**Fig. 5.** Close-up of the fractured area showing the displaced blocks which are in their found positions. Trowel for scale is 29 cm long.

supply. In addition, lightning strikes in the mid-latitudes are likely to increase in frequency under global warming, potentially destabilizing rock slopes even further. (j.knight@exeter.ac.uk)

## Tsunami: a white cobra hits Pangandaran West Java

**A.D. Hawkes, S. Engelhart, & B.P. Horton, (University of Pennsylvania) write** Although over-shadowed by the 26 December 2004 Indian Ocean tsunami, the tsunami that hit Java on 17 July 2006 was not a small event; but it was treated as a 'blip on the radar' by the media and public outside Java. Initial wave height estimates were between 2 m and 3 m, but as the death toll rose past 600, the wave height estimate escalated to some 7 m. Now, measurements on the ground in Pangandaran, West Java, Indonesia made two weeks after the tsunami hit, push the maximum wave height to above 8 m. Furthermore, the death toll would have been more extreme had this event happened during the busy kite festival a day earlier.

On Monday 17 July 2006 at 08:19:28 universal time (UTC), an earthquake of moment magnitude ($M_w$) 7.7 occurred off the south coast of Java, Indonesia (Fig. 6). A local tsunami was generated that damaged a ~200 km swath of the southern coastal communities of Central and West Java, including the most severely impacted community of Pangandaran (7.69503°S, 108.65784°E). The town of Pangandaran is located on an isthmus, which supports sand dominated systems on its west and east coast (figure three). The beach on the east coast of the isthmus is reinforced and backed by a 2 m-high seawall. The extent of the populated isthmus is marked by Pangandaran National Park, a raised coral terrace at the southern end of the isthmus. The estimated tsunami death toll is 659 with an additional 200 missing. Initial tsunami wave height estimates were between 2 m and 7 m, with inundation up to 500 m. This tsunami occurred as the result of movement along a thrust fault where the Australian plate is subducted to the north-northeast beneath the Sunda plate at a rate of 48 mm/yr along the Java Trench (Fig. 6).

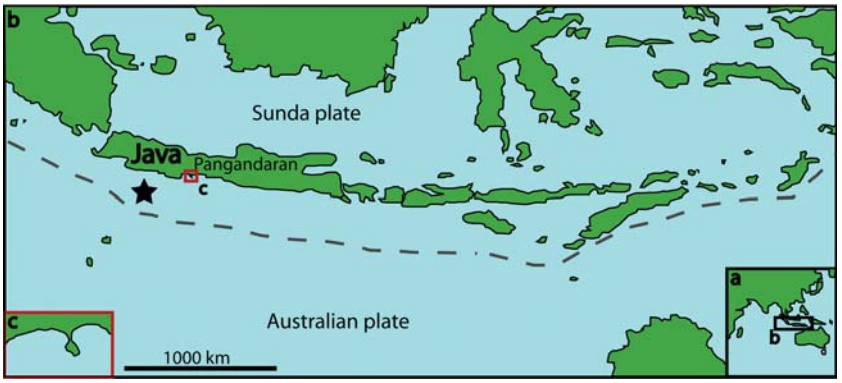


**Fig. 6.** The Australian Plate is being subducted beneath the Sunda plate at the rate of 43mm/yr along the Sunda Trench (dashed line). The Java earthquake epicentre lies between West Java and the Sunda Trench (star). Pangandaran, the study site (c), is the location most severely affected by the 17 July 2006 tsunami, which propagated from the earthquake.

A survey team consisting of scientists from the University of Pennsylvania arrived in Pangandaran, West Java on 30 July 2006. The survey team measured run-up heights and inundation distances, whilst also collecting tsunami sediment samples and recording eyewitness accounts. We made measurements of local topography, tsunami flow depth and direction. Minimum tsunami flow depth estimates were recorded from watermarks on buildings, generally a thin film of mud (Fig. 7). Maximum tsunami wave heights were measured by the height of destruction on buildings and via

**Fig. 7.** Fine films of mud on buildings are taken as measured estimates of minimum tsunami flow depth, whereas damage to buildings and eyewitness accounts are used to estimate maximum tsunami flow depths. These measurements are calibrated to mean sea level (m.s.l.).



 

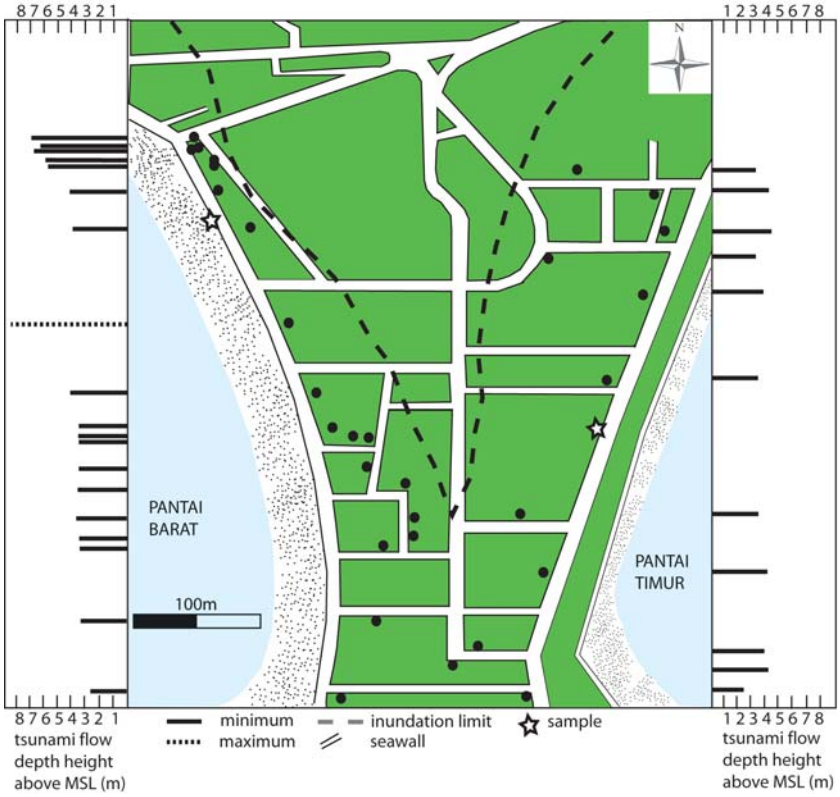


**Fig. 8.** Watermarks on buildings allow the tsunami flow depth to be calculated throughout Pangandaran, a beach-bound isthmus in West Java. The maximum flow depth estimate for the west coast of Pangandaran is 8.41 m (dotted line), while minimum measurements varied between 2.51 and 6.99 m (black lines). The dashed grey line estimates the extent of tsunami inundation from measurements throughout Pangandaran. Analysis of two tsunami-lain sediment samples (stars), indicate that the sediment is fine to medium sand containing abundant inner shelf foraminifera.

interviews with local residents. Each elevation was calculated as a height above mean sea level (a.m.s.l.) to compare between and amongst locations. Each watermark was measured, photographed and the location recorded using a Trimble geographical positioning system (GPS). Elevations were measured using a theodolite and staff with an accuracy of ± 5 cm.

The weather on Monday 17 July 2006 at Pangandaran was clear and the ocean calm. On the eastern side of the isthmus, eyewitnesses ran to higher ground because they saw the sea retreat ~200 m. In contrast, eyewitnesses on the western side of the isthmus did not notice any retreat of the sea and were surprised by the arrival of the first tsunami wave. One man compared the initial wave to a cobra, menacing and white at the front. The first impact of the tsunami's arrival hit Pangandaran during a falling tide approximately 20 minutes after the earthquake. Of those interviewed, no accurate wave arrival times could be elucidated. Many in the community believed that they must stay on high ground for no less than sixteen days following the tsunamis arrival. Eyewitnesses described a three-wave tsunami between 2 m and 10 m high following an ocean drawback of 200 m. Eyewitnesses reported the second wave as being the largest and most damaging, which inundated 200 m to 300 m inland. The second wave destroyed all the street vendor carts on the west coast and tossed them and their owners inland. Many of the shorefront hotels and restaurants on the east and west coast were damaged, some ruined beyond repair by either the force of the tsunami waves themselves or by debris smashing into them. Large pieces of coral and over 30 boats had to be removed from the eastern coastal road following the tsunami. Eyewitnesses had contradictory reports regarding the concurrence of wave arrival at the eastern and western shores, with one eyewitness describing a two-minute delay between the west shore arrival and the east shore arrival.

Analysis of our measurements demonstrated a maximum tsunami flow depth of 8.41 m a.m.s.l. on the western coast of Pangandaran, the 29 other measurements are taken as indication of minimum flow depth (Fig. 8). The maximum inundation distances inland exceeded 300 m. The isthmus experienced complete tsunami over-wash at its narrowest extent (~200 m) on the southern end. We found a 1 cm thick layer of fine to medium sand, between 144 and 425 μm, had been lain down by the tsunami (stars on Fig. 8). The tsunami-lain sediment contained abundant foraminiferal species dominated by *Ammonia* spp., *Quinqueloculina* spp., *Elphidium* spp. and *Parrellina hispudula*. These foraminiferal species indicate that the tsunami's sediment source was predominantly from the inner shelf region.


**Fig. 9.** Aerial view of the Wren's Nest in Dudley, showing the location of main features of geological interest, including the Severn Sisters.