Report of International Tsunami Expedition to Madagascar
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Participants:
Dr. Dallas Abbott- Lamont Doherty Earth Observatory of Columbia University, New York, USA
Dr. Edward A. Bryant-University of Wollongong, Australia
Dr. Vacheslev Gusiakov, Novosibirsk Tsunami Laboratory, Russia
Dr. W Bruce Masse, Los Alamos National Lab, Los Alamos, USA
Andriamiranto Raveloson, University of Antananarivo, Antananarivo, Madagascar
Hoby Razafindrakoto, University of Antananarivo, Antananarivo, Madagascar

Summary
We have found evidence for large tsunami runups at 4 sites:megatsunami chevrons at Faux Cap,Fenambosy, and Ampalaza; and marine sediment dumped at Cape St. Marie. In the field, we documented maximum runups of 86 m above sea level at Ampalaza, 186 m at Fenambosy, 205 m at Faux Cap and 192 m at Cape St Marie. Each of the chevrons represents lateral transport of sediment over many kilometers: 20 km at Faux Cap, 45 km at Fenambosy, and 45 km at Ampalaza. The chevrons, if contemporaneous, represent the highest tsunami runups ever observed over a broad region.

Background
The international tsunami expedition to Madagascar looked at three different chevron complexes. Each of these chevron deposits was found beforehand using satellite imagery at Faux Cap, Fenambosy, and Ampalsa located on the southern tip of Madagascar. Each had slightly different characteristics. The overall goal of the expedition was to verify whether or not the chevrons we saw on satellite images represented megatsunami deposits and if so, whether the inferred runups from the imagery were actually present.

Faux Cap Chevron
Preliminary Observations
At Faux Cap, we had one day in the field. At the start of the day, we followed a road that crossed the chevron near the ocean. The sand deposit here is about 1 m thick. It contains large rocks up to 15 cm in diameter. There are marine shells mixed in with the sand. We found two cowrie shells, a marine animal that is not eaten by the local people.

Later in the day, we traveled to the end of the chevron that is furthest from the ocean. We then performed a traverse across the chevron. The sand layer is uneven in thickness, with three local areas of thicker sand forming bedforms. Each of these areas of thicker sand is a tsunami dump deposit. The dump deposit at the lowest elevation is 61 meters above sea level. We found 1 cowrie shell in this deposit, along with rocks as big as 23 cm in diameter. The lowest dump deposit is 1 km from the ocean. The dump deposit at intermediate height is 150 meters above sea level and 2.4 km from the ocean. This dump deposit contains coarse sand and rock fragments up to 30 cm in diameter. The highest dump deposit is 205 meters above sea level and 4 km from the ocean. This dump deposit contains white carbonate rock fragments up to 5 cm in diameter on a substrate of coarse sand. Small marine gastropods were in third highest dump deposit.

At the end of the traverse, we confirmed that the location of the boundary between the sediment of the chevron and typical weathered soil is the same on the satellite imagery as it is the field. The sand in the chevron is white-to-yellow, while the weathered lateritic soil is red. Thus there is good visual contrast between the chevron deposit and the surrounding soil. The horizontal resolution of the satellite imagery is about 200 meters, within the error of our location of the edge of the chevron in the field.

Conclusions

The tsunami which deposited the Faux Cap chevron came onto shore near our hotel, the Libertalia. It then traveled inland over a horizontal distance of about 20 km and to a height of 205 meters above sea level. Because the tsunami came in at a high angle to the trend of the coastline, it did not pick up as much sediment as the tsunami at Fenambosy and Ampalaza. As a result, the tsunami deposit appears much fainter on the satellite imagery and the average thickness of the sand deposit is much less. Nevertheless, the satellite imagery faithfully reproduced the lateral extent of the tsunami layer, even when it was about 1 cm thick or less.

The faintness of the Faux Cap chevron is probably not due to a difference in age, but instead to a difference in the total amount of sediment that was carried by the tsunami wave. The decrease in the total amount of sediment proved to be an advantage, as marine shells were present in much greater abundance than at the other two chevrons.

The Faux Cap chevron contained relatively large rocks throughout. Most of the rocks consisted of carbonate, but some appeared to be either basalt or gray limestone. Because the tsunami layer is relatively thin at Faux Cap, some of the rocks are simply pieces of bedrock from nearby outcrops.

Fenambosy Chevron

Preliminary Observations

The Fenambosy chevron is the most spectacular of the chevrons. It trends roughly east-west over a distance of about 26 km. At its distal end away from the ocean, the chevron appears to ascend a steep escarpment with a height of at least 170 meters.

In our first traverse, we found that the marine sand layer extended to the base of the escarpment. This layer contained coarse sand and fragments of carbonate rock up to 5 cm in diameter up to the edge of the escarpment. We also found a rock oyster and mollusc in the tsunami deposit close to the edge of the escarpment at an elevation of 86 m above sea level, 4.6 km from the ocean.

In our second traverse, we started at the top of the highest part of the escarpment and traveled towards the ocean. Above the escarpment, we found erosional channels landward of the chevron that had no apparent stream source and were about 2 meters deep. The tsunami layer at the top of the escarpment contains large carbonate boulders at least 50 cm in diameter. The carbonate boulders originate from the rock that makes up the escarpment. We also found rock oyster and cowrie shells in the sand layer. Rock oysters are eaten by the local people; however, cowries are not. In addition, we found a mussel, which lives in a brackish water. The top of the escarpment at the site of our second traverse lies 186 meters above sea level and 8 km from the ocean.

Finally, we looked at the tsunami dump deposit located eastward from our hotel, the Ranch at Lavanono. The dump deposit contained a mixture of rock fragments and marine shell. Many of the rock fragments were not locally derived.

Conclusions

Our traverses showed that as the tsunami reached Lavanono, it began dumping sediment inland for a horizontal distance of 45 km. The sandy sediment was transported northwestward and deposited at the distal end of the Fenambosy chevron in a series of large bedforms. The sediment dumped at Lavanono represents the last sediment transported from the shelf and probably originated as weathered bedrock.

Near the end of its 45 km long path, the tsunami wave traveled up a steep escarpment. As the tsunami traveled over the edge of the escarpment it tore off large boulders. On the landward side of the escarpment, the tsunami deposited boulders at least 50 cm in diameter along with marine shells. In addition, the runoff of water from the tsunami excavated deep erosional channels into the bedrock on the landward side of the escarpment. Based on the need for water to flow over the top of the escarpment at 186 meters, we infer that the tsunami had a minimum run up height of at least 192 meters above sea level at its most landward extent.

Ampalaza Chevron

Preliminary Observations

The first traverse of the Ampalaza chevron started at the landward end of the chevron. The chevron contains multiple internal topographic highs and lows. At the landward end, the internal highs and lows are not covered by vegetation. As a result, the landward end of the chevron is modified by wind. Despite this reworking by wind, the sand grains are not well rounded. Furthermore, the grain size of the sand is too coarse for it to be solely wind blown. Instead, the sand must have been transported by water movement.

The second traverse of the Ampalaza chevron started at the landward edge of the vegetated topographic highs. We found that the sand in these chevrons is completely unsorted. However, the large amount of sand in the chevron made it difficult for us to find any marine shells. We dug down into the chevron near the break in slope of a local hill. This is the best location to find samples of sand that have experienced the least reworking by the wind.

We were not able to sample the seaward edge of the Ampalaza chevron, as it is difficult to access by car. Thus, we do not know if there is a dump deposit at the start of this chevron.

Conclusions

We infer that the tsunami that formed the Ampalaza chevron hit the coast somewhere along the mouth of the Menarandra River. Because the topography is very flat, the tsunami had sufficient energy to entrain large amounts of coarse sand from the river's delta. The sand was then carried inland and deposited in the Ampalaza chevron. The entrainment of large amounts of sand and the deltaic source of the sand mean that this tsunami deposit has a very low concentration of marine shells. Nevertheless the completely unsorted nature and large average grain size of the sand in the Ampalaza chevron are completely inconsistent with a wind blown origin for the Ampalaza chevron. The sand in the Ampalaza chevron lacks the internal bedding and sorting that are characteristic of wind-blown sands. Thus, the sand in the Ampalaza chevron must have been carried inland by a tsunami wave. Based on our field observations and measurements from Google Earth, we infer that the tsunami wave at Ampalaza traveled a horizontal distance of 45 km from the coast, reaching an elevation of 86 meters above sea level. At its most distal point from the coast, the nearest shoreline is 7 km away from the end of the Ampalaza chevron.

Cape St. Marie

Preliminary Observations

On our fourth traverse, we traveled to Cape St. Marie. The tsunami deposits here either begin the Fenambosy chevron or terminate the Faux Cap chevron field. The tsunami traveled over Cape St. Marie from east to west. On the east side of Cape St. Marie, we found a large tsunami dump deposit about 23 m above sea level. Due to the locally strong winds, its surface represents a lag deposit. The dump deposit contained many marine shells, including some cowries, which are not eaten by the local people. The largest rocks in the dump deposit are about 10 cm in diameter. At the highest point on Cape St. Marie, 194 meters above sea level, we found coarse sand that appears to be a tsunami deposit. We found cowries and small marine gastropods in coarse sand at 140 meters above sea level.

Conclusions

Because the eastern edge of Cape St. Marie has steep topography, the tsunami dumped material on the eastern side of the Cape. The tsunami then traveled over the top of Cape St. Marie, reaching an elevation of 194 meters. It is possible that tsunami deposited sand layers further inland at a higher elevation, but time constraints did not permit detailed reconnaissance.

The rocks in all of the tsunami deposits we studied and sampled are located 100 meters or more from local bedrock outcrops and sit on a substrate of coarse sand. Thus, we are reasonably certain that the large rocks we found within tsunami layers were transported by the tsunami and were not eroded from the bedrock after the tsunami event.

Laboratory Work Necessary for Publication

Although our field results are spectacular, further laboratory work is necessary to produce a publishable paper and to strengthen our conclusions. The laboratory work contains 3 components: dating, sieving, and microscope work. We have collected shells for C-14 dating from 2 of the three chevrons. If the C-14 dates confirm that the datable chevrons are in fact the same age, it will strengthen our case for a single regional event. At the moment, our favored source for the tsunami that formed the chevrons is the 29 km Burckle impact crater located at 30S, 61E on a fracture zone of the Southwest Indian Ridge. The Burckle crater is geologically young, most probably about 4500 to 5000 years old. If our C-14 dates are similar to our projected age for Burckle crater, this will be an important result to prove the reality of the threat of cosmogenic tsunamis and that they occurred in the recent past.

We have collected about 30 samples of coarse sand, all of which must be sieved. The grain size distribution of the sieved particles is important for several reasons. The first is that the presence of particles larger than 2 mm in diameter will confirm our inference that the sediment was not transported by the wind. Wind cannot move particles that are larger than 2 mm in diameter. The second is that wind-blown sand is extremely well sorted, and lacks both small silt-sized particles and larger sand-sized particles. Wind-blown sand has a unimodal size distribution. In contrast, sand transported by a tsunami has a broad range of particle sizes, from large rocks down to clay particles. Thus, the size distributions derived from sieving will provide additional evidence that the sand was not transported by wind to its present location.

The sieved samples are also required for our microscope work. Initially, we will use a light microscope that magnifies up to 110 times to look at the type of particles in the sand. We will look for marine microfossils, concoidally fractured grains, rock fragments, and impact spherules. We will use the light microscope to collect candidates for each of these types of grains and to put them on a mount for examination with a scanning electron microscope (SEM). Our SEM investigations will allow us to photograph any marine microfossils with sufficient resolution to determine their species. The X-ray analyzer on the SEM will allow us to identify the minerals in rock fragments and to image concoidally fractured grains. In the past, we have found splashes of Fe-Ni-Cr metal on concoidally fractured grains and marine microfossils. The splashed material is very tiny and is only visible using a scanning electron microscope. Because extraterrestrial material contains a very high Ni content, this Fe-Ni-Cr metal is evidence that these marine fossils and concoidally fractured grains are impact ejecta.