Vanuatu Earthquake and Tsunami Cause Much Damage, Few Casualties

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Vanuatu is a volcanic archipelago located some 2000 km northeast of Australia, in the heart of Melanesia. The islands are mainly agricultural, but are also a tourist destination for Australians and New Zealanders, many of whom come to see the active volcanoes on Ambrym and Tanna, and the annual practice of “land diving” on Pentecost. An earthquake estimated between moment magnitude 7.1 and 7.5 occurred off the east coast of Vanuatu on November 26, 1999 at 13:21 UTC—the earthquake generated a damaging tsunami that struck the coast of Vanuatu, where it reached as high as 6.6 meters above sea level and destroyed an entire village (Figures 1 and 2). Remarkably, only 5 people were killed by the tsunami, most likely because the villagers were well informed about tsunamis and their effects. Two weeks after the tsunami, our group spent six days interviewing eyewitnesses to the disaster, surveying damage caused by the waves, and measuring sand and debris left by the tsunami. We hope to use this data to understand the factors that lead to loss of life during a tsunami, to provide benchmark data for computer simulations of tsunamis, and to understand how to identify the traces left by ancient tsunamis.

The earthquake and tsunami

Vanuatu consists of an island arc formed by the subduction of the Australian plate under the Pacific plate (Figure 2B). Vanuatu is seismically active, with magnitude 5-6 events common, especially in the Central Basin area bounded by Espiritu Santo and Malakula on the west, and Maewo and Pentecost on the east. A magnitude 6.4 event occurred in the central basin in 1965, followed the next day by a magnitude 7.0 earthquake near Epi. A magnitude 7.0 earthquake also occurred in 1981 south of Malakula. Because of Vanuatu’s steep topography, landslides commonly accompany earthquakes—these landslides may also occur offshore. Wong and Greene (1988) noted many large submarine landslides in the Central Basin that could have triggered tsunamis. Previous tsunamis occurred in 1875 (“Vanuatu”), 1961 (south of Efate), and 1965, which saw two tsunamis a day apart (the first in the Central

Basin, and the second near Epi) (Wong and Greene, 1988). It is likely that most tsunamis in the region go unreported simply because the population is so spread out, and because small tsunamis might strike only uninhabited coast. Both the Harvard and USGS solutions for the 26 November 1999 earthquake are not located on the plate boundary, but are close to a large reverse fault (Louat and Pelletier, 1989) in the back-arc. The fault is segmented by transverse faults associated with Vanuatu's active volcanoes. Because the aftershocks are contained within the area bounded by the Aoba and Ambrym transverse faults (Figure 2B), the Harvard solution for the earthquake seems more likely than the USGS solution (which is located in a different fault segment). The Harvard earthquake rupture mechanism shows the failure plane striking at 20 degrees, with a high angle (62 degrees) dip to the east. This mechanism seems consistent with movement on a splay of the large reverse fault of Louat and Pelletier.

The tsunami generated by this earthquake caused damage throughout central Vanuatu (Figure 2C). Eyewitnesses uniformly reported three damaging waves, lead by a leading depression wave, as also occurred during the 1992 Flores, 1994 East Java, 1994 Mindoro and 1996 Irian Jaya tsunamis (Imamura *et al.*, 1996).

Ni-Vanuatu news media reported that the tsunami was up to 10 meters high at Baie Martelli, at the southern tip of Pentecost Island (Figure 2B) (Neil-Jones, 1999). Additionally, the tsunami was blamed for the wreck of a 50-ton ship, the *Halimon*, in eastern Malakula.

A survey plan was drawn up shortly after the earthquake to assess the damage caused by the tsunami. The survey team consisted of experts from Vanuatu, Japan, and the United States. The team considered survey sites as distant as Fiji, where the tsunami registered on a tide gauge as waves less than 10 cm. However, to focus on areas of reported damage, the team limited its survey to Vanuatu.

Tsunami Survey

The survey took place December 14-19, when the team visited the islands of Efate, Ambrym, Pentecost, Espiritu Santo, and Malakula.

Inundation heights above sea level were estimated based on conspicuous indicators of tsunami runup and on interviews with eyewitnesses. The runup indicators included: marks on walls left by dirty water; the landward limit of plants killed by salt water or of debris carried by the water; places identified by eyewitnesses as the landward limit of inundation; and reference points, such as tops of buildings, used by eyewitnesses to describe water depth. The runups determined from these indicators were corrected for tides by referring to a tide chart computed by Y. Tsuji for Port Sandwich, on Malakula (Figure 2), so that the runup heights represent the total elevation gained by the tsunami and not an elevation above mean sea level. The runup measurements were subject to errors of up to several tens of centimeters.

The tsunami reached a maximum of 6.6 meters above sea level, with damage limited to one bay (Figures 2C and D). The east coast of Pentecost and Ambrym, which face the tsunami source, shows runup heights as great as 4.7 m, decreasing with distance from the earthquake. On the east coast of Malakula, which faces the tsunami source through the Selwyn Strait, runup heights were no more than 1.8 m. Especially large waves, observed by eyewitnesses in small bays such as Baie Martelli, imply that the tsunami's energy was focused, or was augmented by nearby submarine landslides, in those areas. No tsunami runup was noted on Espiritu Santo or northern Pentecost, despite the concentration of earthquake damage in northern Pentecost.

Though far removed from the tsunami source, the coast of Efate showed runups of up to 2.6 m. The tide gauge at Port Vila, on the south coast of Efate, showed a tsunami wave height of only 40 cm arriving 25 minutes after the earthquake.

Damage at Baie Martelli

The tsunami reached nearly 6 meters above sea level at Baie Martelli, completely destroying the town (Figure 1). Despite this destruction, only 5 of the over 300 people living in Baie Martelli lost their lives, mostly because the villagers happened to be awake at the time of the waves (after midnight), and because they were well versed in tsunamis.

Destruction at Baie Martelli was reported to have been caused by three waves, led by a receding wave. The first and smallest wave arrived within about 10 minutes of the earthquake. It was followed by two larger waves arriving about 15 minutes apart. The buildings were mostly woven grass walls with corrugated metal roofs, and were totally destroyed. The few concrete structures in the village remained standing, but were very badly damaged. Perhaps the strongest building in town was the church—it survived the tsunami, which dug 1.5 m deep scours at the leading corners of the building. The wave did not itself exceed the height of the church (~4.5 m), but water impounded in front of the church surged over the rooftop, collapsing the roof and flooding the interior.

The tsunami also deposited sand. The total volume of this deposit is about 80 cubic meters. The sand forms a layer 5 - 15 cm thick in almost all areas the tsunami reached. Its likely sources are the shore face, which village residents state was eroded by the wave, and some pits dug into the coastline by the tsunami. The pits are between one and two meters deep that extend about five meters into the shoreline. The deposit shows two fining upward sequences, which probably represent two pulses of sedimentation. This stratigraphy becomes less distinct and thinner landward, until only one pulse can be recognized in outcrop.

The small number of casualties was due to prior education and a party. Because of a wedding on the day of the earthquake, most everyone was still up celebrating when the earthquake occurred. A lookout was sent to note the condition of the sea. When he reported that the water was receding, villagers concluded that a tsunami was coming, and they ran to a nearby hillside to escape the wave. For this response to natural warnings of a tsunami, villagers credited a video of the 1998 Papua New Guinea tsunami, which they had seen a few months before their own tsunami. The only casualties were those too elderly to escape the wave, those who returned for possessions after the passage of the first wave, and a man so drunk on *kava* that he ignored people who were directing him to safety. The tsunami also occurred three days after a full moon, so the village was well lit despite a lack of electricity.

Unusually High Runup on Efate

Although runup on Ambrym and Pentecost shows that wave height decreased with distance from the epicenter (Figure 2C), runup on Efate, farther from the epicenter, locally exceeded 1.5 meters (Figure 2D). These puzzling runups occurred on all sides of Efate, even behind the shelter of other islands and on shores facing away from the earthquake epicenter.

Neither landslides nor constructive wave interference seem adequate to explain the runups on Efate. On Pentecost, many landslides resulted from the earthquake, and coastal landslides usually entered the ocean. It is possible that submarine or subaerial landslides generated by either the main shock or any of the aftershocks could have caused local tsunamis even far away from the epicenter. However, initial computer simulations by one author (Koshimura) suggest that the arrival time of the tsunami at Port Vila, on southwestern Efate, is consistent with the arrival of a tsunami from the earthquake. Increased runup from constructive wave interference, as seen during the 1993 Timor and 1996 Irian Jaya tsunamis, seems unlikely here because this interference usually occurs on the side opposite the oncoming wave. Here the runup is distributed around the island. Runup on Efate is estimated from lines of debris on the shore and not from eyewitness accounts, so it is possible that the debris arrived by some means other than tsunami.

The Sinking of the *Halimon*

Although the tsunami runup on Malakula was low, no more than 1.8 m, the wave caused the sinking of a 50-ton wooden ship, the *Halimon*. Sailors on the ship reported that the *Halimon* was riding at anchor in 10 meters of water in Tisman Bay (Figure 2C), loaded with 18 tons of copra. At anchor only less than one hundred meters away was a steel-hulled ship.

The tsunami began in Tisman Bay as a negative wave, removing enough water from the bay to cause the *Halimon* to settle onto her keel, and causing her to list badly. This awakened the crew, who were asleep at the time—they had not felt the earthquake. In the minutes before arrival of the first positive wave of the tsunami, the crew decided to abandon ship; they swam to the steel ship which, having a shallower draft and being in slightly deeper water, was still afloat. The positive wave of the tsunami was estimated by witnesses praying at a local church to have been 3 meters high in Tisman Bay and to have arrived some 30 minutes after the earthquake. However, the tsunami ran up no more than 0.8 m onto the shore of the bay, probably because the water had already receded so much. The wave struck the listing *Halimon*, sinking her and carrying her into 20 meters of water.

This story is reminiscent of accounts of the August 8, 1868 tsunami in what was then southern Peru, where a negative wave caused the wooden ships of that era to settle onto their keels, only to be destroyed by the incoming positive wave (Billings, 1915). The only marine survivors of this disaster were aboard a flat-bottomed sidewheeler, the *Wateree*, whose first mate wrote "[After the water receded], the round-hulled ships rolled over on their sides, while our *Wateree* sat down upon her flat bottom; and when the sea came back, returning not as a wave, but rather as a huge tide, it made our unhappy companions turn turtle, whereas the *Wateree* rose unhurt on the churning water."

Our research does not suggest that any wave source other than the main earthquake on November 26th is required to generate the tsunami. Arrival times of the witnessed tsunamis are consistent with arrival times from an initial computer simulation of a tsunami spreading from the Harvard epicenter, and do not require a landslide. The unusually high runups on Efate remain enigmatic, but are not well explained by landslides or wave focusing either.

Data from this study will be used in several aspects of tsunami study, including calibrating computer simulations of tsunami movement around islands, understanding the nature of tsunami deposition so that ancient tsunami deposits may be recognized, measuring the force exerted by tsunamis on coastal structures, and understanding human response to tsunamis so that evacuation systems can be better planned. All of these investigations are ongoing, and rely heavily on data that disaster survey teams provide.

Vanuatu is a tsunami-prone country in a tsunami-prone region. In order to understand how to mitigate the hazard posed by these waves, we must not only understand what went wrong, (as in Aitape in 1998, where over 2000 people died), but also what went right. In Pentecost, few lives were lost because fortune and geography dictated that people were awake when disaster struck, and they had a nearby place of safety. Perhaps more importantly, people were quick to recognize the threat, and quick to respond to that threat.

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Figure 1. The village of Baie Martelli after the tsunami. Only concrete buildings remain standing, and those are too badly damaged to remain inhabited. The large structure in the center of town is the village church. Water surged over the top of the church (4.25 m above ground surface), crushing its corrugated metal roof.

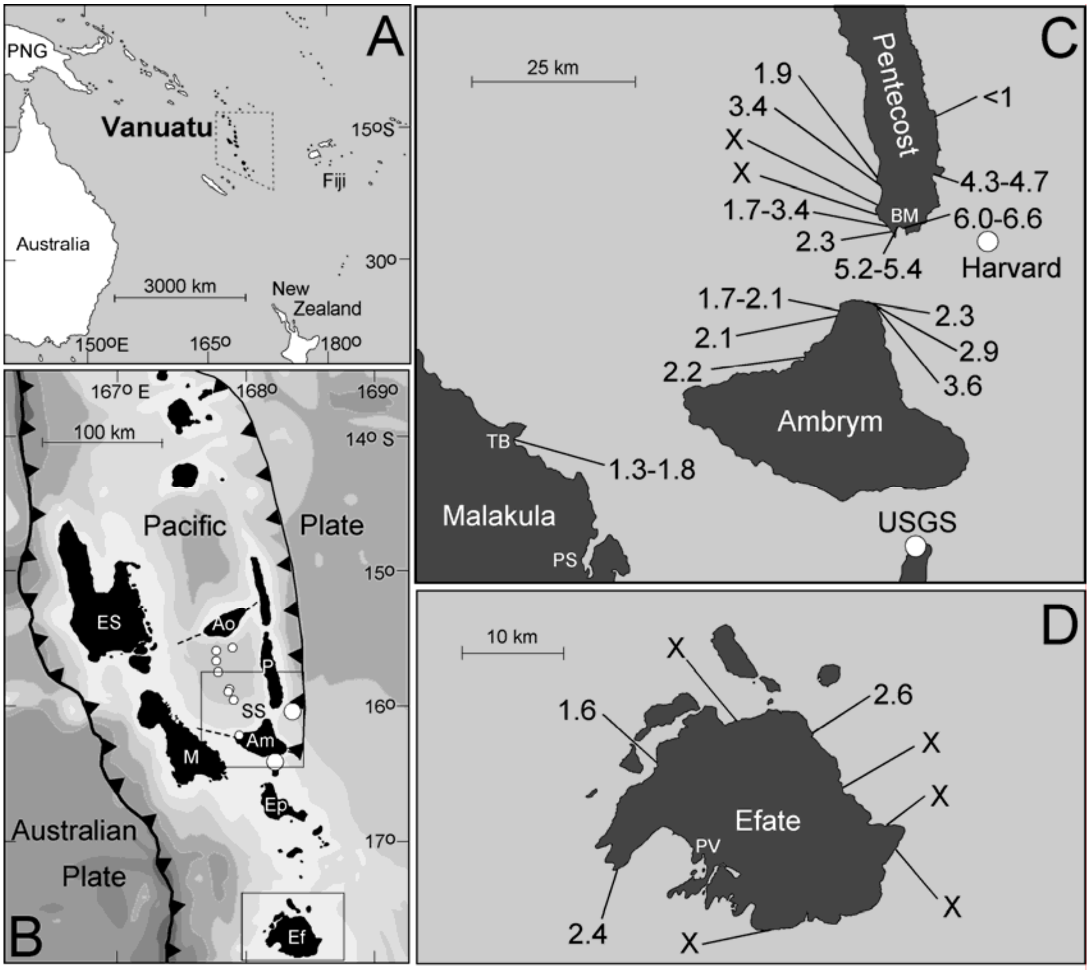

Figure 2. Maps of the Vanuatu earthquake and tsunami. A. Location of Vanuatu in the southern Pacific Ocean. B. Tectonic and bathymetric map of northern and central Vanuatu. Large circles are the Harvard (northern) and USGS (southern) epicenters for the earthquake, smaller circles are aftershocks from the NEIC catalogue larger than M=4.5. Bathymetric contour interval is 1000 m. Ambrym is labeled “Am”, Aoba “Ao”, Efate “Ef”, Epi “Ep”, Espiritu Santo “ES”, Malakula “M”, Pentecost “P”, and the Selwyn Strait “SS”. C. Runup in meters for locations surveyed on Pentecost, Malakula, and Ambrym. Where more than one measurement was taken at a single site, a range of heights is shown: sites where signs of runup were not found are marked “X”. BM marks the location of Baie Martelli, PS Port Sandwich, and TB Tisman Bay. D. Runup in meters on Efate. Sites where signs of runup were not found are marked “X”. PV marks the location of Port Vila.