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Viewpoint

Misattributed tsunami: Chile, Sumatra and the subduction model

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ABSTRACT

Tsunami intensity is poorly correlated with earthquake magnitude. The distribution of aftershocks that immediately followed the 2010 Maule (Chile), the 2004 Sumatra–Andaman and the 2005 Nias (Indonesia) events supports the view that faulting within an accretionary wedge or an outer rise can sometimes disrupt the seafloor more effectively than a megathrust even if the associated seismicity is minor. Monitoring offshore faults would thus seem an effective way to supplement modes of tsunami early warning which hinge on instrumental earthquake detection or wave height and period.

1. Introduction

The subduction earthquake model, in which upper plate rebound may result in a tsunami, has served us well in educating the public and apprentice Earth scientists. This paper asks whether the oversimplified version presented in some publications inhibits hazard assessment by limiting the potential range of seismogenic and tsunamigenic structures and chronologies.

The question gains urgency from the poor correlation that is found between earthquake magnitude and tsunami intensity and that helps to account in the limited success of tsunami forecasting based on teleseismic data and wave monitoring. Fig. 1, based on a figure displayed on a USGS website, is accompanied by the statement that 'Near the earthquake source, local tsunami size increases with the magnitude of the earthquake, although there is significant variability in this relationship....The term *tsunami earthquake* refers to anomalous earthquakes, in which the tsunami is larger than expected from the magnitude of the earthquake. These earthquakes tend to rupture the interplate thrust near where it approaches the sea floor at the trench.'

Setting aside the point that earthquakes smaller than expected also qualify as 'anomalous', the features discussed here, the accretionary wedge to be found at the rear of some trenches and the outer rise that may form the seaward margin of a trench, are potential sources of tsunami earthquakes when the related structures intersect the sea floor, that is to say more by virtue of their geometry than of their seismic vigour. Their neglect may owe something to location close to the trench, as any earthquakes they generate could be mistaken for shallow interplate events or for activity on splay faults (Cummins et al., 2001). For accretionary wedges the neglect also derives from the assumption that high pore-fluid pressures lead to low friction levels (Davis and von Huene, 1987) even though wedge sediments can exhibit strengths greater than those indicated by their porosity (Morgan and Ask, 2004; Fruehn et al., 1997). Outer rise seismicity may have been overlooked in 'doublet' events where it is associated with an interplate event. At the Tonga subduction zone slip between the plates is largely aseismic; on 29.9.2009, a 'slow' megathrust earthquake ($M_w = 8.0$) may have triggered the normal-fault earthquake ($M_w = 7.9$) in the outer rise that was probably the principal source of nearfield tsunami damage and was detected in global seismic data. As Beavan et al. (2010) observe, one cannot be certain that earlier (that is to say before teleseismic records began to be made) great historical earthquakes in the region were underthrusting events. The outer rise off central Chile has displayed both extension and compressional events which reflect flexural changes linked to the progress of subduction of the Juan Fernández Ridge, with a change from compression in the early 1980s to tension in 2001 (Clouard et al., 2007), but assessment of any related seafloor disruption awaits progress in fine-detail bathymetry (Mofjeld et al., 2004).

Tsunami forecasting is currently based primarily on modelling data on the earthquake location and magnitude and real-time sea-

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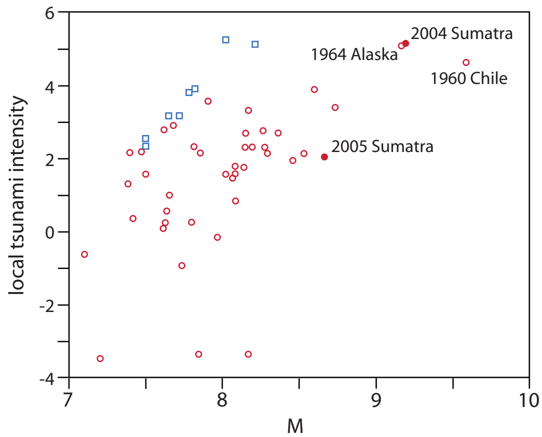

Fig. 1. Earthquake magnitude (*M*) versus local tsunami intensity for subduction zone earthquakes from 1896 to 2005.
(Sligthtly modified after walrus.wr.usgs.gov/../images/ioMw_vs_m.gif. circles=normal tsunamigenic earthquakes, squares=anomalous tsunamigenic earthquakes in which the tsunami is larger than expected from the magnitude of the earthquake. Simplified after http://walrus.wr.usgs.gov/tsunami/sumatraEQ/seismo.html).

level information obtained by bottom-pressure recorders (http://nctr.pmel.noaa.gov/tsunami-forecast.html). This paper suggests that monitoring seafloor deformation at the accretionary wedge, the outer rise or both could provide a signal which is unambiguously linked to wave generation and precedes it.

2. The 2010 Maule (Chile) earthquake

The Maule earthquake of 27.2.2010 ($M_w = 8.8$) had a hypocentral depth of 35 km (the Harvard CMT solution favours 24.1 km), with a nodal plane striking 17.5°E and dipping 18°E (http://earthquake.usgs.gov). Plate convergence hereabouts is put at 70 mm/year, and the rupture extends over some 500 km. Differences in earthquake and tsunami magnitudes between the Maule segment and the Chiloe segment to the south (host to the 1960 $M_w = 9.5$ earthquake) have been explained by the width of the frontal accretionary prism (FAP) – respectively 20–40 km and ≤10 km – and the thickness of the subduction channel – <1 km vs ~1.5 km – on the grounds that the prism controls the location of the updip limit of the seismogenic zone and a thick subduction channel encourages the propagation of the earthquake rupture (Contreras-Reyes et al., 2010).

The seaward limit of aftershock distribution is thought to coincide with the FAP 'backstop' because seismic energy can dissipate through the unconsolidated sediments of the FAP as anelastic deformation or as stable aseismical sliding (Moscoso et al., in press). The mapped trench is bordered by a secondary aftershock concentration which delivered 10% of the total number of aftershocks of $M > 4$ between 34.5°S and 38°S during 27 February–1 August 2010. The structures responsible for this activity are described as outer-rise faults and the earthquakes as bending-related. The CMT catalog includes two extensional events for 1.3.2010, one with $M_w = 5.3$ at a depth of 12 km and the other west of it with $M_w = 4.9$ at a depth of 16.5 km (www.globalcmt.org).

The FAP accounted for 2% of the aftershock in the period surveyed by Moscoso et al. (in press); the shorter period sampled here (27–28 February 2010, Fig. 2) is consistent with that result. Multichannel seismic reflection lines (Contreras-Reyes et al., 2010) reveal a number of landward-dipping structures which show that the FAP deposits are capable of supporting substantial faults. The aftershock data suggest that slip can indeed be seismic.

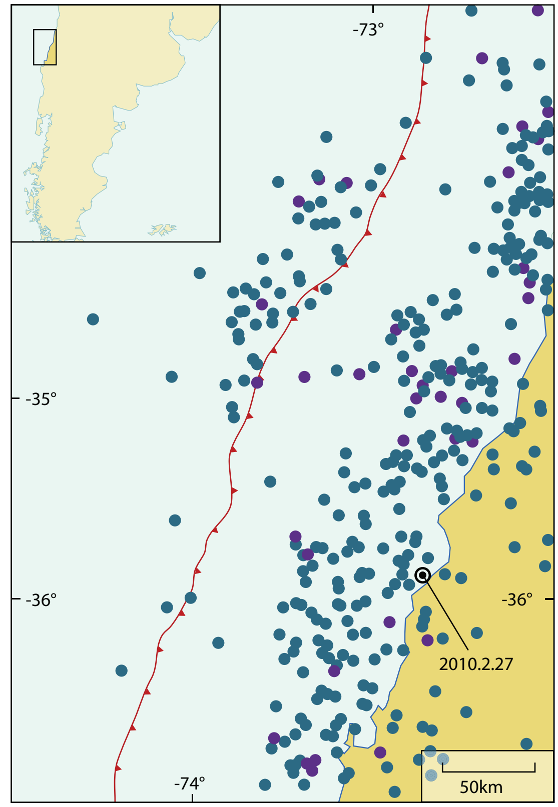

Fig. 2. Aftershocks off Maule ($m_b \geq 4.0$) during 27–28.2.2010 (data from http://neic.usgs.gov). Depths: purple = 0 to −33 m and blue = −33 to −70 m. Note a small number of shallow events landward of the trench where the accretionary wedge is located and the many events at the outer rise seaward of the trench.

In short, the Maule offshore region contains two zones which give rise to aftershocks and are strategically placed to generate tsunami. Compared with a rupture zone measuring ~500 km averaging 6.5 m of slip the energy they can release is doubtless puny but they have the advantage of a submarine location with water depths of up to 4 km.

3. The 2004 Sumatra–Andaman and the 2005 Nias (Indonesia) Sumatra earthquakes

The earthquakes of 26.12.2004 ($M_w = 9.3$) and 28.3.2005 ($M_w = 8.7$) off western Sumatra have been the subject of an unprecedented range of seismological and geodetic observations combined with palaeoseismological and oceanographic analyses. An earlier paper (Vita-Finzi, 2008) referred to Holocene evidence on Nias and Simeulue for deformation distributed among imbricate faults in the accretionary wedge, of which the two islands are emergent portions. The intention here is to complement that discussion with aftershock data.

The aftershocks for a day after each of the two earthquakes offer a partial explanation for the contrasting tsunami histories, it being understood that locations, as well as depths, are approximate. The 2004 events ranged in depth from 15 to 50 km and in magnitude from $m_b = 4$ (the specified minimum for the plots) to 6.1. In 2005 depths ranged from 19 to 40 km and magnitudes again from $m_b = 4$ to 6.1. Both populations include compressional and extensional Harvard CMT solutions. The main difference lies in the distributional pattern (Fig. 2). In 26–27.12.2004 it was diffuse (with 125 events > 4) and extended well to the seaward of the outer-arc ridge, whereas in 28–29.3.2005 the aftershocks (with 272 events > 4) were concentrated on the seaward margins of Nias and Simeulue. Besides having a larger main shock the 2004