures of tsunamis provide clues to tsunami hazards that are unknown or poorly understood from written and instrumental records alone. In northeast Japan, western North America, Norway, and Scotland, tsunami deposits serve as long-term warnings of unusually large tsunamis that could otherwise take these areas by complete surprise (Nanyama et al. 2003; Atwater et al. 2005; Bondevik et al. 2005).

Because there was no historical precedent for an event the size of the Indian Ocean tsunami of 26 December 2004 along the Aceh–Andaman subduction zone, countries affected by the tsunami and their neighbours were not adequately prepared for the disaster. If geological records of tsunamis in the Indian Ocean region had been studied before the event, the regional tsunami hazard may have been recognised and the impact may have been reduced through the implementation of education programs and early warning systems.

Deposits from ancient tsunamis

Historical and instrumental records of tsunamis have been gathered for a much shorter period than the recurrence intervals of large tsunamis. Studying the geological signatures of past tsunamis therefore extends the tsunami record by thousands of years, leading to a better understanding of tsunami frequency, magnitude and flow dynamics, and a greater appreciation of tsunami hazard and risk.

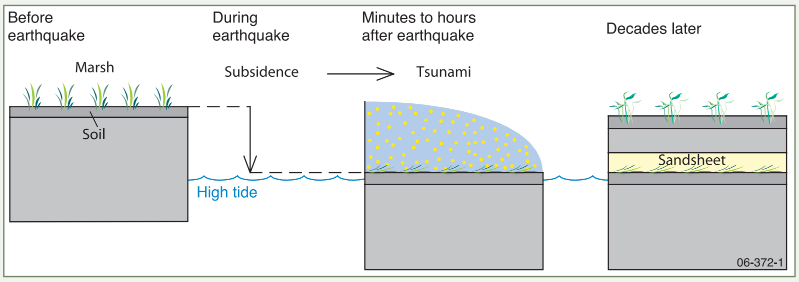

Figure 1. The formation of tsunami deposits during a subduction zone earthquake. Co-seismic subsidence occurs during the earthquake, lowering the land level and drowning coastal marsh deposits. Minutes to hours after the earthquake, several sediment-laden tsunami waves wash over the drowned marshlands, leaving behind sediment sheets. Over the next few decades, the land stabilises, allowing vegetation to recolonise the area and a soil profile to develop.

Geological evidence for tsunamis varies from large boulders to erosional features. The most common tsunami signatures are landward-tapering, higher energy sediment sheets preserved within lower energy depositional environments (figure 1). The composition of the sediment sheets varies with the available onshore and offshore sediments, but fine to medium sand generally dominates.

Tsunami sediment sheets range in thickness from a few centimetres to tens of decimetres, and mantle beach-ridge plain, estuarine marsh or lake bottom sediments. They characteristically have a sharp, erosional contact with the lower unit (usually soil), indicating some scouring before deposition (figure 2). The sediments may contain local or far-field gravel, mud and soil rip-up clasts mixed with sand and silt (figure 3). Multiple, normally graded layers are evident in some deposits, allowing the differentiation of specific waves in the tsunami wave train.

Microfossil assemblages (ostracods, diatoms, foraminifera and pollen) provide evidence of sediments transported and deposited by tsunamis. Tsunami deposits generally contain a mixture of fossils from terrestrial, tidal and deepwater environments, indicating both landward and seaward transport of sediments during inundation and backwash. Geochemical signatures, such as stable isotopes of carbon and oxygen, are also useful in distinguishing sediment sources, as they can be used as indicators of fresh and saltwater influxes.

If several tsunami deposits occur in stratigraphic sequence, dating of the deposits using radiogenic or luminescence techniques allows estimates of tsunami frequency (Cisternas et al 2005). This information can provide the basis for tsunami hazard assessments. Detailed studies of the sedimentology of tsunami deposits can yield constraints on tsunami behaviour, such as flow depth and velocity (Jaffe and Gelfenbaum 2002, Atwater et al 2005), providing empirical data for tsunami modelling and allowing better hazard estimation. The mapped geographical extent of tsunami deposits can contribute to probabilistic hazard maps and to calibration, testing and enhancement of tsunami run-up modelling. Furthermore, tsunami deposits can be a focus for public education about tsunami hazards.

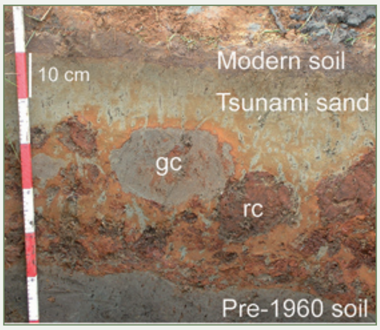

Figure 2. Soil and sediment rip-up clasts in the 1960 Chile tsunami deposit near Maullin, Chile. gc = soil rip-up clast; rc = sediment rip-up clast.

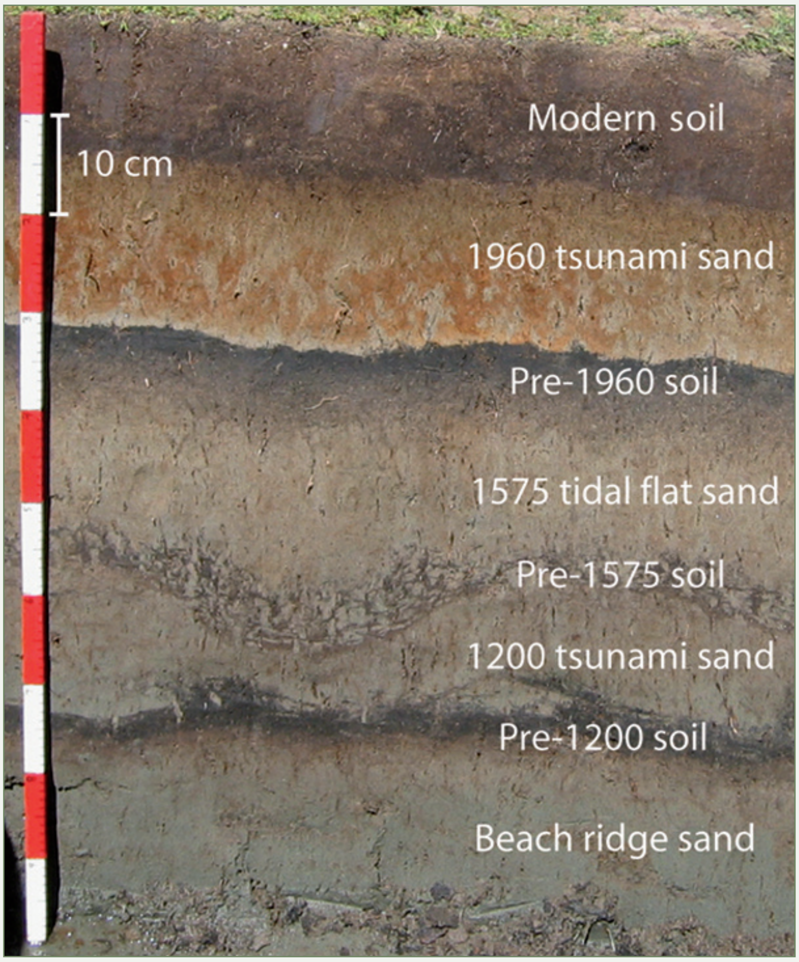

Figure 3. An example of tsunami sediment sheets, soil profiles and tidal flat deposits in stratigraphic sequence from Maullin, Chile. The tsunami events have been constrained by radiocarbon dating (Cisternas et al 2005). Note the sharp contact between tsunami sand sheets and underlying soil, indicating scouring before deposition. The bioturbated pre-1575 soil profile indicates subsidence.

Identification of far-field tsunami deposits is often more difficult than identification of earthquake-generated deposits close to a tsunami source region. In plate margin settings, tsunami sediment sheets are preserved in conjunction with evidence for co-seismic subsidence landward of the subduction zone. Such evidence includes drowned trees in growth position, a change in biota from supratidal to subtidal assemblages, highly bioturbated soil profiles, and a change in deposit sedimentology between the upper and lower units (figure 2). This additional evidence makes identification of a sediment sheet as tsunamigenic more certain. Furthermore, co-seismic subsidence makes it more likely that the tsunami sediment sheet will be preserved.

In coasts prone to severe storm events, tsunami hazard assessment is complicated by

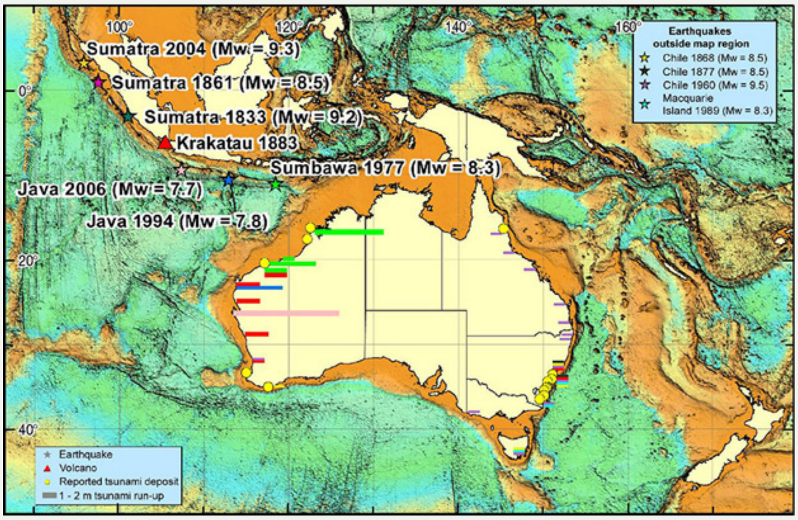

Figure 4. The Australian region, showing locations of tsunamigenic earthquakes and volcanic eruptions, oil and gas production facilities, and palaeotsunami deposits on the Australian coastline (reported from Bryant and Nott 2001). Known tsunami run-up heights are scaled and colour-coded with their sources.

the potential for storm surges to deposit sediment sheets that may be difficult to distinguish from those left by tsunamis. Recent studies of historic tsunami and storm deposits have suggested some criteria for distinguishing between them. These include:

- tsunami deposits are generally of greater lateral extent
- stable isotopic analysis of offshore sediments can be used to identify freshwater flux to the continental shelves caused by storm events.

Nonetheless, the differentiation of palaeotsunami and palaeostorm deposits, particularly for distantly generated events, remains problematic. More work is needed to link the sedimentology of tsunami and storm deposits with the physics of sediment erosion, transport and deposition (Tuttle et al 2004, Atwater et al 2005, Rhodes et al 2006). It is therefore important for the characterisation of the tsunami threat to Australia that evidence be considered not only from the Australian coastline but also from neighbouring subduction zones where there is a better chance of preserving less equivocal tsunami signatures.

Several authors have reported erosional and depositional features along the Australian coastline purported to be tsunamigenic (Bryant and Nott 2001, Switzer et al 2005). However, most are large boulders and erosional features, or their origin is enigmatic. They are not as useful for tsunami hazard estimation because they do not yield information about tsunami frequency.

Hazards from the north…

Tsunamis can be generated by any process that vertically displaces the sea surface, including landslides into the sea, underwater landslides, volcanic collapses and bolide impacts. However, undersea subduction zone earthquakes are the most common mechanism. Tsunamis generated from earthquakes around the Australian margin could potentially reach Australian shores within hours (figure 4).

The Sunda Arc south of Indonesia, where the Australian Plate is subducting beneath the Sunda Plate, poses the greatest tsunami threat to Australia's northwest coast. Although population density is fairly low, iron ore production facilities and extensive oil and gas infrastructure are concentrated in this region (figure 4). Furthermore, if a large tsunami occurs in this region, the remoteness of the settlements along the northwest coastline may hamper the delivery of aid. Tsunami inundation along this coastline, therefore, has the potential to cause considerable human and economic loss.

The 2004 event confirmed that the western Sunda Arc is capable of generating truly giant earthquakes. On the Western Australian coast, the 2004 tsunami displaced boats from their moorings and dragged swimmers out to sea. However, due to the orientation of the arc in relation to the Australian coastline, most tsunami energy was directed away from Australia and towards the Indian Ocean Basin (figure 5a; Dominey-Howe et al, in press).

Open-ocean tsunami propagation modelling has shown that large earthquakes in the eastern Sunda Arc could have a significant impact along Australia's northwest coastline (figure 5b; Burbidge and Cummins, in preparation). The 1977 Sumbawa earthquake and the 1994 Java earthquake in the eastern Sunda Arc generated four-metre to six-metre tsunamis on the northwest Australian coastline. The two earthquakes were rated at Mw 8.3 and Mw 7.8 respectively (Mw is a logarithmic measure of earthquake size, similar to the Richter scale but better suited to very large events). The 2006 West Java earthquake (Mw 7.7) also had a significant impact on parts of the Western Australian coastline.

There is still debate about whether the eastern Sunda Arc is capable of generating earthquakes greater than Mw 9, which could potentially cause a large tsunami along the entire west Australian coast (Burbidge and Cummins, in preparation). This will be important in the future characterisation of tsunami hazard to Western Australia.

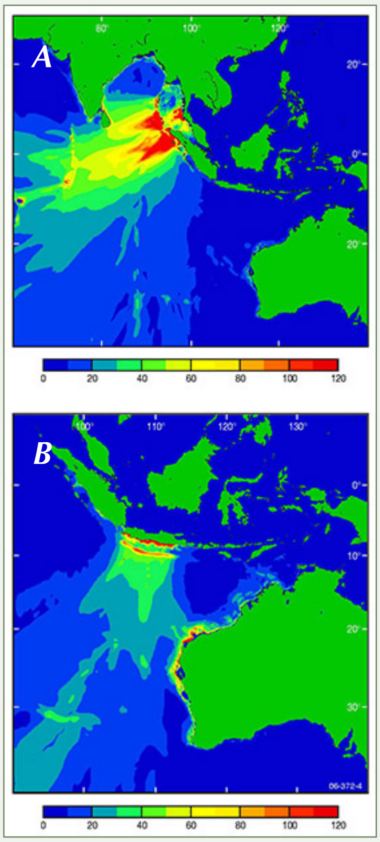

Figure 5. Open-ocean tsunami propagation of Mw 9 earthquakes on the Sunda Arc.
A: The 2004 Sumatra tsunami did not significantly affect Australia (Dominey-Howe et al, in press).
B: An earthquake in Java would have a greater impact on northwestern Australia (Burbidge and Cummins, in preparation). This modelling is accurate for tsunami propagation in deep water. Run-up of the tsunami onto the shoreline is likely to increase the tsunami amplitude severalfold. Figures courtesy of David Burbidge.

… and from the east

Along the eastern Australian coastline, where most Australians live, the tsunami threat comes from several sources. Although they have produced few historical tsunamis, the Solomons trench, the New Hebrides trench off Vanuatu, the Tonga–Kermadec trench north of New Zealand, the Alpine fault in New Zealand and the Puysegur trench south of New Zealand may all have the potential to produce earthquake-generated tsunamis capable of reaching Australian shores. More work needs to be done to characterise the earthquake mechanisms in these regions, including assessments of the maximum magnitude earthquake that each zone might generate and the expected nature of earthquake rupture.

The steep slopes of the continental shelf on the eastern Australian margin may induce underwater landslides capable of producing localised tsunamis. In the Australian Tsunami Database (Allport & Blong 1995), several large waves of unknown source are documented along the eastern coast between Hobart and Newcastle. It has been suggested that these waves—recorded on otherwise calm and clear days—may be localised tsunamis generated by submarine slumps. The most famous such incident occurred on Sydney's Bondi Beach in 1938, when three waves encroached on the beach in quick succession. The backwash was strong enough to drag swimmers out to sea. More than 200 bathers required assistance and five people were drowned on a day that became known as Black Sunday.

Over a hundred features suggested to be slump scars have been identified along the southeast coast between Sydney and Wollongong. Higher resolution bathymetry data and offshore coring and dating are necessary to characterise the age, magnitude and tsunamigenic potential of these features.

Another source of tsunami hazard for the Australian region is the arc of many active volcanoes, in Indonesia and the

Pacific, that encircle the Australian margin. The famous Krakatau eruption of 1883 caused 36 000 deaths in Indonesia and generated a four-metre tsunami in northwestern Australia. The 1453 eruption of Tongola in Vanuatu is reported to have been four times as powerful as Krakatau, but it is not known whether the tsunami generated by this eruption reached Australia.

Geoscience Australia's role in palaeotsunami research

Geoscience Australia has been building expertise in tsunami geology and is well placed to take a leading role in palaeotsunami research and hazard and risk estimation in the region.

In February 2006, staff participated in a field-based training course in Chile, the source location for the Mw 9.5 earthquake and subsequent trans-Pacific tsunami of 1960. The course enabled us to develop our expertise in tsunami geology and fostered collaborative contacts with tsunami geologists from other nations. In May 2006, we continued our collaboration with Indian Ocean and United States scientists through participation in a tsunami deposit reconnaissance program in Java. It is expected that continuing collaboration in this region will help to characterise the tsunami hazard from the enigmatic eastern Sunda Arc subduction zone, which potentially poses the greatest tsunami hazard to Australian shores.

Over the next year, Geoscience Australia will conduct a pilot project focusing on the southeast coast of Australia, where tsunamis might be generated by submarine slumps off the steep continental shelf and by earthquakes south of New Zealand. This project will complement tsunami propagation and inundation modelling and a high-resolution study of the potential of the continental margin to generate underwater landslides.

Future work in the characterisation of tsunami hazard to the Australian region will require onshore and offshore investigations along the Australian coastline, as well as collaboration with regional neighbours, in order to better characterise the threat from plate margin earthquakes. The work will involve interdisciplinary collaboration between sedimentologists, geomorphologists, micropalaeontologists, tsunami modellers and emergency managers. Through an understanding of the magnitude, frequency and flow dynamics of past tsunamis, tsunami deposits can improve our understanding of the tsunami hazard and provide a means of assessing future risk.

More information

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