Geological Survey of Canada

EFFECTS OF THE 26 DECEMBER 2004 INDIAN OCEAN TSUNAMI IN THE REPUBLIC OF SEYCHELLES

Report of the Canada-UNESCO Indian Ocean Tsunami Expedition
19 January – 5 February 2005

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Contributions:
This is a contribution to IO-GOOS (the Indian Ocean component of the Global Ocean Observing System) under the auspices of the Intergovernmental Oceanographic Commission (IOC) of UNESCO. This study also results from an ad-hoc collaboration between the Government of Canada and the Government of the Republic of the Seychelles. This is a contribution of the Geological Survey of Canada and the Earth Sciences Sector of the Department of Natural Resources of the Government of Canada.

Cover photograph:
Tsunami damage and debris on main coastal road, Anse Royale, Mahé, December 26, 2004. Photograph by Sabrina Didon, Le Relax Hotel, Mahé, Republic of Seychelles.

EXECUTIVE SUMMARY

- Beginning about mid-day on 26 December, 2004 and continuing into the following day, numerous tsunami waves impacted the coast of the Seychelles archipelago. This study was undertaken to document the timing, elevation, and effects of these waves on the largest granitic islands of this archipelago, Mahé and Praslin, and to collate any available information on effects on other islands of the Seychelles archipelago.

- The tsunami impacted Mahé and Praslin as a sequence of waves at intervals of tens of minutes to hours. The first tsunami wave struck at low tide, but others occurred through several tidal cycles, so that some waves arrived at high tide.

- The first indication of the tsunami on the Mahé tide gauge (sampling interval 4 minutes) was a rise in water level to lower than higher high water at large tides between 08:08 and 08:12 UTC (between 12:08 and 12:12 local time). This initial rise in water level was corroborated by some observers on Mahé and Praslin. They stated that the first effect was in fact an increase in water level from the low tide to the normal high tide level, or just above. This is in contrast to accounts of most observers who noticed an initial lowering of sea level far below the level of the lowest tides but missed the preceding rise of sea level.

- The highest water levels, highest run-ups, and maximum distances inland that tsunami flooding reached were in coastal lowlands generally facing east toward the source of the tsunami.

- However, tsunami inundation and damage were not confined to east-facing shores. Run-up and damage were locally as severe along shores of Mahé and Praslin facing away from the source of the tsunami. Some observers on the west sides of both islands reported water approaching from two directions (from northwest and southeast).

- The highest flood levels on Mahé ranged from ~ 1.6 m to more than 4.4 m above mean sea level. On Praslin they ranged from ~1.8 m to 3.6 m. Maximum withdrawal of water was not recorded by the tide gauge at Mahé, because the stilling well went dry, but we have evidence from observers that it dropped as much as 4 m below mean sea level.

- Maximum inundation of coastal areas of Victoria occurred about 16 hours after the arrival of the first tsunami wave at the Mahé tide gauge.

- The damage to coastal infrastructure on both eastern and western shores was most severe where natural coasts have been modified, i.e., where natural beach berms have been removed from the tops of beaches, where roads are immediately adjacent to beaches, and where hotel structures are either adjacent to the high water mark or project seaward over the beach. In some instances, a berm of no more than 0.65 m high protected houses from inundation. In one case, a hotel with no berm was flooded, while houses 50-100 m away behind a natural berm were not.

- There were two deaths in the entire Seychelles archipelago. Both occurred on Mahé: one person fishing near Northeast Point died immediately; another caught in the wave at Anse Royale died some time later from injuries. Tragic as this is for the families of those individuals, this is a very small casualty figure compared to the totals elsewhere in the Indian Ocean basin. Seychelles was spared a higher death toll because the initial and largest tsunami waves occurred at low tide. Had the waves occurred at high tide and during a normal weekday, when docks would have been busy and schools along the coast occupied, we believe the loss of life could have been far higher.

- Most damage was experienced at hotels and restaurants, these establishments being deliberately located in coastal embayments adjacent to beaches. In some places, homes were flooded and some incurred structural damage. Dock structures were damaged in Port Victoria, causeway bridges failed between Victoria and the airport, and coastal roads were damaged in a number of places.

- Most impacts to private property consisted of minor structural damage (walls and fences knocked down, minor floor and wall cracks, damage to appliances, electrical equipment, computers, cars, household furnishings and other personal effects). The damage to electrical wiring and air conditioners was sufficient to shut down The Paradise Sun, a major resort hotel on Praslin.

- Major structural damage occurred to private property at one hotel (La Reserve) on Praslin. At this site, the damage was caused primarily by the draining of tsunami waters, which eroded and undermined foundations, causing distortion of the structures to the extent that they will have to be demolished. Direct wave impacts were also sustained, resulting in broken windows and interior damage.

- Damage to public works was greatest in Victoria, capital of The Republic of Seychelles. The central business and government district was flooded. Although the effects, compounded by heavy rains after the tsunami, were generally minimal, major structural damage occurred along the north side of the inner harbour. Lateral spread failures developed in artificial fills extending several hundred metres along this shore. The failures were caused by inundation and saturation of the fill during tsunami run-up and flooding followed by rapid draw-down during flood drainage. The sheet piles that form the dock-face were not engineered to resist pressure of the resulting liquefied fills on their landward sides.

- Washouts occurred on two sections of highway causeway crossing reclaimed land south of Victoria. These breaches, caused by failure of culverts that drain lagoons and channels on the inner side of the reclaimed land, have been studied in detail by Seychelles government officials and were not examined further in this study. As in the case of the dock failures, these road washouts resulted from inundation and subsequent drainage of floodwaters.

- As noted above, direct observations by the study team were confined to Mahé and Praslin. These are two of the granitic islands in the northern Seychelles group, located on a shallow seabed shelf. Other islands in the Seychelles archipelago outside this group are coral atolls located on seamounts that rise from abyssal depths. As far as we have been able to determine, through discussions with officials and other observers, damaging effects of the tsunami were confined to the granitic islands. The lack of impact on the atolls is due, we believe, to the deep water surrounding them, resulting in minimal shoaling and amplification of the long wavelength and low-amplitude tsunami waves.

- It appears that the shallow (<200 m) shelf platform surrounding the granitic islands refracted the tsunami waves, allowing them to approach the islands from various directions. The refracted waves, as they approached the coast, may have been further refracted and amplified so as to cause higher run-up in specific coastal embayments such as Anse Royale and Anse à la Mouche on Mahé.

- In many places, the tsunami waves broke on the outer reef and then propagated across the reef as a bore. Complex motions developed in some bays through topographic effects on wave breaking, refraction, reflection, and amplification through wave interaction. Coastal sites facing reef gaps sustained some of the highest run-up elevations.

- Bottom velocities of tsunami surges were in the 3.6 to 4.4 m/s in some locations based on the transport of large boulders.

❑ The December 2004 tsunami in the Seychelles provides an instructive example of tsunami interaction with an island group on a shallow shelf and further bathymetric modification of the wave in shallow water. The data collected for this report may be useful in further studies, including tsunami wave modeling.

❑ It is evident that important progress in reducing the impact of future tsunamis could result from adoption of appropriate coastal management practices, in particular recognizing the vital role of natural coastal features such as berms and mangroves in creating a buffer against storm and tsunami waves.

Frontispiece: East-coast road looking north toward Anse Royale, Mahé, showing high-relief coast in granitic rocks, with massive granite blocks in foreground and sandy beach with wide fringing reef platform beyond. Photo: DLF (GSC), 2 Feb 2005.

CONTENTS

INTRODUCTION

The magnitude 9.0 earthquake that occurred off the west coast of northern Sumatra on Sunday, December 26, 2004 at 00:58:47 UTC (Park et al., 2005) touched off a tsunami that killed more than 200,000 people. This extraordinary disaster far outstripped the devastating impacts of the 1883 Krakatoa volcanic explosion off the coast of Java, which caused more that 38,000 deaths, most as a result of the associated tsunami waves (Abercromby et al., 1888; Winchester, 2003). In addition to the humanitarian response triggered by the December 2004 tsunami disaster, an international scientific effort was launched to document the tsunami and its effects.

Immediately following the earthquake, the International Tsunami Society (ITS) contacted tsunami specialists around the world to assist with the coordination of scientific response to the disaster. ITS contacted Natural Resources Canada (NRCan) to determine whether we were sending a post-tsunami disaster response team to the affected region. Following approval for this response from the Assistant Deputy Minister of the Earth Sciences Sector of NRCan, a team of several specialists was identified and began immediate preparations to join the international science efforts. Site selection was coordinated by the International Tsunami Information Center (ITIC) in Hawaii and the Intergovernmental Oceanographic Commission (IOC) of UNESCO to comply with international directives and protocol. Various destinations were initially proposed, but eventually the team focused on the Seychelles Islands at the request of UNESCO, to complement information collected from other areas in the Indian Ocean.

The Canada-UNESCO Indian Ocean Tsunami Expedition departed Canada on the evening of January 19 2005 and assembled in London. The team continued via Paris and landed on the island of Mahé in the Republic of Seychelles on the morning of Saturday, January 22nd. Consultation with Seychelles authorities and field surveys on Mahé began immediately and continued for seven days. On the morning of Friday, January 28th, the team traveled by sea from Mahé to the island of Praslin, where surveys were conducted over three days. The field party returned to Mahé on the evening of Sunday, January 30th. One member of the team departed on January 31st and the others continued field surveys and additional consultations for another three days, departing for Paris and London on Thursday, February 3rd. One team member continued the next day to Canada, while two remained in London to conduct additional archival research, returning to Canada on Saturday, February 5th.

Members of the field team were Lionel Jackson (team leader), Donald Forbes, Vaughn Barrie and John Shaw. Gavin Manson prepared remote sensing data prior to departure, with assistance from other staff, and processed GIS vector and image data on the team’s return. Michael Schmidt advised on the selection of GPS equipment and undertook data processing as the GPS data became available. Other contributions by GSC colleagues and others are noted in the acknowledgements section.

THE TSUNAMI OF DECEMBER 26 2004

Tsunamis are waves that develop when an earthquake causes deformation of the sea floor. Tsunami waves propagate away from the source at speeds that vary as the square root of water depth. Thus, they travel faster in deep water. As a tsunami wave moves into less deep water on a continental slope and shelf, the wave speed decreases and the amplitude increases. The wave crest (with a greater water depth) maintains a higher speed than the trough (with a lesser water depth), leading to steepening of the leading wave. Contrary to popular belief, most tsunamis do not result in giant breaking waves. Rather, they approach the shore like strong, fast tides. Much of the damage inflicted by tsunamis is caused by strong currents and floating debris.

A tsunami can have a wavelength in excess of 100 km and period on the order of one hour. As a result of their long wavelengths, tsunamis behave as shallow-water waves. A wave becomes a shallow-water wave when the ratio between the water depth and the wavelength is small. Commonly, ocean waves 'feel' the bottom in depths equal to about one quarter of the wavelength. Wave crests bend as the tsunami travels into shallower water, a phenomenon called refraction. Wave refraction is caused by variations in wave speed as the water depth along the crest varies. Wave shoaling and refraction played an important role in determining the extent of impacts on the granitic islands of the Seychelles archipelago because they are located on a shallow shelf surrounded by deep water. On the other hand, many of the out-lying islands of the Seychelles archipelago were not severely affected, despite their low relief, because they form the upper parts of seamounts rising from abyssal depths and there was little opportunity for shoaling of the tsunami waves.

The tsunami waves generated by the earthquake on December 26 2004 spread away from the earthquake source in all directions. The waves were triggered by seafloor deformation along a fault extending several hundred kilometres from the epicentre off the west coast of Sumatra to the northern end of the Andaman Islands. Waves moving east soon made landfall on the coastlines of Indonesia Thailand and Malaysia and thus did not continue eastwards towards the China Sea and other parts of the Pacific Ocean. Waves moving toward the west, on the other hand, traveled long distances. The wave propagation pattern can be seen in the various model animations that have appeared since the event.

The animation on the National Oceanic and Atmospheric Administration (NOAA) web site (www.ngdc.noaa.gov/spotlight/tsunami/tsunami.html) shows the wave train propagating west and experiencing refraction when encountering the Maldives, the Chagos Islands, then Mauritius, Réunion, Seychelles, and finally eastern Africa. As the wave train approached Seychelles it was refracted by the seafloor plateau surrounding the granitic islands, such that wave trains traveling north and south met in the lee of Mahé. This is of critical importance to the understanding the tsunamis impact in the Republic of Seychelles.

The global wave animation at the same site records the continued travel of the waves south of Africa into the south Atlantic and beyond. A train of waves entered the Pacific from the east, encountering waves moving east from the southwest Pacific Ocean. Other waves continued into the North Atlantic and were registered by the Halifax, Nova Scotia, Canada tide gauge. The first wave at Halifax had a height of 0.43 m, a period of 45 minutes, and a travel time of 31.5 hours (www-sci.pac.dfo-mpo.gc.ca/osap/projects/tsunami/tsunamiasia_e.htm). On the Pacific, the first wave was recorded on the west coast of Vancouver Island with a height of 21 cm, a period of 42 minutes, and a travel time of 35 hours. For Seychelles, the Boxing Day tsunami velocity computes as 615 km/hr (travel time 7.16 hours). This compares well with the Royal Society figure for the velocity of the Krakatoa Tsunami (621 km/hr) (Abercromby et al., 1888).

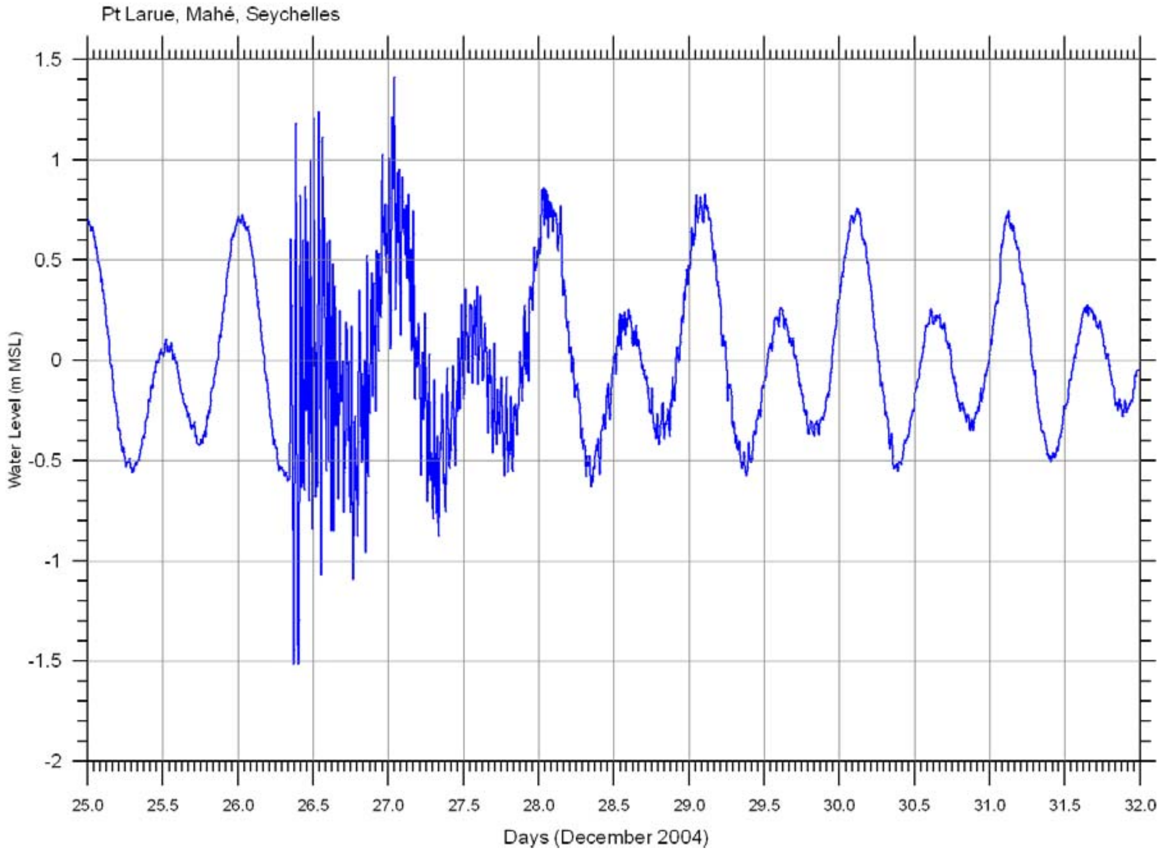

Fig. 1: The 4-minute water-level record from the tide gauge at Mahé (Seychelles), showing the arrival of the tsunami wave train and ongoing oscillations over several days (data courtesy of SOEST, University of Hawaii).

Other web sites display the tsunami travel times as derived from numerical model simulations. The site for the Japan National Institute of Advanced Industrial Science and Technology (http://staff.aist.go.jp/kenji.satake/Sumatra-E.html) shows the waves reaching the Seychelles about 6 hours after the quake, at about 11:00 local time (07:00 UTC).

The tide gauge at Point Larue, at Seychelles International Airport, Mahé, recorded the event beginning between 08:08 and 08:12 UTC (between 12:08 and 12:12 local time). The record (Fig. 1), with a sampling interval of 4 minutes, shows a rapid water-level increase to 0.59 m above mean sea level datum [MSLD] (1.55 m above tide-staff zero or 1.63 m Chart Datum), a level lower than the previous high tide, followed by a minor trough and lower peak, then a drop to -1.53 m MSLD (-0.57 m on the tide staff) at 08.56 ± 2 minutes UTC. The first high wave arrived at 09:12 ± 2 minutes UTC and peaked (on the 4-minute water-level record) at 1.16 m MSLD (2.13 m above tide-staff zero). The water level then continued to oscillate with decreasing amplitude over the next few days (Fig. 2). Both at 09:36 and at 09:40 UTC, a water level of -1.53 m MWL datum was again recorded on the gauge. This was 0.57 m below the tidal-staff zero and is approximately the base of the stilling well (Shikiko Nakahara, SOEST Hawaii, personal communication, 2005). Therefore we believe that the gauge was not registering the maximum drop in water level during the first two deep troughs of the wave train (Fig. 1).

This interpretation is supported by reports from two experienced local dive-masters that water level during the initial drop was very low. Mr. Charles Savy, operating from Port Victoria, claimed that the water level on his sounder was "3.5 m below the lowest tides he had ever seen." Mr. Arnaud Vanacore, based at the Paradise Sun Hotel, Anse Volbert on Praslin, claimed that the water level was 2.5 to 3.0 m below a 'normal sea level' (sic). Mr. Selvan Pillay, Seychelles Meteorological Office, stated in an e-mail dated 8 February 2005 that "the gauge could not have been able to measure the lowest water level during the tsunami period … because the water rushed out completely, leaving the wells completely dry." This statement is consistent with the observations of the two witnesses (above) and we conclude that the water level early in the event dropped to lower than -1.53 m MSLD and possibly as low as 3.5 m below low water at large tides (approximately 4 m below mean sea level).

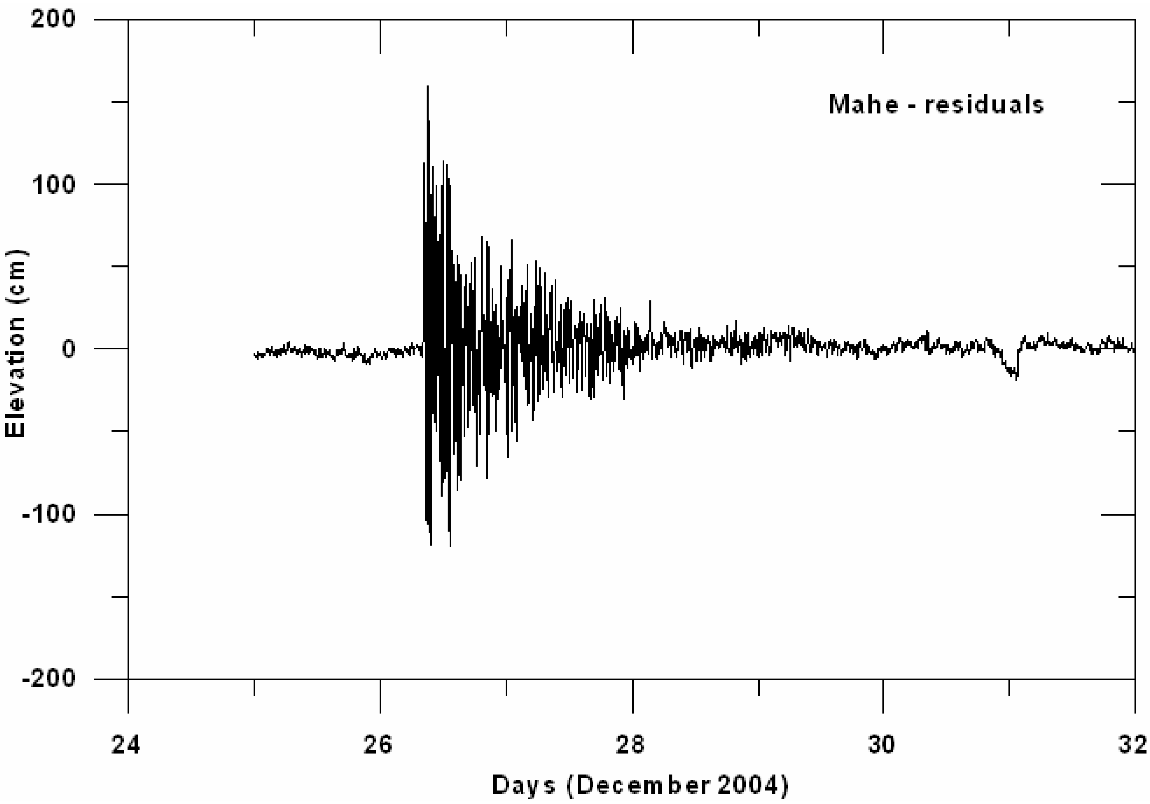

Fig. 2: Residuals from the tide gauge at Mahé (data courtesy of SOEST, University of Hawaii). Note the typical series of water-level oscillations, with the amplitude decaying through time. Although the oscillations ceased by January 29, locals claimed that the tides had been changed.

Another interesting aspect of the record is that it shows an initial water-level rise, followed by a rapid fall to a very low level. This is consistent with the observations of only two witnesses, both of who we considered to be reliable. One was an experienced fisherman, who was on the beach as the event started; the other was a dive-master on Praslin, who was also at the beach throughout the event. Interestingly, a seismologist who observed the tsunami arrival on a beach in Sri Lanka noted that the initial event there was a rise to just above the normal high-tide level (Chapman, 2005).

Many informants claimed that the tides were not the same even a month later. In Anse Royale, Mahé, one person interviewed observed that tourists familiar with the area said that low tides were lower than before.

We are not sure how to assess these accounts, but there may be an element of truth if the tsunami reworked the seabed sediments such as to alter the bathymetry through to the intertidal zone.

Archival research indicated that besides the 1883 tsunami created by the catastrophic eruption of Krakatoa, another tsunami struck the island in 1883 (Estridge, 1883). This was almost certainly due to the great earthquake along a plate margin in the eastern Indian Ocean in that year (Zacharaisen et al., 1999).

THE SEYCHELLES ARCHIPELAGO

The Republic of Seychelles and the archipelago of the same name comprise some 155 islands lying in the western Indian Ocean north-northeast of Madagascar off the East African coast (Fig. 3). The northern group of islands is predominantly composed of Precambrian granitic rock. The remainder of the islands are scattered coral atolls that extend more than 1000 km to the southwest. Aldabra and the nearby island of Assumption, the most southwesterly islands in the Seychelles archipelago, lie just 300 km north of Madagascar. The granitic islands in the northern group are the subaerial parts of a micro-continent that was formed by rifting from Madagascar in the mid-Cretaceous (Collier et al., 2004). These islands sit on a broad (300 km x 150 km) continental shelf with water depths less than 200 m (Fig. 4). The many coral islands, on the other hand, have no such shelf (see Series DOS 604, Sheet Seychelles, published by the Government of the United Kingdom, Directorate of Overseas Surveys, 1983) and rise, in most cases, abruptly from abyssal depths.

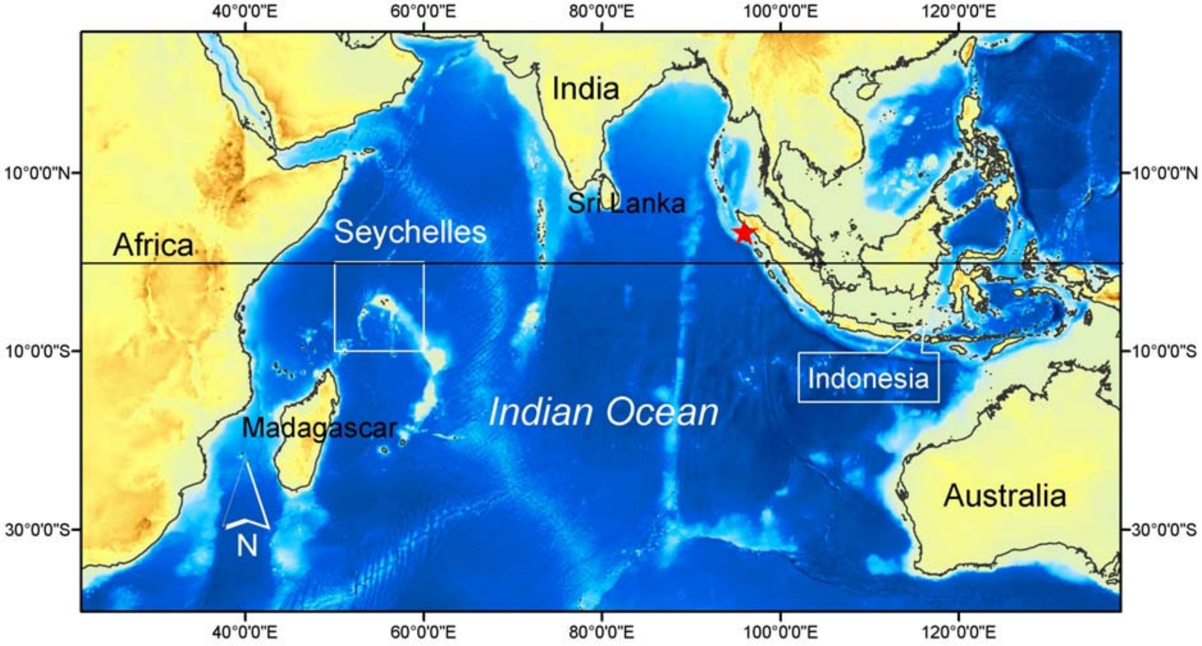

Fig. 3: Indian Ocean showing location of granitic islands of the Seychelles archipelago (in box). Red star shows the epicentre of the 26 December 2004 Sumatra earthquake. Westernmost islands of Seychelles, including Aldabra, lie outside lower left corner of box north of Madagascar.

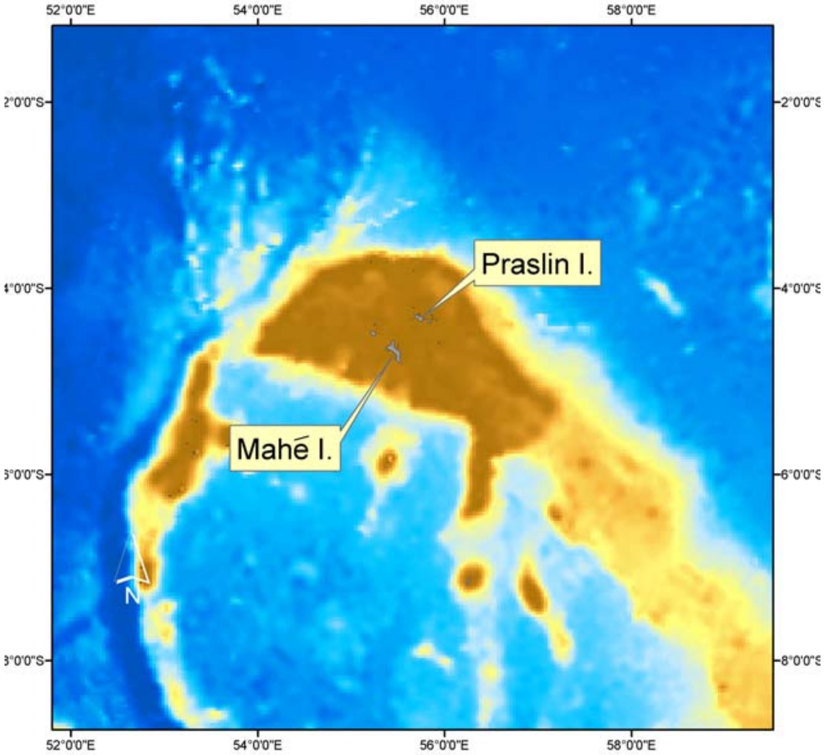

Fig. 4: Locations of the two largest granitic islands and bathymetry of Seychelles Bank, a continental fragment (Collier et al., 2004). Brown areas are <500 m depth.

FIELD OPERATIONS IN THE REPUBLIC OF SEYCHELLES

Investigation of the tsunami involved collection of eyewitness accounts and documentary evidence while carrying out field surveys of tsunami run-up and inundation at representative sites along the coasts of Mahé and Praslin (Fig. 4). Evidence was obtained through interviews with eyewitnesses (including written accounts) and collection of digital still photographs and video imagery, along with compilation of documentary material supplied by government officials and the Seychelles Broadcasting Corporation. Information on impacts in other parts of the Seychelles archipelago was provided through other contacts.

Field methods included surveys of shore-normal profiles from the reef flat landward to the limits of tsunami inundation. These surveys were carried out using a pair of graduated rods fabricated on-site, with a tape measure for distance and an ocean horizon (or hand level if a horizon was not available) to measure the change in elevation between successive points along the profile (modified method of Emery, 1961; see also Krause, 2004). Notes on the surface material, vegetation, tsunamic deposits, and other features relevant to interpretation of tsunami impacts were made along the profile.

The profiles were positioned using dual-frequency, geodetic quality, Global Positioning System (GPS) instrumentation. Raw GPS observables (code and carrier phase) were recorded in either static or kinematic mode as required. A minimum of one static point was established along most profiles; water-level reference points were also occupied with GPS at some sites where no profiles were surveyed. Simultaneous GPS observations were made at reference stations established to support the surveys. These were located at Anse Forbans during surveys on Mahé (AF01) and at the Praslin airport (meteorological station) during surveys on that island (PRA1). In most cases, the distance between the base station and the survey site was less than 15 km (usually much less). A few points on Mahé (specifically survey sites in and north of Victoria) were more distant, and for these surveys an intermediate base station (BMG5) was established at the airport. However, due to data overlap gaps, BMG5 was not used in the final processing. AF01 proved adequate for these northern sites. Quality checks in the field were followed by post-processing using two different methods.

The raw data from the newly established GPS reference stations were processed using the on-line Precise Point Positioning (PPP) service at the Geodetic Survey Division of Natural Resources Canada. PPP utilizes precise orbital products from the IGS (International GPS Service) to provide coordinates consistent with the International Terrestrial Reference Frame (ITRF-IGb00). The precision of the PPP service is nearly consistent with that of phase-differential GPS processing, but there is no requirement to collect GPS data simultaneously at a reference site. Therefore PPP is ideally suited for an application such as this survey, where it was difficult to locate stable and secure reference stations with established coordinate values. The coordinates, as determined by the PPP processing were subsequently used to constrain the reference station positions in the phase-differential processing carried out using Ashtech Solutions^{TM} version 2.7 software. This software permitted the processing of both static and kinematic data collected along the profiles. The GPS ellipsoid elevations (WGS-84) were converted to orthometric heights using the EGM96 geoid model in Ashtech Solutions^{TM} . Additional conversions were carried out using the on-line calculator at UNAVCO (http://sps.unavco.org/geoid/).

The GPS surveys were tied to surveyed control points on Mahé to determine the geoid undulation value appropriate for conversion to elevation above mean sea-level datum. The GPS surveys enabled the determination of elevations for the upper limits of inundation, as well as reference to the tide gauge during the tsunami event. Leveling data provided by the Seychelles Meteorological Service (Lands and Survey data) and by Shikiko Nakahara (SOEST, Hawaii) enabled us to determine the vertical offsets between tide-staff zero (TSZ, the datum for the water-level data), mean sea-level datum (MSLD, the vertical datum for land surveys), and Chart Datum (CD), as follows:

MSLD = TSZ + 0.97 m
TSZ = CD + 0.07 m
MSLD = CD + 1.04 m

GPS observations at TP4 (a tide-gauge reference pin set into the cap of the seawall on the north side of the tide-gauge jetty) and at BMG5 (a benchmark near the radiosonde facility) yielded a mean geoid undulation of -40.48 m) for conversion of elevations to MSLD (Table 1) for sites on Mahé. It is not known what vertical datum these existing survey points are referenced to. The mean geoidal undulation for this area derived using EGM96 Geoid Model is -41.175m, a difference of 0.695m.

Another control point, 1704, was established in 1998 on the glide-path at Seychelles International Airport, with an observed ITRF94 ellipsoid elevation of -38.21 m (MAPS geosystems, 1998). That project reported standard deviations of height ranging from 0.022 m to 0.029 m for the ITRF network on Mahé, Coétivy, Desroches, Assumption and Farquhar, using vectors between these five islands and to International GPS Service (IGS) stations at Diego Garcia, Mahé, and Malindi (Kenya). Holding the ITRF network points fixed, they then established control to the remaining islands, including Praslin, with standard deviations ranging from 0.030 m to 0.085 m in height. Our elevation for point 1704, based on a 30 min occupation, was -38.0113 ± 0.2498 m (2σ), referenced to the ITRF (IGb00) reference frame. For our surveys on Praslin, we were unable to relocate the 1998 control points because subsequent airport construction work destroyed them. Consequently, an autonomous control site was established and occupied over 2 days. Elevations were computed using the same approach adopted on Mahé, comparing EGM96 orthometric heights with elevations determined by reference to local sea level at the time of surveys.

DETAILED DESCRIPTIONS OF INVESTIGATED SITES ON MAHÉ ISLAND

This part of the report presents observations from 12 coastal sites on Mahé, the largest island in the granitic group and the largest in the Seychelles. This is where the majority of the population of the Republic of Seychelles resides. It includes the largest communities, including the capital, Victoria, the major port for the nation, its international airport, most commercial and industrial activity, and a large proportion of tourism-oriented businesses and infrastructure. For each of the 12 sites, a cross-section shows local topography and documents the maximum flooding level. Zero (0) is mean sea level datum (MSLD). Local times are presented for events except where reference is made to the tide gage (Fig. 1). Local time is UTC plus 4 hours.

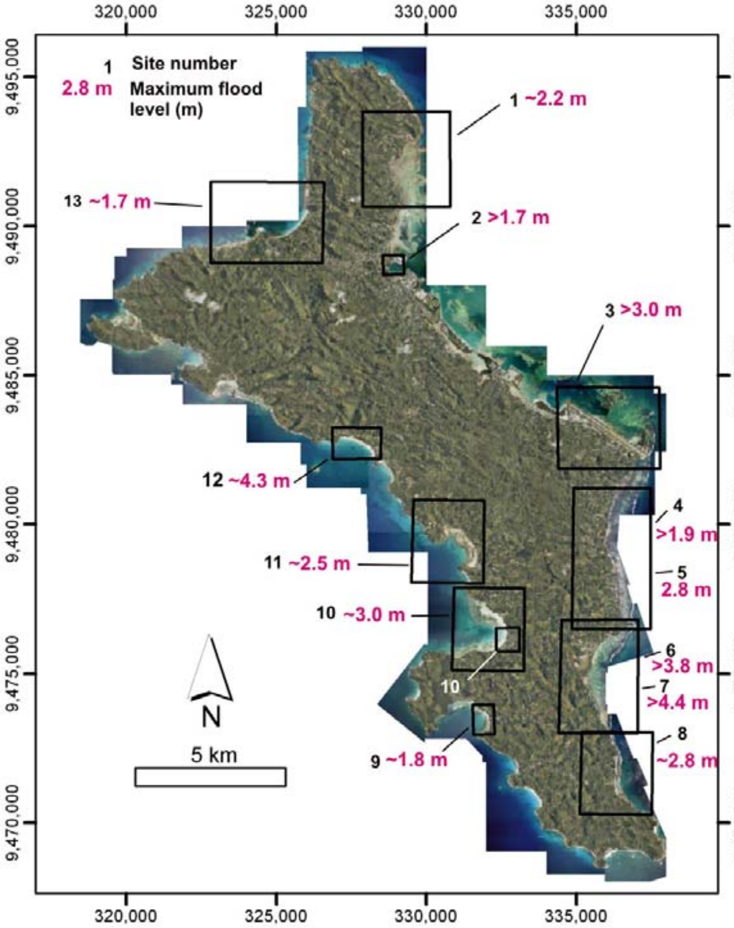

Fig. 5: Orthophoto mosaic of Mahé Island. Boxes show the locations of detailed imagery in other figures in the report. Location numbers in black. The red numbers refer to the maximum water levels above mean sea level at each location (see Table 2). The map labels refer to UTM co-ordinates. This and all other orthophotos are in UTM Zone 40S. Source of mosaic: Ministry of Land Use and Habitat, Republic of Seychelles (courtesy Francis Coeur de Lion, Director, GIS, MLUH).

Data for GPS static sites occupied on Mahé during this study are shown in Table 1. The table shows multiple occupations at several sites as a basis for estimating the vertical precision and accuracy. Differences between GPS ellipsoidal elevations and surveyed elevations tied to control (Lands and

Surveys data for TP4 and BMG5) were used to derive the geoid undulation applied to the other sites and show a precision of better than ±0.1 m. Differences between GPS derived orthometric elevations (derived by applying the mean undulation as described above) and surveyed elevations derived from water levels tied to the Mahé tide-gauge record (all z_{MSL} reported to the centimetre level) range from -0.39 m to +0.59 m, within ±0.4 m excluding the one large positive value. Part of this difference is attributable to tidal variations in water level between the tide gauge and the survey sites, part to error in the value of the geoid undulation, part to survey errors in the field, and part to errors in the GPS data and analysis. This data is preliminary and subject to change following further analysis

Table 1: Subset of GPS sites on Mahé: pre-existing survey elevations (z_{MSL}), ellipsoidal elevations (GPS_E), and estimated orthometric elevations (GPS_{MSL}). Survey elevations (z_{MSL}), for TP45 and BMG5 from Lands and Surveys; others are based on tidal data.

point	**date**	**site**	**location**	**z_{MSL}**	**GPS_E**	**s_E**	**GPS_{MSL}**	**$2s_{MSL}$**	**GPS_{MSL} EGM96**
	dd-mm-yy		**(comments)**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**
NEP2	01-02-05	1	NE Pt (1)	n/a	-38.478	0.105	2.003	0.210	2.844
VA20	31-01-05	1	NE Pt (1)	n/a	-38.246	0.022	2.235	0.043	3.064
VA01	27-01-05	2	Victoria (2)	n/a	-39.041	0.175	1.440	0.349	2.199
VA02	27-01-05	2	Victoria (3)	n/a	-38.682	0.016	1.799	0.031	2.558
VA11	31-01-05	2	Victoria (3)	n/a	-38.522	0.027	1.959	0.053	2.718
VA03	27-01-05	2	Victoria (4)	n/a	-38.583	0.029	1.898	0.057	2.661
VA12	31-01-05	2	Victoria (4)	n/a	-38.487	0.024	1.994	0.047	2.757
VA04	27-01-05	2	Victoria (5)	n/a	-38.700	0.027	1.781	0.053	2.545
VA13	31-01-05	2	Victoria (5)	n/a	-38.485	0.031	1.996	0.061	2.760
VA05	27-01-05	2	Victoria (6)	n/a	-38.755	0.032	1.726	0.063	2.494
VA15	31-01-05	2	Victoria (6)	n/a	-38.604	0.022	1.877	0.043	2.645
TP45	25-01-05	3	SEZ airport (7)	1.374	-39.165	0.007	1.315	0.015	2.102
BMG5	25-01-05	3	SEZ airport (8)	1.268	-39.130	0.020	1.350	0.041	2.136
BMG5	27-01-05	3	SEZ airport (8)	1.268	-39.120	0.019	1.361	0.038	2.146
BMG5	31-01-05	3	SEZ airport (8)	1.268	-39.125	0.020	1.355	0.040	2.113
BMG5	01-02-05	3	SEZ airport (8)	1.268	-39.212	0.025	1.268	0.049	2.054
1704	27-01-05	3	SEZ airport (9)	n/a	-37.893	0.119	2.587	0.237	3.369
ARN1	01-02-05	6	Anse Royale N (10)	2.23	-37.960	0.007	2.521	0.014	3.198
ARS1	01-02-05	7	Anse Royale S (11)	2.56	-38.312	0.004	2.169	0.008	2.827
AF1B	24-01-05	8	Anse Forbans (12)	2.18	-38.518	0.000	1.963	0.000	2.589
AF1C	24-01-05	8	Anse Forbans (13)	2.61	-38.123	0.002	2.358	0.004	2.984
AF2B	24-01-05	8	Anse Forbans (14)	2.13	-38.473	0.002	2.008	0.004	2.634
AF2C	24-01-05	8	Anse Forbans	2.53	-38.123	0.002	2.358	0.004	2.984
AM01	26-01-05	10	Anse à la Mouche (16)	1.79	-39.080	0.006	1.401	0.012	2.051
CAN1	01-02-05	10	Anse à la Mouche (17)	n/a	-37.995	0.014	2.486	0.028	3.144
BOWL	26-01-05	11	Anse Boileau (18)	2.44	-37.449	0.163	3.031	0.326	3.719
GA01	26-01-05	12	Grande Anse (19)	4.24	-36.296	0.027	4.185	0.054	4.862
GA2X	26-01-05	12	Grande Anse (20)	n/a	-34.980	0.045	5.501	0.090	6.180

Comments: 1. Playing field; 2. Clock tower; 3. Independence Ave 1 w CT 4. Independence Ave wRAB; 5. Independence Ave eRAB; 6. SFA; 7. TP4 jetty seawall cap; 8. BMG5 radiosonde garden; 9. south end glide path; 10. mon by petrol station; 11. by road on berm; 12. AF1B on line 1; 13. AF1C on line 1; 14. AF2B on line 2; 15. AF2C on line 2; 16. AM01 along fence; 17. debris line Les Cannelles; 18. top of wall; 19. crest of beach ridge; 20. run-up limit on beach. NB: GPS_{MSL} EGM96 Heights for NEP2,TP45,BMG5,1704,BOWL calculated using on-line EGM96 calculator at UNAVCO (http://sps.unavco.org/geoid/); all other GPS_{MSL} EGM96 Heights calculated using Ashtech Solutions^{TM}.

Table 2 presents a summary of maximum flooding (water) levels and estimates of the maximum distance inland of flood penetration for 12 sites around the coast of Mahé. Where more than one elevation value is given, the first is an estimate of the highest water level near the shoreline and the second is an estimate of wave run-up or highest inundation level some distance landward from the shore. Both are with respect to MSLD. Maximum flood level data is preliminary and subject to change following further analysis of GPS survey data.

Table 2: Summary of investigations on Mahé Island (see text for detailed information on individual sites)

Site	Name	Latitude	Longitude	Max flood level (MSLD)[1]	Distance inland[2]
1	Northeast Point	04°35.087' S	55° 27.749'E	~2.2 m	~100 m
2	Victoria downtown core and inner harbour	04° 37.395' S	55° 27.522' E	>1.7 m >1.4 m	>200 m
3	Seychelles International Airport	04° 40.925' S	55° 31.974' E	>3.0 m	~200 m
4	Anse aux Pins – Casuarina Hotel	04° 42.217’ S	55° 31.303’ E	>1.9 m	>50 m
5	Pointe au Sel – Fairyland Hotel	04° 43.874’ S	55° 31.492’ E	2.8 m 2.3 m	<35 m
6	Anse Royale north – Seychelles Petroleum petrol station and Kaz Kreole Restaurant	04° 31.247’ S	55° 31.118’ E	>3.8 m ~3.0 m	>100 m
7	Anse Royale south – across main road	04° 45.120’ S	55° 30.925’ E	>4.4 m	>45 m
8	Anse Forbans – Chalets d’Anse Forbans	04° 46.839' S	55° 31.397' E	~2.8 m	~20 m
9	Baie Lazare – Anse Gaulettes	04° 44.479’ S	55° 29.220’ E	~1.6 m	~20 m
10	Anse à la Mouche – Anchor Café and numerous residences	04° 44.376’ S	55° 29.419’ E	~3.0 m (3.5 m)[3] ~2.5 m	250 m
11	Anse Boileau – Sheila Shop	04° 42.377’ S	55° 28.734’ E	~2. 5 m	53 m
12	Grand Anse	04° 40.586 S	55° 26.631 E	~4.3 m	~0 m
13	Beau Vallon	04° 36.514' S	55° 25.897 E	~1.7 m	~10 m

[1] Estimated wave run-up at coast and (where more than one value) near limit of penetration.
[2] Run-up distance defined from top of beach.
[3] Height of wave surge damage at Anchor Café.

Site 1: Northeast Pointe

Location: Area immediately west of Northeast Pointe on the east coast of the northern peninsula of Mahé (04°35.087'S, 55°27.749'E), approximately 4 km north of the town centre of Victoria.

Environment: The shoreline has been extended from a natural rocky coastline through artificial fill of a former mangrove swamp or back reef shallows that were extensive along this part of Mahé. The coast here is open to the Indian Ocean to the east but largely protected behind an extensive area of recent artificial fill across the narrow channel.

Fig. 6: Boat tied to goalpost on soccer field at Northeast Point. Grass in foreground is flattened and strewn with fine marine organic debris. Photo: DLF (GSC), 23 Jan 2005.

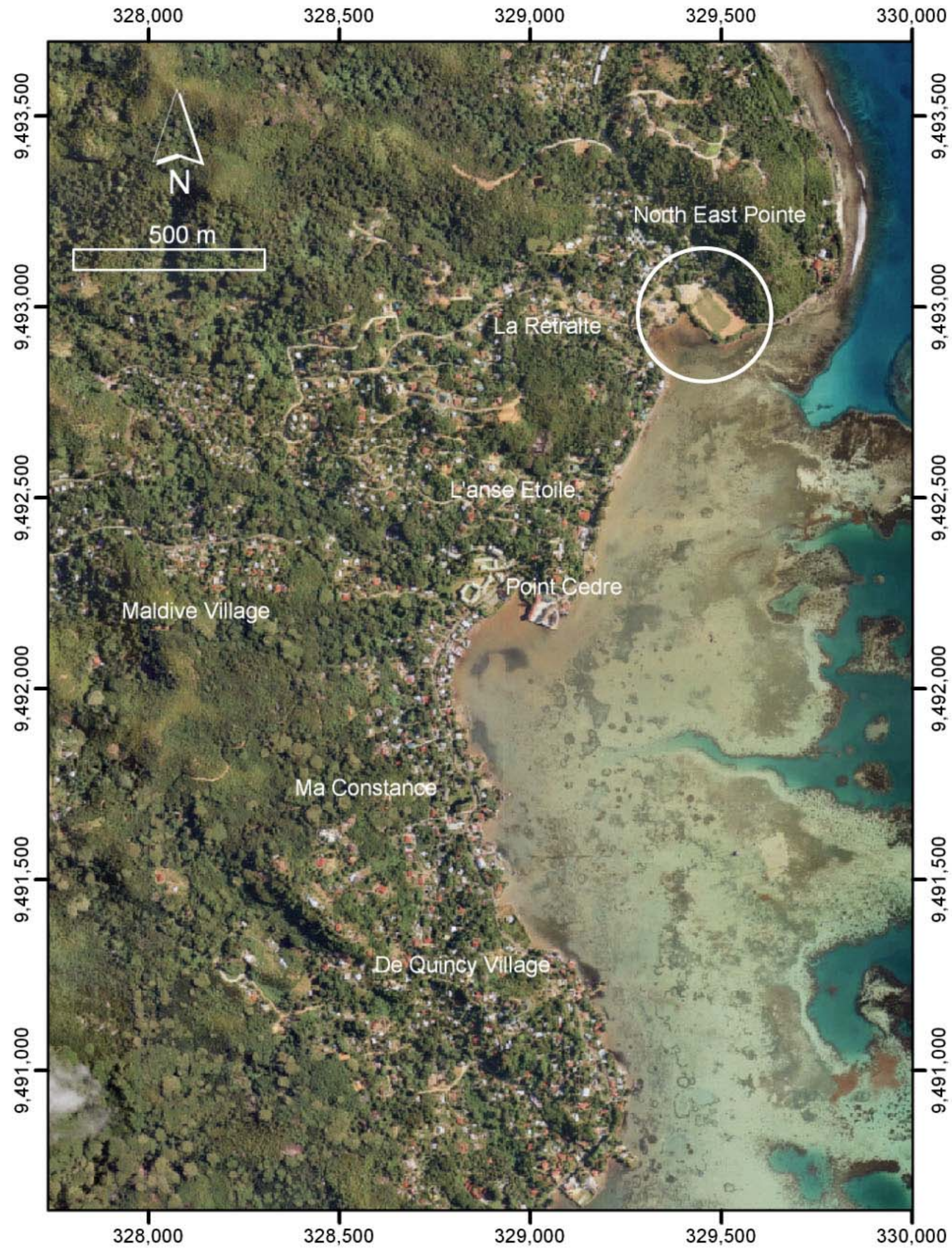

Fig. 7: Location of Northeast Pointe, on the northeast coast of Mahé. The elevation data were collected on the soccer field - the pale green rectangle immediately below the place name of Northeast Pointe. Since this photography was taken, extensive land reclamation has taken place on the reef flat seaward of this coast, extending from the south end of the image all the way to Northeast Pointe. Much of the coast now lies behind a low-energy lagoon landward of the reclamation project, but the embayment on the south side of the soccer field remains open to the east.

Description: Although facing directly east, the tsunami only flooded the soccer pitch and did not reach the coastal road or businesses. A few homes on the coastal side of the road were slightly flooded with no structural damage. The property in the head of the cove just west of the playing field sustained the most damage in this area. Part of the seawall cap alongside the road to Victoria across the cove to the southwest was also destroyed. Witness Alan Bristol placed the tsunami arrival time between 11:30 and 12:00 noon local time, based on recollection from memory. We consider this estimate to be up to 40 minutes early, based on the tide-gauge record from the airport. The tide was observed to rush out then rush in. Local fishermen fought to pull their boats above the flood so that they would not be battered and pulled out to sea with the draining of the tsunami waters. The distance of travel of the tsunami inland was a few tens of metres to 100 m at the most, depending on local topography.

Damage: This site is notable as being close the location where a fisherman drowned during the course of the tsunami (one of two fatalities).

Maximum run-up level: Approximately 2.2 m MSLD. This was based on the upper limits of extensive plant debris on the soccer field.

Site 2: Victoria

Location: Urban core and inner harbour, Victoria, Mahé (04°37.395'S, 55°27.522'E).

Environment: Victoria developed initially on irregular terrain sloping down to the harbour on the northeast side of Mahé. A massive landslide triggered by heavy rain in 1862 buried part of the town and created an area of low-relief natural fill along the waterfront (Scarr, 2000). Much of the urban centre and harbour infrastructure has been subsequently constructed on this natural fill and additional areas of artificial fill along the waterfront. The landing along the north side of the inner harbour (Figs. 8 and 9) is about 1 m above normal high tide and much of the business district of Victoria is less than 2 m above normal high tide. This low relief area is prone to flooding in heavy rainfall, as occurred following the December 2004 tsunami in Mahé. A network of large-capacity open and covered storm drains exists parallel to all streets in the area and open channels carry runoff from the higher slopes inland.

Description: The waterfront and downtown core of Victoria were inundated beginning at approximately 13:00 (09:00 UTC on Figure 1) when the tide was low (Fig. 10) and again at approximately 16:30 to 17:00 local time by a tsunami wave coincident with high tide (Fig. 1, 12:30 to 13:00 UTC). The initial wave drove boats on shore and its impact was sufficient to topple concrete walls (Figs. 11, 12). Another period of flooding occurred at approximately 05:00 December 27. The airport tide gage recorded the highest water level during the December 26-27 tsunami event at this time (ca. 01:00 UTC on Figure 1). Floodwaters covered Independence Avenue and penetrated landward of the Clock Tower, a landmark in the center of Victoria, but did not reach the grounds of Government House.

Fig. 8: Aerial view of the Fishing Harbour, Port Victoria, Mahé. The white and black dashed lines indicate the approximate extent of severe fissuring on the wharves and in the waterfront park to the west. Independence House can be seen on the lower left side of the roundabout on the west side of the waterfront park.

Impacts and damage: The tsunami carried sediment from the harbour floor into the centre of town and deposited large amounts of this sediment in the storm-drain system. This resulted in impeded drainage and withdrawal of tsunami floodwater and later meteorological floodwaters from the city.

Our attention was drawn initially to structural damage along the waterfront (Figs. 8-15) in an interview with Rondolph Payet, Executive Director of the Seychelles Fisheries Authority. Much of the following description is based on a rapid survey of the damaged harbour area and interviews with Charles Poole, a civil engineer and Mahé resident who has studied the damage and submitted recommendations for remediation to the port authorities.

The north side of the inner harbour basin was created over the years by a series of artificial fills. New fills expanded the docking facility southward into the harbour in 1989 and 1999-2000. The wall of the fill (dock face) consists of sheet piles that are laterally braced by an anchor wall or piles that run parallel to sheet piles 10 to 12 m north (landward) of the dock face and are buried within the fill. The sheet piles are connected to the anchor structures by 32 mm rods at approximately 1.2 m spacing. Flooding of the fill along the north side of the inner basin in the area of the fishing port was followed by rapid drawdown as the first large wave withdrew. This, or subsequent wave inundations and withdrawals later in that day and early the next day caused displacement of the sheet piles and of the anchor walls or failure of the anchor rods along 200 m of the waterfront in post 1989 fills and older fills that underlie a park to the east (Figs. 13-15). The high pore pressures in the fill generated by submergence followed by rapid drawdown of water levels in the harbour turned the sheet pile wall into a dam. The loss of shear strength within the fill permitted the displacement and failure of the anchor structures and movement of the sheet pile wall seaward. Surface fissuring marks the displacement of the anchor wall or piles. It is not known when the initial failure of the fill structure occurred. It may have happened as a result of the initial inundation and rapid drawdown with each additional cycle compounding the damage. These failures are among the costliest and perhaps least expected impacts to infrastructure resulting from the tsunami in Seychelles.

Fig. 9: Oblique aerial (looking south) view of the fishing harbour, from the north, 26 Dec 2004, during a low-water phase. The exact time of this photograph is not known, but the walls and paving on the fishing dock remain intact at this time. A fishing boat lies on its side to the left of the large white warehouse at lower left and some of the failure of the dock in that area may already have occurred. Photo courtesy of Dan Holtzhanse.

Fig. 10: Oblique aerial view of the fishing harbour on 26 Dec 2004 during a flooding phase. The buildings, including the Seychelles Fisheries Authority at left, are easily recognizable in the preceding figure. Photo courtesy of Dan Holtzhanse.

Fig. 11: Concrete wall toppled by the force of the tsunami, inner harbour, Victoria. Photo: LEJ (GSC), 25 Jan 2005.

Maximum flood level: Much of the industrial and commercial areas of Victoria were flooded. Pier facilities were inundated by at least 1 m of water several times. GPS measurements along Independence Avenue in Victoria suggest water levels of at least 1.7 m MSLD.

Remarks: Engineers have recommended extensive excavation of the fill and construction of a new sheet pile wall in the area of damage. A similar failure in an older fill to the west has cut across an office building and adjacent paved parking lot and extended approximately 50 m west into the waterfront park, parallel to a stone seawall that showed no evidence of structural damage.

Fig. 12: Boat carried on to a dock by the tsunami, inner harbour, Victoria. Photo by Stephen and Liz Englert, 26 Dec 2004.

Figure 13: Tensional cracking due to movement of sheet piles toward the harbour. Repeated recession of floodwaters eroded a chasm beneath the offset concrete slab. Photo: DLF (GSC), 25 Jan 2005.

Fig. 14: Fissures created by dragging of anchor wall seaward. Adjacent sub-parallel cracks were caused by additional spreading of fill inboard of anchor wall (colour divisions on scale 10 cm). Photo: LEJ (GSC), 25 Jan 2005.

Fig. 15: Lateral spread failure intersecting building. Photo: DLF (GSC), 25 Jan 2005.

Site 3: Seychelles International Airport

Location: On east coast of Mahé south of Victoria (Fig. 16).

Environment: The airport is located on reclaimed land, and is composed of coralline rubble fill emplaced on a fringing reef, with a rubble mound revetment. The tide gauge is situated on the north side of a jetty that extends eastward onto the reef flat north near the southern end of the airport runway (Figs. 16 and 17).

Description: Coordinates for various parts of the airport were obtained by MAPS geosystems (1998). Elevations for the physical threshold at the southern end of the strip (Runway 31 threshold [310°]) and the northern end (Runway 13 threshold [130°]) are -37.61 m and -37.59 m, respectively. Applying our best estimate of the geoid undulation at this site, these correspond to orthometric elevations (relative to MSLD) of 2.87 m and 2.89 m. It was initially surprising to find that these elevations are equivalent because the flooding occurred primarily at the south end of the strip.

Damage: According to reports from officials in the Seychelles Weather Office, fish and coral debris were deposited over the first 200 m of the runway at the south end (Runway 31). Flooding covered half the width of the runway near the road crossing to the Met Service radiosonde facility and further along the side of runway in vicinity of the tide gauge jetty. Additional structural damage was sustained at the tide-gauge jetty as a result of a lateral spread failure (Fig. 17).

Fig. 16: Location of the international airport. GPS sites are circled.

Fig. 17: Tide-gauge stilling wells and staff, showing structural damage to the wharf at the outer end of the jetty. Photo: LEJ (GSC) [DLF camera], 25 Jan 2005.

Maximum flood level/maximum run up: We estimate maximum flood level to have been about 3.0 m MSLD based on the elevation of the runway threshold (see above) and the nature of the debris deposited at the south end of the strip.

Remarks: Debris was deposited on the runway by the first large wave shortly after 13:00 local time. Firefighters and others were immediately dispatched to clear the runway, as it could not be used until this material was removed. Because the runway thresholds are at the same elevation, it appears that the tsunami wave at the airport approached from the south.

Site 4: Anse aux Pins (Casuarina Hotel)

Location: East coast of Mahé south of the airport (04°42.217'S, 55°31.303'E).

Environment: This hotel is located on the beach front in Anse aux Pins (Fig. 19). Entering the hotel, one walks through the lobby, into the bar, and out to an area of tables set on the sand of the berm. All this is on the same level (Figs. 18 and 19).

Fig. 18: Casuarina Hotel from the sea, showing chairs on the berm, with hotel beyond. A very exposed location. Photo: JS (GSC), 25 Jan 2005.

Description: The manager, whom we interviewed, was in Victoria at the time of the tsunami. He had heard news of the tsunami from the Maldives. He drove to the hotel but was stopped by the broken bridge. He was not sure of the time at which he arrived at the hotel. Water had come over the low walls at the rear of the beach into the bar, lobby and other rooms through the main entrance to the road. The water reached about 0.5 m above the floor level. There was a layer of sand, water, and fish on the floor.

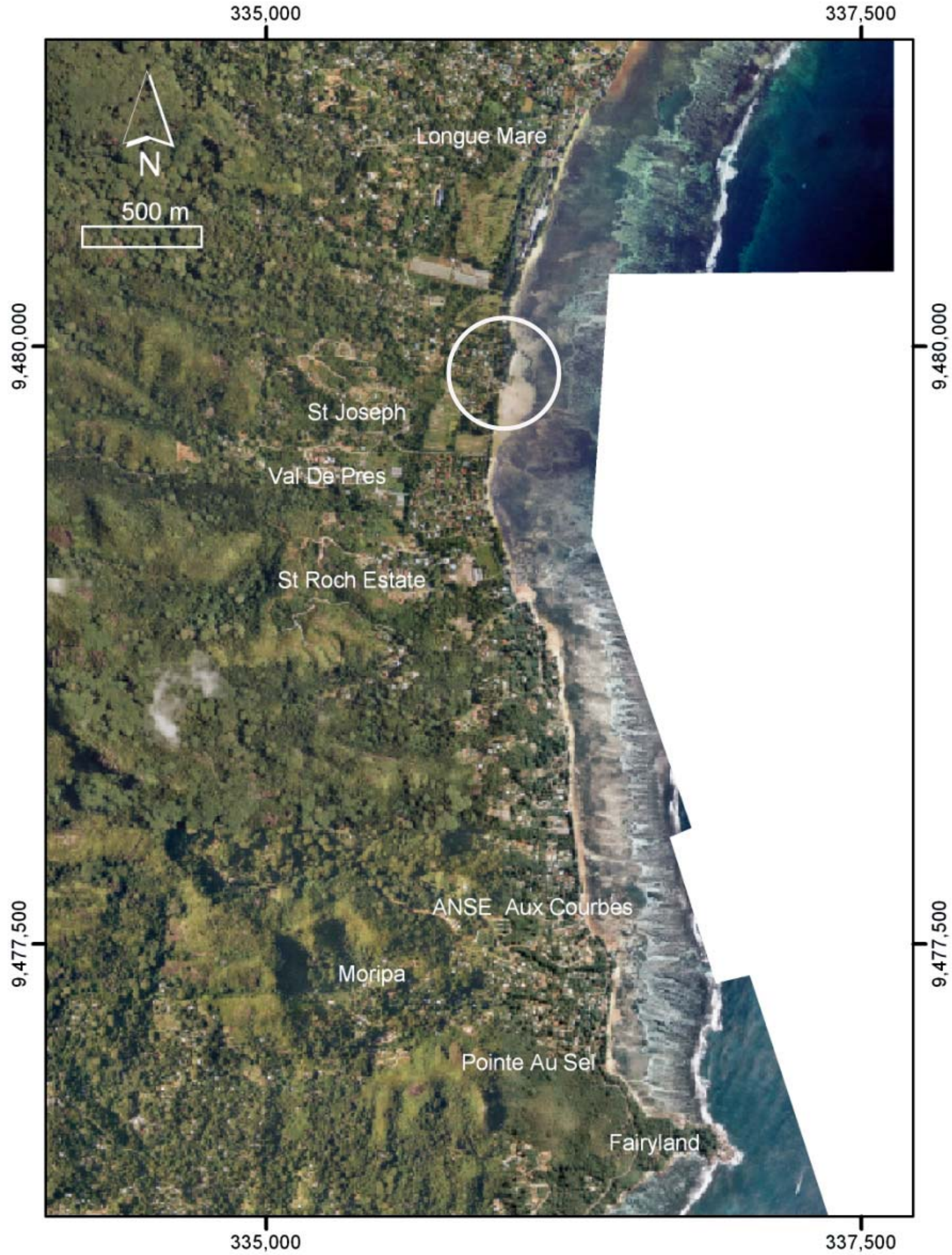

Fig. 19: Location of Casuarina Hotel in Anse aux Pins. Note the widening of the beach around the hotel, perhaps the effect of a groyne or groynes?

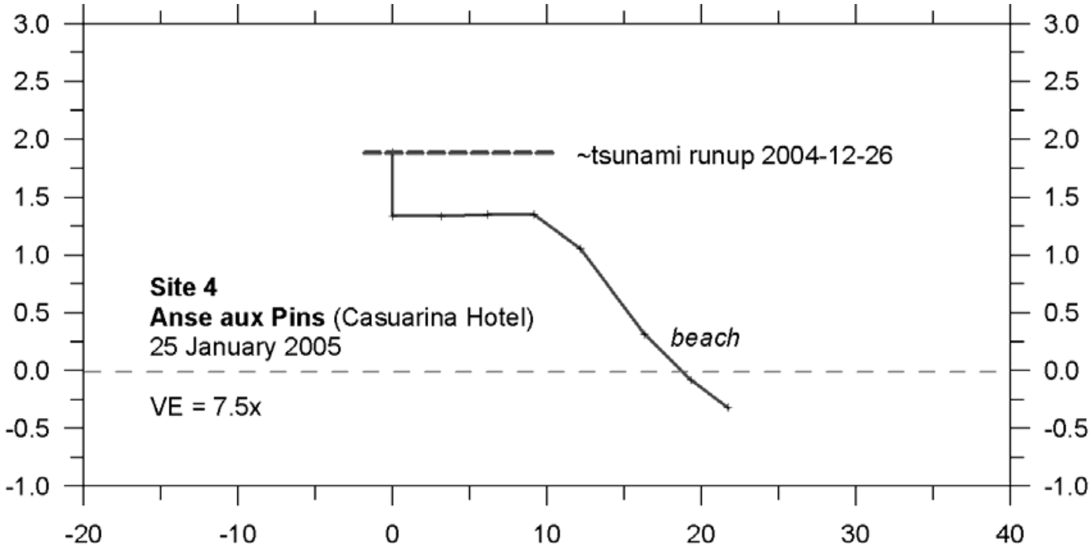

Fig. 20: Profile at Casuarina Hotel, 25 January 2005. Water level at 15:55 is the lowest value on the profile. The floor of the hotel is more or less at the same level as the flat sandy berm.

Damage: Minimal, mainly flood damage to computers and related equipment.

Maximum flood level: At least 1.9 m MSLD (Fig. 19).

Maximum run-up distance: Water reached the road but not beyond.

Remarks: This is one of several sites where, unfortunately, the natural coast has been modified (Figs. 18 and 19). The coastline is fixed and the hotel floor is at the same level as a rather low berm.

Site 5: Fairyland Hotel (Pointe aux Sel)

Location: Along the southeast coast of Mahé (04°43.874'S, 55°31.492'E).

Environment: The Fairyland Hotel site is located at the southern limit of a sandy beach abutting the granitic headline of Pointe au Sel, which rises abruptly to tens of metres above sea level immediately to the south (Figs. 19, 21, 22). The hotel and adjacent beach are sheltered by a coral reef about 250 m offshore, and by an outcrop of granite which is totally emergent at low tide directly seaward of the hotel. The beach has been modified to accommodate the hotel. A low beach berm was removed to facilitate construction and beach access (Figs. 23-26).

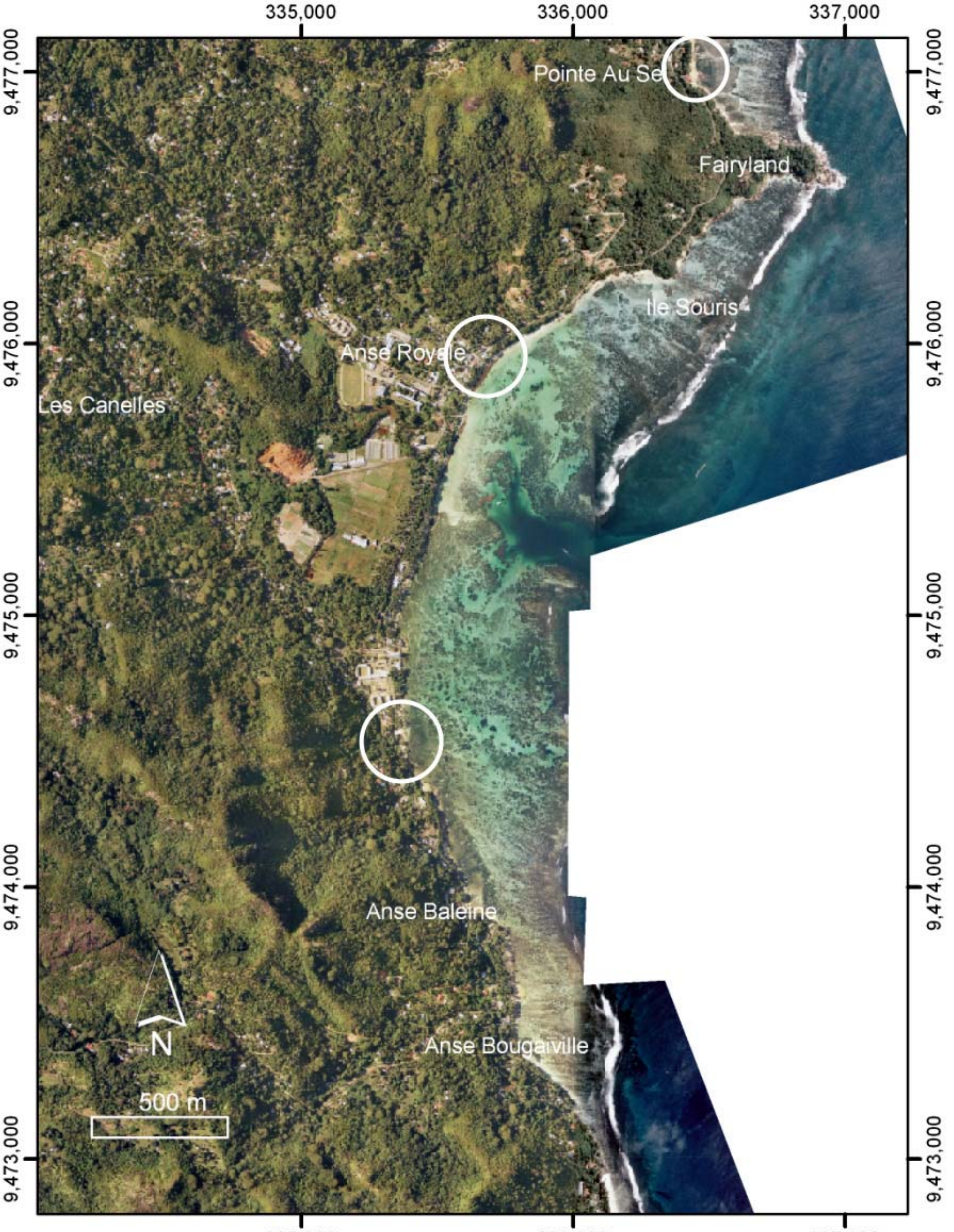

Fig. 21: The Anse Royale embayment showing the location of the Fairyland Hotel (circled at top), the Kaz Kreole Restaurant in the settlement of Anse Royale (centre circle), and the surveyed profile just south of the school at the south end of the embayment (bottom circle). The coast is characterized by a narrow sandy beach with limited sand supply located along the inner edge of a wide, shallow, reef flat.

Fig. 22: Enlarged view of the site of the Fairyland Hotel.

Description: The witnesses at Fairyland Hotel reported drainage of water from the bay at about 12:00 local time. They became aware of the first tsunami wave approaching minutes later when they heard the sound of rain but it was not raining. Three waves struck spaced about 15 minutes apart by their estimation, with extensive recession of the sea in between waves. The first two waves arrived from due east but the witnesses noted that the third wave arrived from the southeast. The third wave was the highest and most destructive, flooding the first level of the hotel, smashing doors, and destroying all electrical appliances. The surge of water beneath a wooden deck beside the hotel shoved planks loose from beneath and carried them inland.

Damage: Flood damage to hotel interior, electrical appliances, impact of wave detached wooden planks from exterior sun deck.

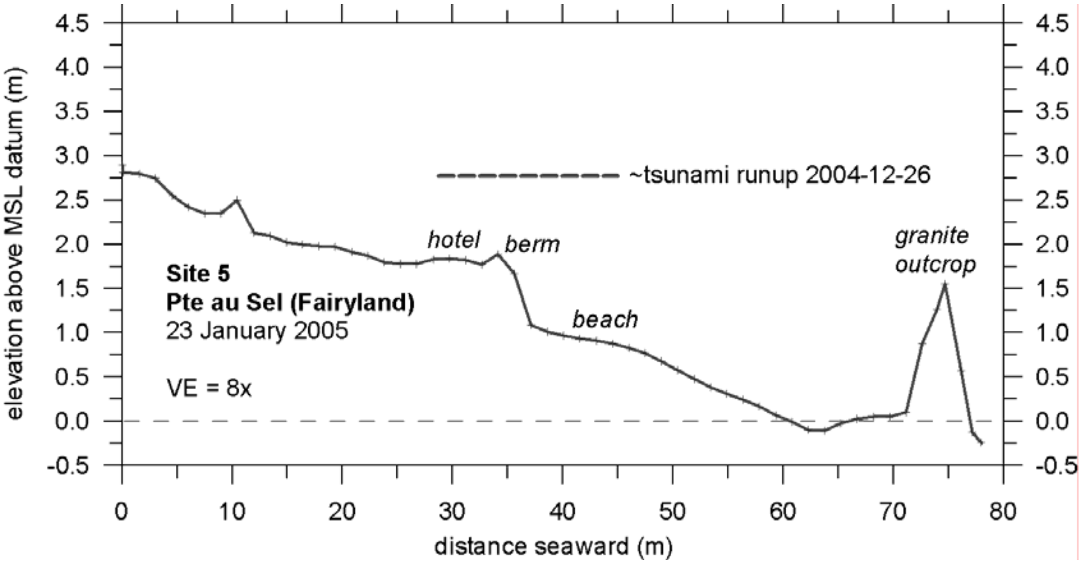

Fig. 23: Profile at Fairyland, from near top of driveway parallel to hotel on north side, out across beach, flats, and granite outcrop on reef flat.

Fig. 24: Fairyland Hotel. Highest tsunami water level reached to approximately the top of the railing along the first floor. Note the location of the building on the beach. A former beach berm has been removed and replaced by a low seawall. Photo: DLF (GSC), 24 Jan 2005. See also cover photo.

Fig. 25: View of approximately 3 m high bedrock outcrop from first level of Fairyland Hotel, showing drawdown between waves, 12:00-13:00, 26 Dec 2004. Photo by Giles Platt.

Fig. 26: Water rushing in within a few minutes of photograph above. Note turbidity in the usually crystal clear and azure waters of Seychelles. Highest water level at this site was level with the rail in foreground. Photo by Giles Platt.

Maximum run-up level: A survey of mud lines on buildings and upper limits of debris, as indicated by the hoteliers, indicate that the water rose to at least 2.8 m MSLD (Fig. 23). The water rapidly retreated following the third wave and there was no subsequent flooding.

Remarks: Adjacent properties immediately to the north suffered far less inundation and damage. It should be noted that these properties had unaltered beach berms that stood about 70 cm above the level of the highest beach deposits at Fairyland. This made a significant difference in the depth and extent of flooding of these areas.

Site 6: Anse Royale north

Location: Near the north end of the community of Anse Royale (04°31.247'S, 55°31.118'E).

Environment: Sandy beach at the Kaz Kreole Restaurant.

Description: This is the site of a restaurant located on the beach berm – or what remains of it – in Anse Royale (Fig. 21). The location is shown in detail on Fig. 27. An interview with a person working in the restaurant at the time of the tsunami revealed that December 26 was a normal Sunday, with customers in the restaurant, and with lunch soon to be served (at 12:00 local time). The interviewee said that the tide was very low and she noticed people running on the beach about 11:45. Water came to top of the beach berm, by the base of the coconut trees (Fig. 28). The water then dropped very low and coral was exposed, forming islands offshore. Then the water came back at ca. 12:45 in a wave described as very large and sounding ‘like a bomb’. It was very forceful and caused a lot of damage. The person interviewed ran away when the second wave came. Her colleague, who stayed behind, reported the waves reached the branches of the broad leaf tree beside the palms in Figure 28. Based upon this, the height of the wave is estimated to be about 2 m above the adjacent berm top. The water reached about 30 cm above the level of the bar in the restaurant. There was another wave at 16:00 but she had gone home by this time. She said there had been a radio warning and she heard that the wave had already hit Praslin.

Damage: The village of Anse Royale received significant damage, including damage to structures and flooded cars (cover photograph). A church was damaged and the petrol station was flooded, but sustained no additional damage. This was one of the sites where a life was lost, the person dying of injuries some days later. However, interviews with shopkeepers revealed that the water did not pass through closed and shuttered shops, suggesting that the flooding was short-lived. With the big wave, clients' cars floated away at the restaurant, the roof covering the beach seating area collapsed (Fig. 28), and the bar was damaged. The restaurant has been closed since. The restaurant floor was covered by 30 cm or more of sand, coral, and fish.

Maximum run-up level: We estimate a maximum run-up elevation of more than 3.8 m MSLD at the berm adjacent to the restaurant (Fig. 29) and a water level of about 3.0 m MSLD across the road at the petrol station. This latter level may represent standing water along the road behind the berm. The berm crest elevation is 2.7 m MSLD, indicating a water depth of more than 1 m during the maximum overtopping event.

Maximum run-up distance: Water crossed the road and went beyond it. In some parts of the area, the run-up distance varied from less than 50 m to possibly as much as 100 m or more inland from the beach berm.

Remarks: Although this was one of the worst-hit sites, it reflects a common pattern of damage to structures located directly on the beach with a reduced berm and no vegetative buffer.

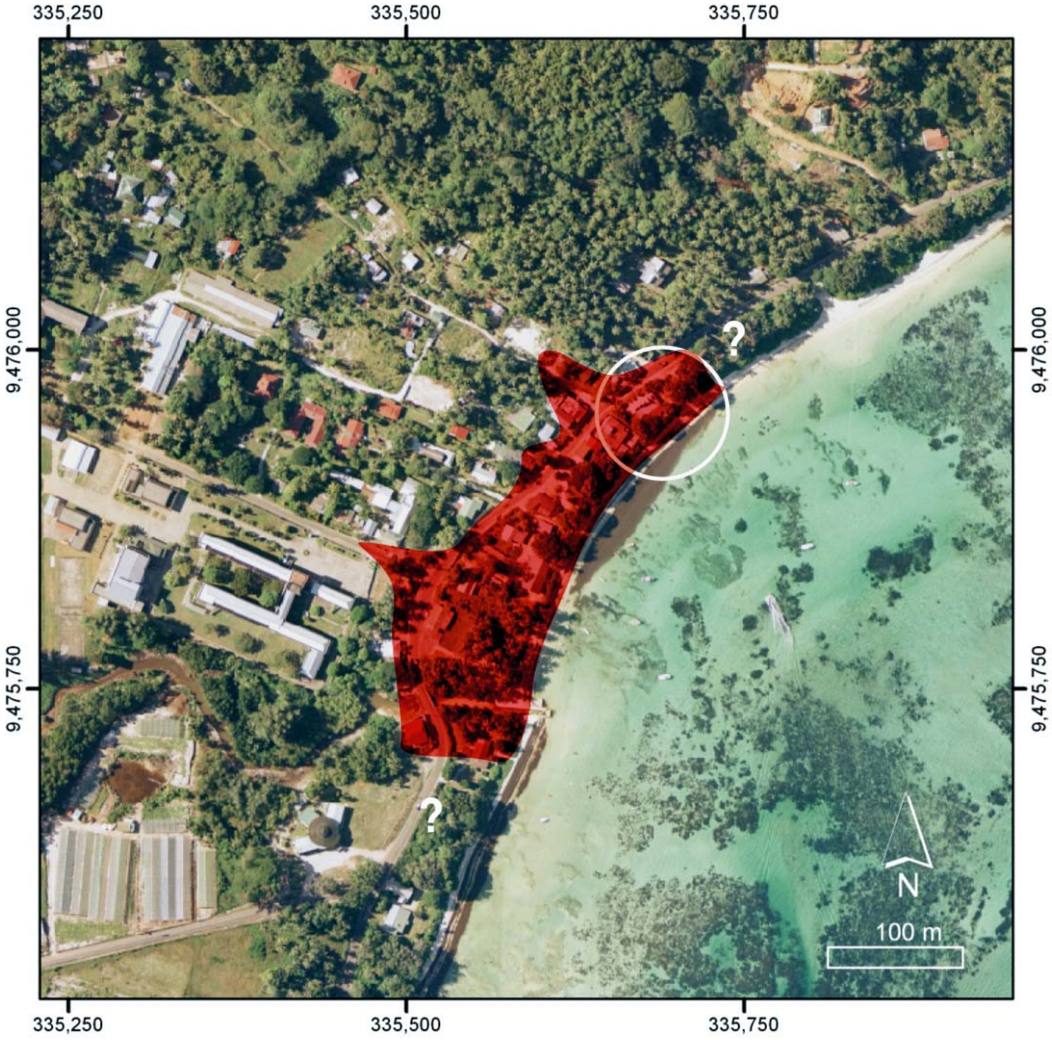

Fig. 27: Anse Royale. The Kaz Kreole restaurant location is shown by a circle. The limit of flooding in the village is approximated by the red shading. The northern and southern extensions of the flooded zone were not investigated.

Fig. 28: The exposed location of Kaz Kreole restaurant is shown here. Note collapsed roof. Photo: JS (GSC), 1 Feb 2005.

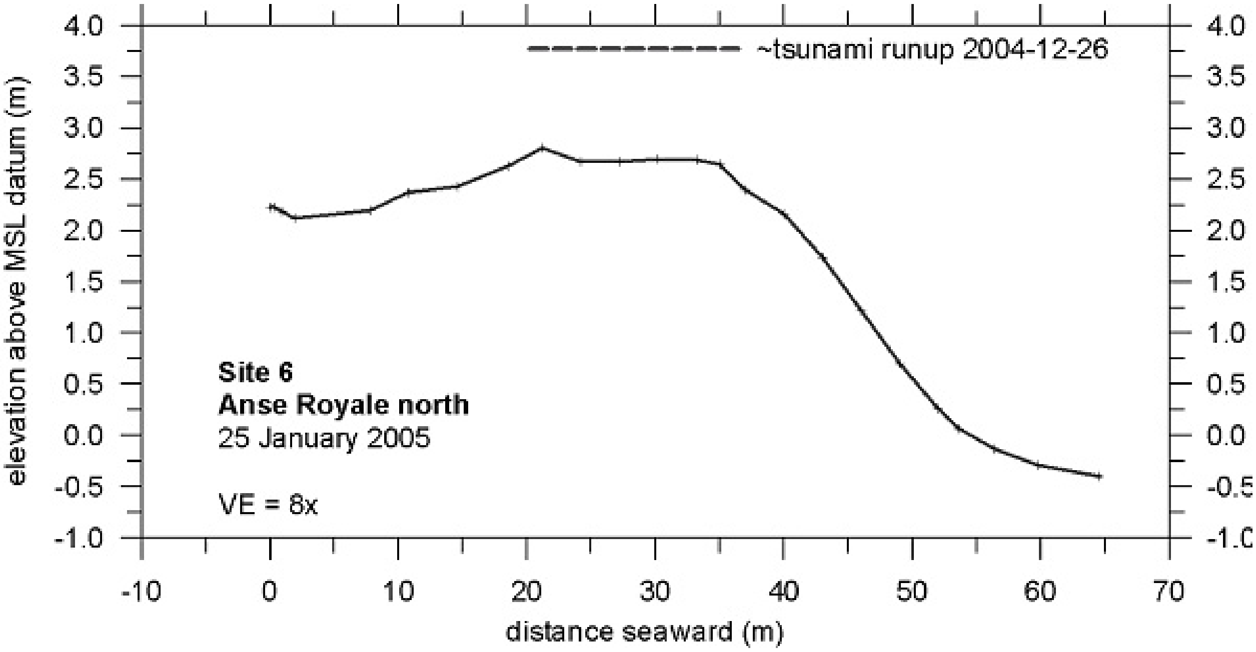

Fig. 29: Profile at Anse Royale north, immediately north of the Kaz Kreole restaurant (Fig. 28), which is located on the crest of the berm.

Site 7: Anse Royale south

Location: South end of the Anse Royale embayment (04°45.120'S, 55°30.925'E).

Environment: This site is on a segment of beach at the extreme south end of the sandy beach in Anse Royale (Fig. 21). It is just south of a school where a seawall was damaged, and is located adjacent to where a stream crosses under the road in a set of pipes, and debouches on the beach. Just south of here the beach terminates against rocky headlands. There is a narrow strip between the beach and the road. The natural berm is either very low or is heavily eroded. Rip rap has been applied immediately south of the site.

Description: There was no one to interview here. We based our interpretation on physical evidence alone (Figs. 30-32). Water crossed the road, spreading sand and vegetative debris into the low-lying area on the far side. On a later visit to survey the site with GPS, we noticed vegetation above our heads in the trees and against a telephone pole support wire, and also a piece of corrugated iron wrapped around a pole.

Damage: A seawall (Fig. 32) just north of the profile was partially knocked over during the tsunamis. Debris was deposited on the road but was removed prior to our arrival.

Fig 30: Track crossing low berm at the Anse Royale South profile site (note man for scale). Photo: JS (GSC), 25 Jan 2005.

Fig. 31: Plant debris wrapped around a steel guy wire to a height of 2 m above the berm at Anse Royal south. Photo: JS (GSC), 1 Feb 2005.

Fig. 32: Seawall that was damaged during the tsunami event just to the north of the profile. Photo: JVB (GSC), 25 Jan 2005.

Maximum run-up level: At least 4.4 m MSLD (Fig. 32).

Maximum run-up distance: About 45 m landward from mean water level, across the road.

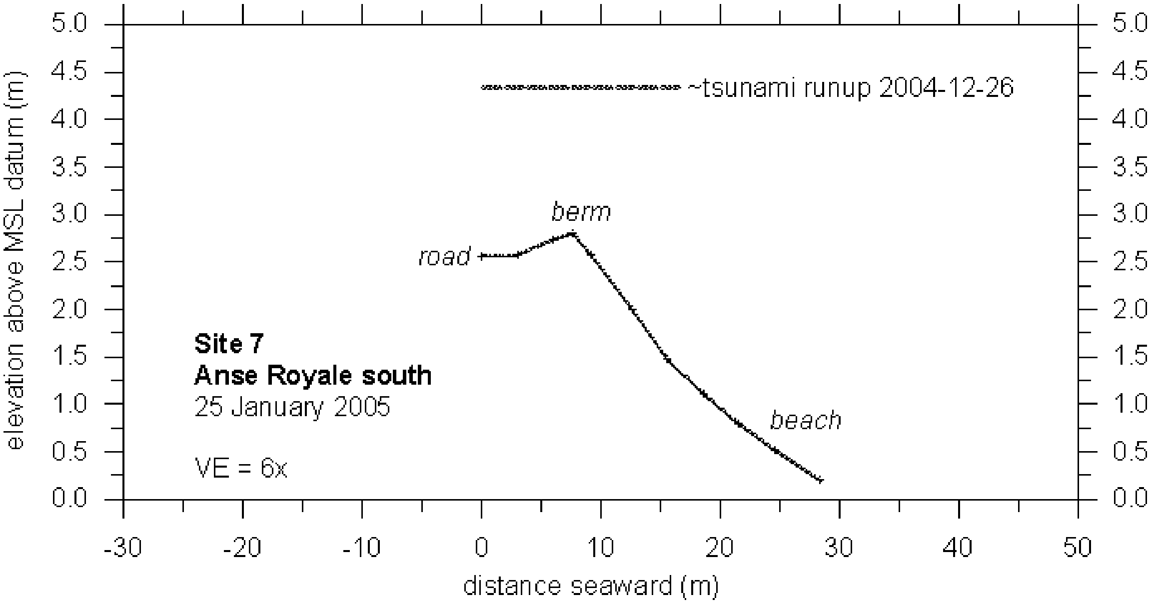

Fig. 33: Profile at Anse Royale south. The berm crest at 2.89 m above MSLD was overtopped in the tsunami. However, immediately south of this site we observed debris that was approximately 1.6 and 2.0 m higher than the berm elevation (Fig.31). There was evidence of strong currents flowing at 320° (berm alignment 355°), suggesting control of flow by the steep rock slope immediately behind the road. We estimate the maximum run-up level therefore to have been about 4.36 ± 0.2 m MSLD.

Remarks: Apart from the seawall, no other infrastructure was damaged in this area. This is one site where the road infrastructure, combined with local topography, deflected the wave, causing some of the flow to run parallel to the shore along the back of the berm for a short distance.

Site 8: Anse Forbans

Location: Along the southeast coast of Mahé (04°45.030'S, 55°30.939'E).

Environment: Anse Forbans is the location of Chalets l'Anse Forbans, the expedition's base of operations during surveys on Mahé. The chalets are located on a low grassy terrace lying behind a relatively undeveloped beach berm, with coconut trees and other vegetation. Beyond is a sandy beach in a coastal compartment that is bounded by granite outcrops and fronted by a 200 m-wide coral reef (Fig. 34).

Description: The eyewitness account of Jean-Pierre Laporte, a member of the family who own the resort, provided a complete and reliable record of the tsunami on Mahé Island. This is because he was expecting the tsunami, based upon news reports that he accessed via the Internet, and he observed the sea throughout the daylight hours and noted the times of wave arrival.

The reef at Anse Forbans was totally emerged due to the withdrawal of the sea at 11:45, 26 Dec. 2004. At noon, he was having lunch when he heard a sound like rain on the roof. The tide had come in very quickly and the sea was boiling and hissing. The water reached a level on the beach equal to a 2 m tide. It then retreated to beyond the reef. A standing wave was created over the reef by the rapidly receding water. The large brain corals were exposed. Then the sea slowly came in again reaching a static sea level with small waves traveling across the surface. Just before 13:10 the tide receded and again the reef was exposed.

Fig. 34: Anse Forbans. The chalets (where the field party stayed) are in the white circle. The tsunami waves did not breach the sandy coastal berm behind the upper beach.

At 13:10 PM, the largest wave struck, reaching the top of the beach berm, spilling over it, depositing sand (Fig. 35), and causing minor flooding with no damage to buildings. It looked like a wave that had already broken and it was about 1.0 to 1.3 m in height. Within about 3 minutes, the water receded and the reef was dry again. For the rest of the afternoon, waves arrived, first with an interval of about 45 minutes and progressively lengthening in time between waves to about 1 hour and 15 minutes. There was a notable wave at about 17:00 that caused the reef to go dry prior to its arrival. It was of lesser height than the 13:10 wave.

Fig. 35: Anse Forbans resort, photo taken from crest of beach berm looking toward bungalows. The sand marks the limit of the spill-over of tsunami beyond the crest of the berm. Photo: JS (GSC), 25 Jan 2005.

Maximum run-up level: The maximum run-up elevation was about 2.8 m MSLD (Fig. 36).

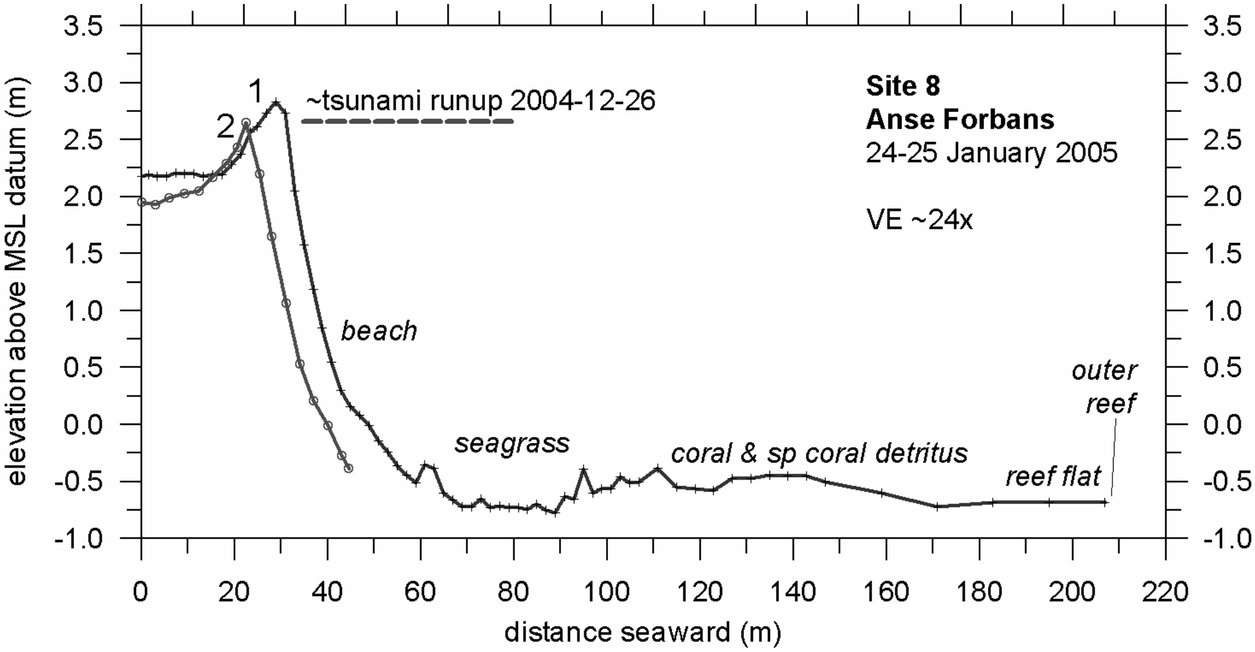

Fig. 36: Anse Forbans profile. The highest waves associated with the tsunami barely spilled over the level of the natural berm, which is 0.65 m above the level of the flat area (extreme left of the profile) on which the chalets are sited. This illustrates the vital importance of retaining natural coastal berms.

Maximum run-up distance: A small amount of water spilled over the beach crest Fig. 35).

Remarks: At this site, a comparatively well-preserved coastal frontage was sufficient to provide protection from flooding. Without the 65 cm berm, the chalets would have been surrounded by water more than 0.5 m deep.

Site 9: Baie Lazare

Location: Near southwest extremity of Mahé (04°45.887'S, 55°29.418'E).

Environment: Baie Lazare is a south-facing, semi-circular cove protected to the west and east by the granite headlands of Pointe Lazare and Pointe Maravi, respectively. A fringing reef lies immediately offshore (Figs. 37 and 38).

Description: Deposits marking maximum tsunami run-up were identified on a beach along the east side of the cove adjacent to the shoreline highway. These were found at 1.2 m above water level at 14:40 local time, 23 January, 2005 (the time of investigation). This limit was almost level with the island highway. The owner of a souvenir shop directly across the highway confirmed that the tsunami did not inundate the highway. Consequently, the tsunami rose only about 65 cm above a normal high tide.

Fig. 37: Baie Lazare looking south. Photo JVB (GSC), 20 Jan. 2005.

Damage: None

Maximum run-up level: Approximately 1.6 m MSLD (slightly above high tide level; Fig. 39).

Maximum run-up distance: Did not advance beyond berm at the crest of the beach in front of the road.

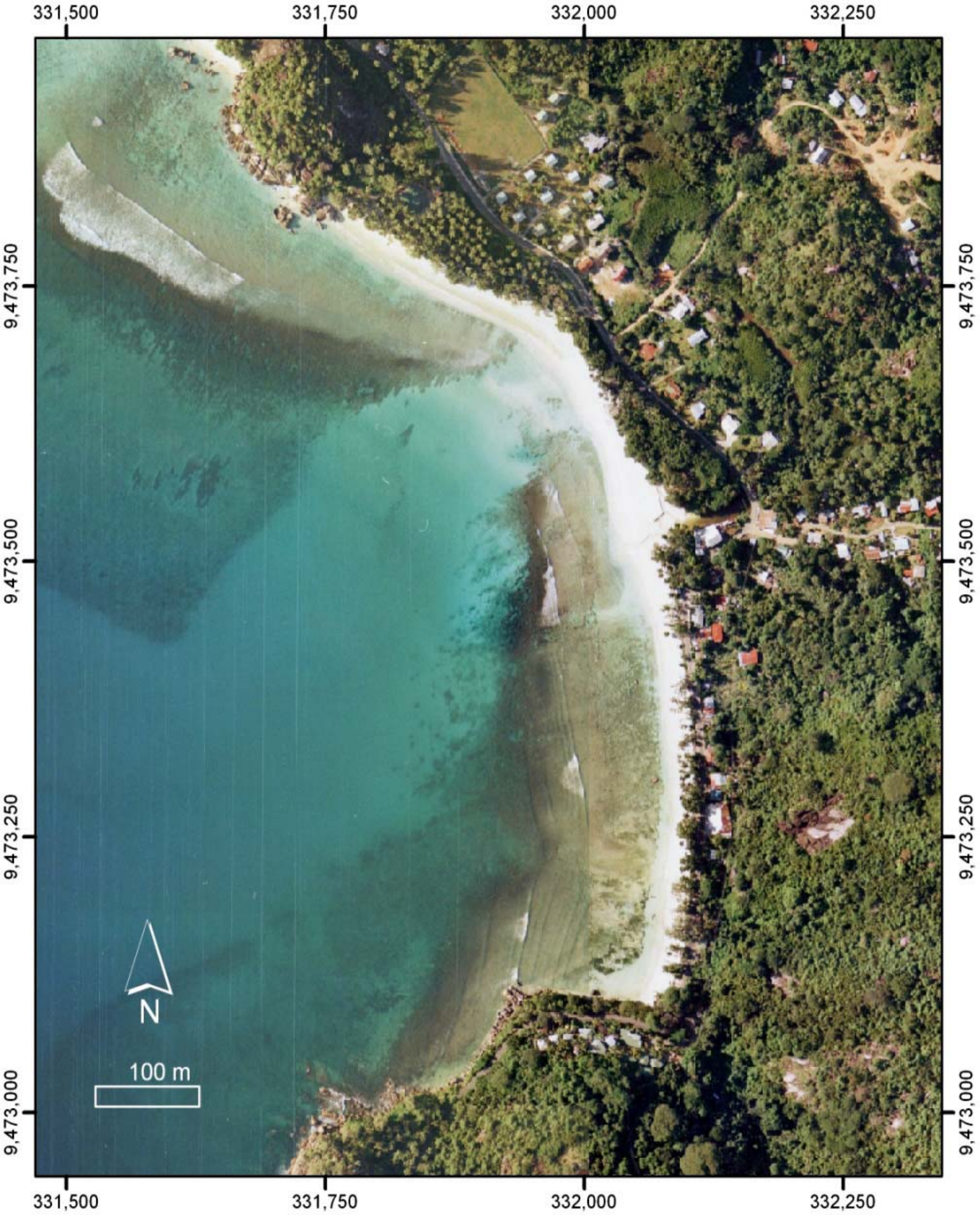

Fig. 38: Baie Lazare.

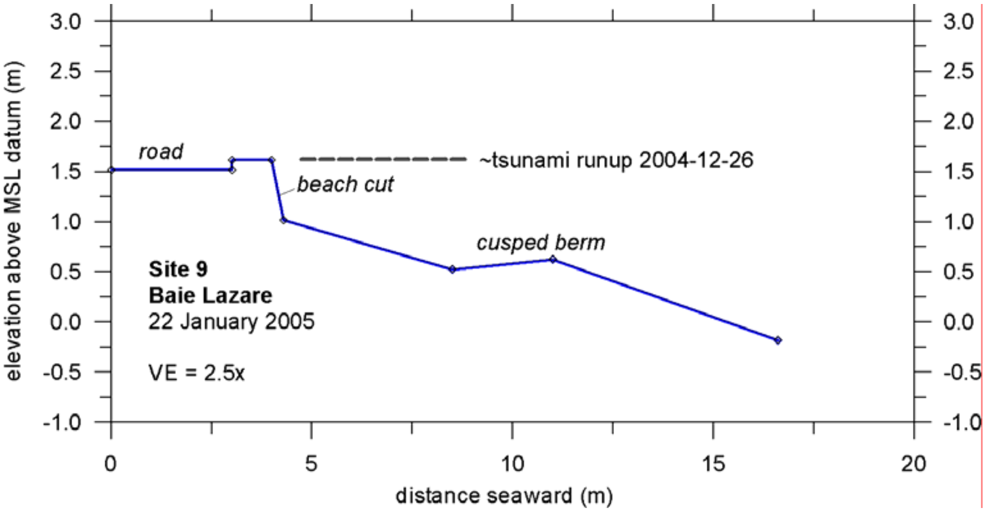

Fig. 39: Profile across beach with cusped berm at Baie Lazare, showing beach cut in upper berm in front of the road.

Remarks: The maximum run-up and flood level slightly above high tide level here is in marked contrast to Anse à la Mouche (site 10), a west-facing cove less than 3 km to the north. This underscores the importance of exposure, coastline morphology, and bathymetry on tsunami behaviour along the west coast of Mahé.

Site 10: Anse à la Mouche

Location: West coast of Mahé (04°44.376'S, 55°29.419'E).

Environment: This bay is on the west coast of the island and is oriented almost due west (Figs. 40 and 41). At the rocky headlands at the northern boundary of the bay the reef flats are very narrow. The reef edge extends in a southerly direction for a considerable distance, as the bay curves away to the east, resulting in an extensive reef. Midway across the bay the reef edge turns sharply and runs almost due east, creating a deep re-entrant in the bay. In the innermost part of the bay the reef is relatively narrow. The beach is low, and there is almost no natural berm (Figs. 42 and 43). Instead, the road runs along the water's edge, separated in places by a few palms. In front of the most damaged area – in the vicinity of the Anchor Café – there is no protection except for a few granite rip rap boulders. A small river enters the bay via a concrete channel immediately south of the Anchor Café. Behind the narrow coastal lowlands, the land rises steeply.

Description: Keith Berke, proprietor of the Anchor Café (Fig. 44), provided extensive information. Interesting observations came also from Henri Barralon, a local fisherman. Mr. Berke's daughter heard of the earthquake and tsunami on CNN. Having lived in Hawaii, Keith recognized the potential danger, checked the warning sites, and told his wife to expect a tsunami on the islands. However, he expected nothing to happen at this location on the west side of the island, facing away from the direction of tsunami approach. At 12:30 local time, his sons said "come look at this". They watched the water evacuate from the bay, exposing reefs never seen before. They drove up the nearby mountain, and met people from the other side of Mahé, where the tsunami had already hit. They watched for another 10 minutes, and then they went back down to investigate. The boys hopped out of the vehicle to see the water come over the road. It was 13:25 local time. Mr. Burke climbed into his truck as a water level continued to rise occurred – not like a wave. He felt that water had circulated around the bay and approached his site from the north and offshore. He claimed that some other observers on hilltops with good views to the west could see water converging on the bay from north and south.

Fig. 40: Anse à la Mouche showing approximate area inundated (red) by the most destructive (17:30) tsunami.

Fig. 41: Anse à la Mouche area showing the Anchor Café (1), the approximate location of the tortoise pens (2) and the freshwater ponds (3) that contained marine fish after the 17:30 flooding event. The limit of flooding lay landward of the ponds. One of the most reliable measurements of flood limits was a GPS measurement taken on the Chemin les Canelles (4). This location was identified using a photograph of flood debris on the road.

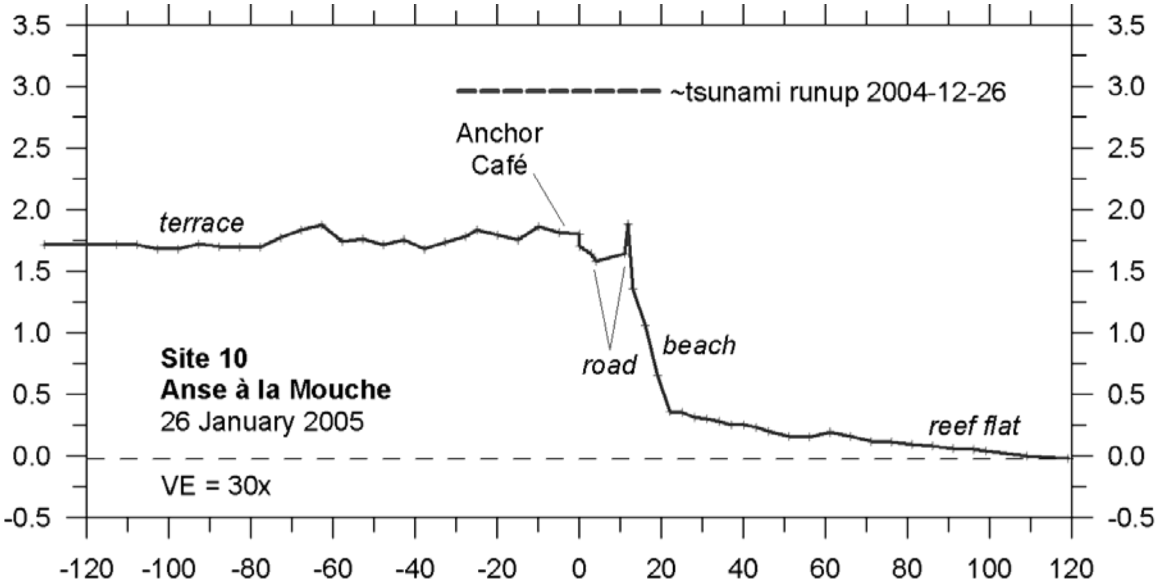

Fig. 42: Beach profile across the coastal terrace and beach and out onto the reef flat in front of the Anchor Café. The ocean is to the right.

Fig. 43: The seafront at Anchor Café. Note the low boulder rip rap, the road, and the café beyond. Prior to the tsunami, there was enough land on the seaward side of the road for a kayak shed. Photo: JS (GSC), 26 Jan 2005.

The 13:00 (local time) event caused water to go over his veranda at the Anchor Café and into his home on the adjacent lot. No serious damage was done and they commenced a clean up. There were many surges, some 15s apart. At 17:20 local time, the water was rising again as they were pulling in a fisherman's boat. The water rose rapidly and engulfed them, pushing the boat past them, and causing extensive damage. His car was flooded and his truck was moved into the trees. The force of the incoming flood pinned one son against the chain-link fence beyond the house, together with dogs, tortoises etc. The other boy swam with the flood and was entangled in a tree alongside the creek. He climbed up for safety. This 17:30 local time event tumbled walls around the café, pushed out a chain-link fence along the road, exposing the concrete foundations of posts; water reached above the power outlet on the café wall (Fig. 44), rushed into the café, flooded the toilets, and surged up above the toilet door. The road and beach were eroded by the backflow and a considerable area of land on the seaward side of the road disappeared. There was already standing water from earlier events, so this later flooding was worse. This 17:30 event occurred on high tide, unlike the earlier event. Water went inland, 200 m beyond the house.

Damage: Extensive property damage was done and several homes were flooded in this area. Walls were toppled (see estimation of surge velocity below) and a fence was pushed over. There was extensive damage to property (Mr. Berke provided an extensive inventory of losses) and lumber floated away. Large Aldabra tortoises (up to 1 m in length and more than 100 years old) that were kept in an enclosure near the Berke home were floated out of their concrete pens and escaped (they were recaptured the next day!)

Fig. 44: Anchor Café. The high water level was level with the counter top behind V. Barrie. Photo: JS (GSC), 26 Jan 2005.

Maximum flood level: About 3.0 m MSLD at the café close to the shore and 2.5 m further inland near Les Cannelles. At the café, water rushing against the building ran up to 3.5 m in places (Fig. 42).

Maximum run-up distance: About 250 m.

Remarks: The absence of a coastal berm and the low-lying, poorly drained location are factors that contributed to vulnerability at this site. It was further at risk because of its location near the inner end of an embayment in the reef.

Estimation of minimum tsunami surge velocity: Large spherical granite boulders were placed along the shore side of the road near the Anchor Café to discourage parking along the road. These were rolled about 10 m by the tsunami surge. The largest measured 100 x 80 x 60 cm. The minimum flow velocity required to initiate movement of this boulder can be estimated from empirical equations used in civil engineering. Estimates for flow velocity (***U***) based on the intermediate diameter of 80 cm and a specific gravity of 2.5 are assumed. The results are listed below:

equation	**estimated *U*** (m/s)
Mavis and Laushey (1949):	3.6 (bottom velocity)
Perterka et al. (1956):	4.4 (bottom velocity)
Torpen (1956: equation B):	6.0 (mean velocity)

Site 11: Anse Boileau

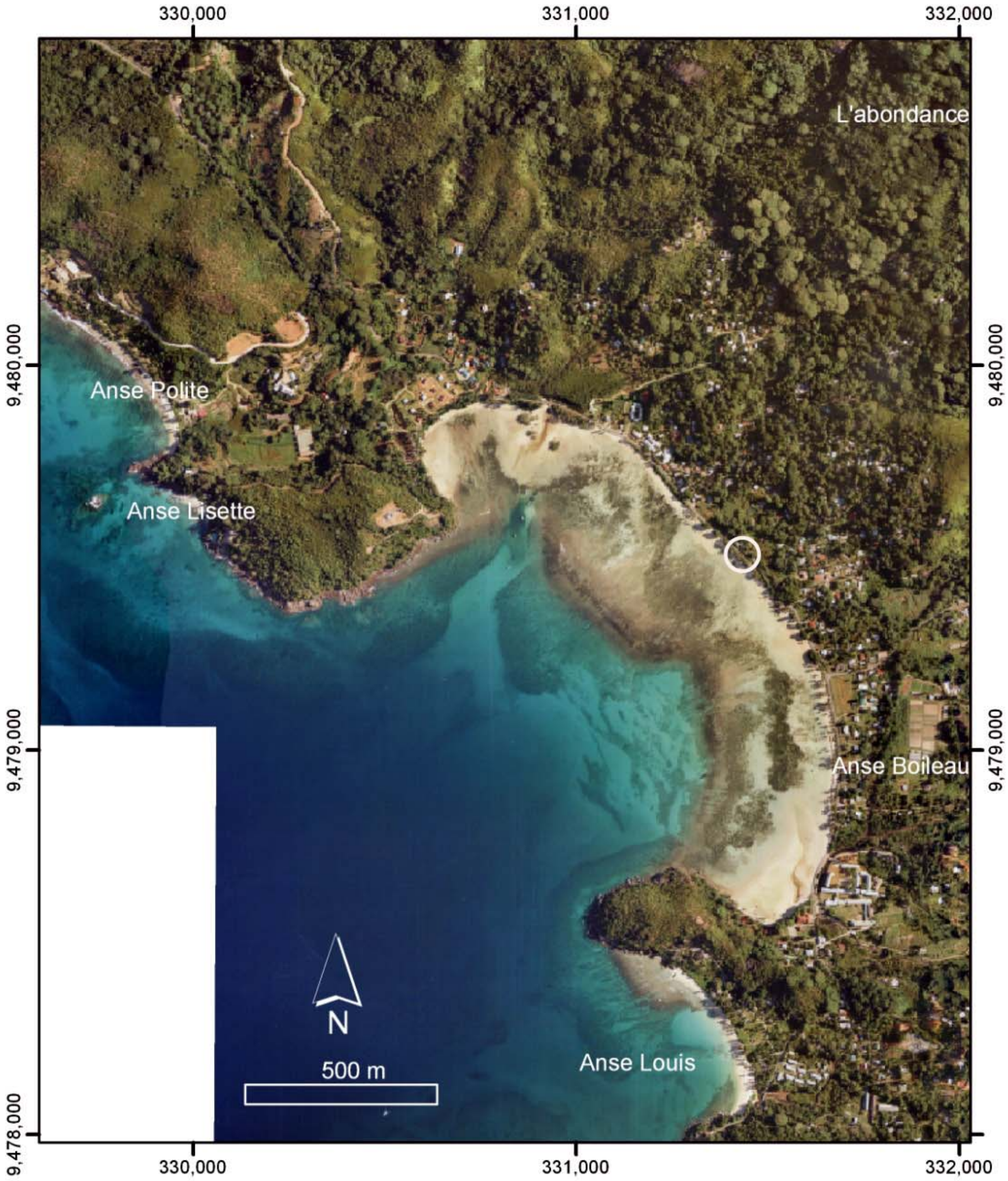

Fig. 45: Anse Boileau, with profile site circled. The beach lies behind a wide reef, and is backed by a low wall, behind which lies the coast road. We have described the flooding here as minor, but have seen photos suggestive of more extensive flooding, particularly in the southern end of the bay.

Location: Central west coast of Mahé (04°42.377'S, 55°28.734'E).

Environment: This site lies on the west side of the island in a bay that faces southwest (Fig. 45). The bay has a moderately wide reef, backed by sandy beaches. The site lies immediately seaward of a coastal road, bordered by a low stone wall.

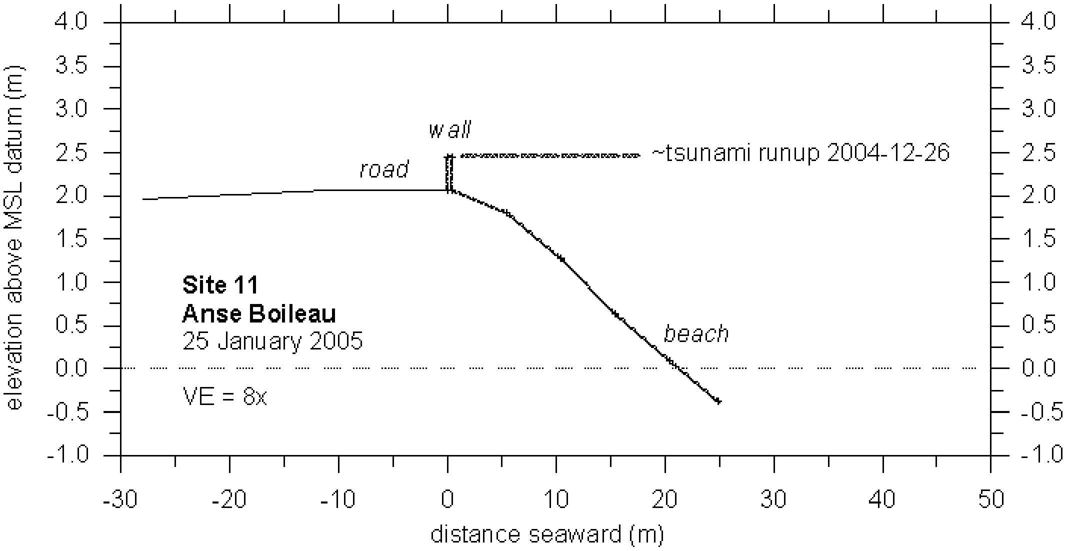

Fig. 46: Profile at Anse Boileau. Water barely covered the wall, and drained to the road behind, causing minor flooding.

Description: Flooding was minimal according to a local informant. The water slopped over the wall and crossed the road to reach the shops (Figs. 46 and 47). However, a newspaper photograph showed the main road in Anse Boileau with mud and debris.

Damage: The large house in the southernmost part of the bay (Fig. 45) was flooded, otherwise little damage was reported.

Fig. 47: At rear of beach at Anse Boileau. The tsunami waves spilled over the wall, and water ran across the road as far as the store at the other side. Top of wall is GPS site BOWL. Photo: JS (GSC), 25 Jan 2005.

Maximum run-up level: About 2.5 m MSLD (Figs. 46 and 47)).

Maximum run-up distance: About 25 m beyond the wall at the back of the beach

Remarks: We surveyed this site mainly because it showed minimal flooding, in contrast to nearby Anse à la Mouche, just 3 km to the south, which was heavily impacted.

Site 12: Grande Anse

Location: West coast of Mahé (04°40.586'S, 55°26.631'E).

Fig. 48: Grande Anse, a wide sandy beach without a reef, fully exposed to Indian Ocean wave energy. The tsunami waves merely reached as high as normal storm waves or a high tide level. The profile location is circled and the school located by the arrow.

Environment: This site lies at the west side of the island, and consists of a long wide sandy beach exposed to the south-southwest (approximately 210°) in an open reef-gap setting (Figs. 48 and 49). There is a low wave-cut scarp at the top of the beach, cut into a heavily vegetated upper berm (Figs. 50, 51). The beach has protected status, and there are no major roads running parallel to the high water line. There is a school part way along the beach, about 30 m landward of the beach crest. Access to the beach is via wooden steps. A river enters at the north end, where it has carved a steep-sided channel into the beach sand. Large beach cusps were present on January 26 but had not been noted on January 25, demonstrating the dynamic nature of the beach.

Description: Our information on the events that took place came from two interviews with a man who identified himself as a 'beach policeman'. Over two short interviews on consecutive days, he indicated that the water reached the berm at landward side of the beach. This was confirmed by parents waiting for their children at the beachside school nearby. This agrees with the physical evidence that we found on the berm. We sited our GPS receiver on the run-up limit identified by the beach policeman whose estimate was within 10 cm of the level based on our evaluation of physical evidence.

Damage: None.

Maximum run-up level: About 4.3 m MSLD (high but not high enough to overtop the beach berm in this area; Fig.50).

Maximum run-up distance: Did not travel past the berm, except along the flanking stream channels.

Fig. 49: Cusps on the high-energy, reef-gap, sandy beach at Grande Anse. Photo: DLF (GSC), 26 Jan 2005.

Fig. 50: Team member L. Jackson holding a rod at the position of maximum run-up (according to the informant leaning on the steps). This is GPS site G2AX. Photo: JS (GSC), 26 Jan 2005.

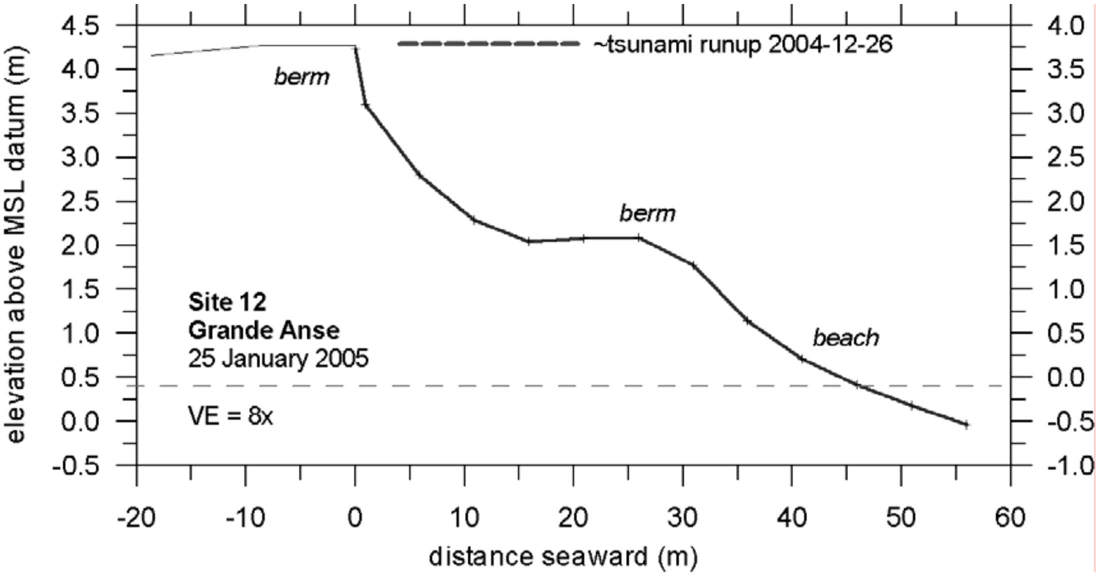

Fig. 51: Profile at Grand Anse. The ocean is to the right. Note prominent cusped berm at 25-30 m on the profile.

Remarks: This is an exposed beach (no reef) so it is a wide and extends over a large vertical range. When the tsunami struck at low tide it only managed to run-up to the vegetation zone at the rear of the beach, perhaps causing some minor cliffing and depositing some debris.

Site 13: Beau Vallon

Location: In large bay on northwest coast of Mahé (04°36.514'S, 55°25.897'E).

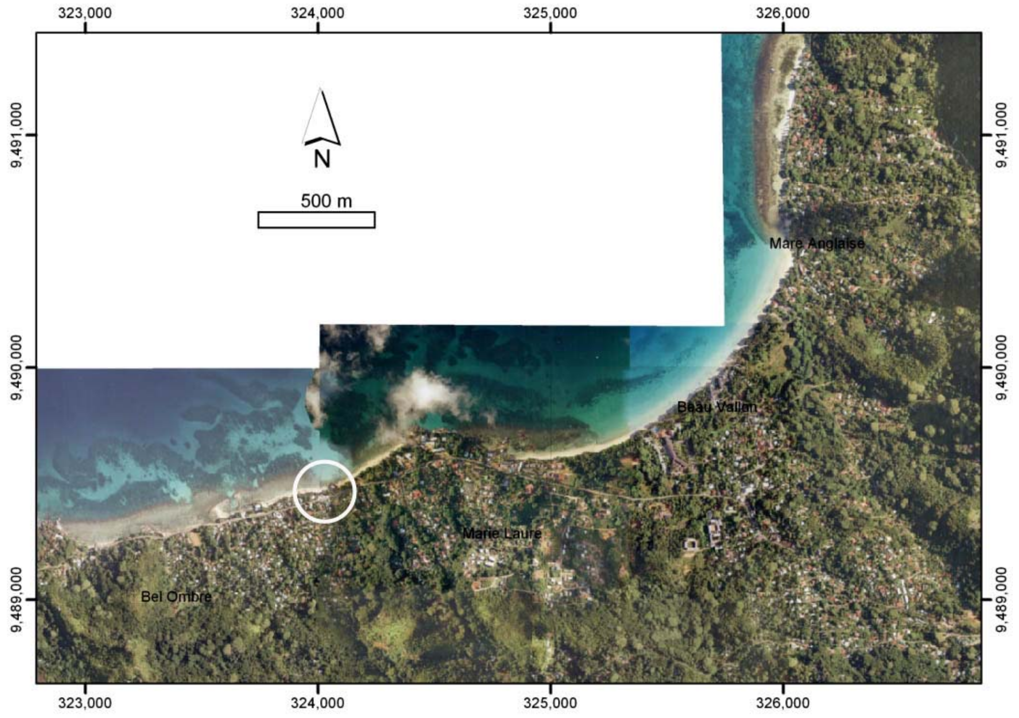

Fig. 52: The beau Vallon site is located on a sandy beach in an embayment on the northwest of the island.

Environment: Baie Beau Vallon is formed by the intersection of the west coast of the northern peninsula of Mahé Island and the west-to-east trending coast of the northwestern extremity of the Island. The Beau Vallon area is one of the premier destinations for visitors with a variety of aquatic activities. Granite hills rise abruptly from its north and northwestern facing sandy beach. For the most part, the beach lacks a coral reef barrier.

Description: Draw-down of the water level of Baie Vallon was noted by witnesses around noon, December 26 but the tsunami surge only reached slightly above the normal high tide level. Warnings were given to people on the beach and it was evacuated. Three surges were noted with no other remarkable waves noted during the balance of the afternoon.

Damage: None. Water just reached the thresholds of beachside business (Fig. 53).

Maximum run-up level: Slightly above normal high tide ~l.7 m

Maximum run-up distance: Approximately within the high tide range

Remarks: The Baie Beau Vallon area is remarkable for the minimal impact of the tsunami compared with other areas on Mahé Island such as Anse à la Mouche, also on the west side of the island, which were impacted by maximum run-up levels approximately twice as high. It illustrates the significant effect that orientation and bathymetry played in mitigating or exacerbating the effects of the tsunami. However, if the tsunami had struck during higher tide, there would have been extensive flood damage to homes and businesses in this area.

Fig. 53: Tsunami waters just reached the step upon which the two men are standing at Baobab Pizzeria, Beau Vallon. This is about 1.6 m above sea level shown in picture, or approximately at higher high tide level. Photo: LEJ (GSC), 23 Jan 2005.

OVERVIEW OF TSUNAMI EVENT AND FIELD WORK ON PRASLIN ISLAND

The tsunami struck Praslin (Fig. 52) as two distinct surges starting at about 12:10 local time (08:10 UTC) on December 26. This was about one hour before the first large wave was detected on the Mahé tide gage. As on Mahé, the coincidence of the tsunami with low tide spared the Praslin from far more extensive damage and likely fatalities. There was extensive draining of water from the shore between 11:00 and 12:00 prior to the first wave and between the first and second wave. The second surge was the largest and stopped a clock in the Turcotte house (site 15) at 12:20. Although additional waves continued to reach the island throughout the afternoon, none caused additional flooding. A particularly notable wave that reached the top of the beach berm was noted at Chevalier Bay around 17:00. Tables 3 and 4 summarize GPS survey data and computed water levels. These values are preliminary and subject to change following further analysis of survey data.

The tsunami caused extensive damage along the northeast coast of Praslin Island, particularly in the Anse Possession, Anse Petite Cour, and Anse Volbert areas, all of which are exposed to the direction of tsunami wave approach. Beach-front hotels and homes in these areas experienced significant inundation and damage, the latter attributable to drainage of tsunami waters following inundation. Low-lying areas of Grande Anse on the southwestern coast of the island were also extensively flooded, despite being on the leeward side of the island. The southeast-facing Baie Ste. Anne area was completely spared damage, with tsunami inundation only reaching the normal high tide level. However, strong currents were generated by the sudden incoming tide and coral heads were broken off and washed into shallow areas of the bay. The west-facing coast in the vicinity of the Palm Beach Hotel experienced flooding. The hotel owner claimed that the highest water level came overnight (debris appeared to a higher level than had been observed during the day).

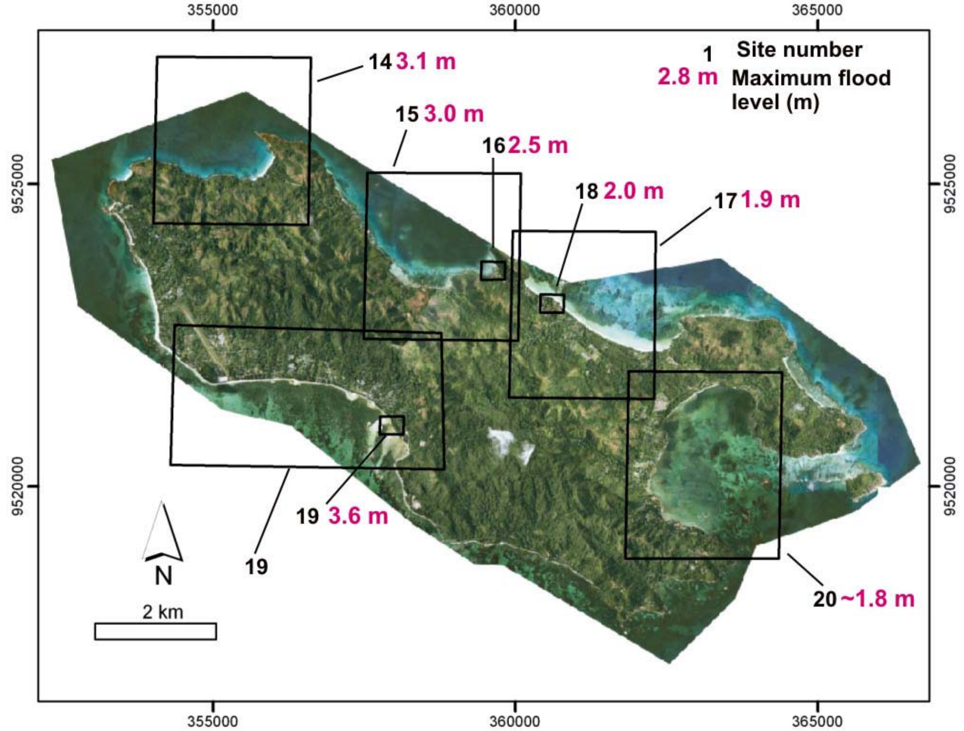

Fig. 54: Praslin: rectangles show areas enlarged in detailed figures below. Location numbers in black. Red numbers refer to the maximum flood level at each location (Table 4). Source of mosaic: Ministry of Land Use and Habitat, Republic of Seychelles (courtesy Francis Coeur de Lion, Director, GIS, MLUH).

Table 3: Data for GPS sites on Praslin (cf. Table 1).

point	**date** dd-mm-yy	**site**	**location** (comments)	**z_{MSL}** (m)	**GPS_E** (m)	**s_E** (m)	**GPS_{MSL}** (m)	**$2s_{MSL}$** (m)	**GPS_{MSL} EGM96** (m)
PRA1	28-01-05	0	Airport (1)	n/a	-39.253		2.805		2.787
PRA2	29-01-05	0	Airport (1)	n/a	-39.253		2.805		2.787
PLA1	29-01-05	15	Chevalier Bay (2)	n/a	-39.388	0.003	2.670	0.006	2.717
PLA2	29-01-05	15	As above (3)	n/a	-39.053	0.005	3.005	0.010	3.054
PLA3	29-01-05	15	As above (4)	n/a	-38.685	0.006	3.373	0.011	3.421
PLA4	29-01-05	15	As above (5)	n/a	-38.999	0.004	3.059	0.008	3.106
PLA5	29-01-05	15	As above (6)	n/a	-39.680	0.009	2.378	0.018	2.422
PLR1	28-01-05	16	Anse Petite Cour (7)	n/a	-39.081	0.009	2.977	0.018	3.057
PLR4	29-01-05	16	Anse Petite Cour (8)	n/a	-39.994	0.026	2.064	0.051	2.143
PPS1	28-01-05	17	Anse Volbert (9)	n/a	-40.183	0.015	1.875	0.029	1.959
PVO1	28-01-05	18	As above (10)	n/a	-40.154	0.006	1.904	0.012	1.993
PVO2	28-01-05	18	As above (11)	n/a	-40.034	0.009	2.024	0.018	2.110
PVO3	28-01-05	18	As above (12)	n/a	-40.105	0.008	1.953	0.016	2.043
PPB1	28-01-05	19	Grande Anse (13)	n/a	-42.083	0.017	-0.025	0.033	-0.013
PPB2	28-01-05	19	As above (14)	n/a	-40.545	0.014	1.513	0.027	1.525

comments 1. reference station; 2 Anse Lazio high WL; 3. Anse Lazio WL lemon tree; 4. Anse Lazio house floor dry; 5.Anse Lazio terrace profile; 6. Anse Lazio limit on south side; 7. La Reserve pool lip; 8. La Reserve step (add 0.45 m); 9. Paradise Sun high WL; 10. Berjaya cnr concrete slab; 11. Berjaya upper run-up limit; 12. Berjaya berm remnant; 13. Palm Beach WL; 14. Palm Beach upper beachface. NB: GPS_{MSL} EGM96 Heights for EP2,TP45,BMG5,1704,BOWL calculated using using Ashtech Solutions^{TM}

Table 4: Summary of investigated sites on Praslin Island

Site	Name	Latitude	Longitude	Max flood level (MSLD)	Distance inland
14	Chevalier Bay (Anse Lazio)	04°17.600' S,	55°42.124' E	3.1 m	140 m
15	Anse Possession (Turcotte home)	04°18.727’ S	55°43.611’ E	3.0 m	65 m
16	Anse Petite Cour (La Reserve Hotel)	04°18.626' S	55°44.147' E	2.5 m	225 m
17	Anse Volbert (Paradise Sun Hotel)	04°18.743’ S	55°44.387’ E	1.9 m	100 m
18	Anse Volbert (Berjaya Praslin Restaurant)	04°18.860’ S	55°44.652 E	2.0 m	>100 m
19	Grande Anse (Palm Beach Hotel)	04° 19.930’ S	55° 43.185’ E	2.8 m 3.6 m	>50 m
20	Baie Ste Anne	04° 20.50’ S	55° 46.0’ E	~1.80 m	0 m

DETAILED DESCRIPTIONS OF SITES ON PRASLIN

Site 14: Chevalier Bay (Anse Lazio)

Location: Northwest tip of Praslin (04°17.600'S, 55°42.124'E).

Environment: Chevalier Bay is a semicircular bay facing to the northwest (Fig. 54). It is shielded by rugged granitic headlands to the northeast and southwest, and lacks a coral reef. To the east and southeast of the sandy beach known as Anse Lazio is low-lying terrain that was likely a former tidal marsh before a network of drainage channels were created. This lowland has been developed into small estates and a few hotels. The beach with its large breaking waves and the beachside Bon Bon Plume Restaurant make it a popular destination for visitors.

Description: The Anse Lazio area and the northern coast of Praslin Island were among the most extensively impacted areas in the Republic of Seychelles. The account of Richelieu Verlaque, owner of the Bon Bon Plume Restaurant, is the chief source of the chronology of events.

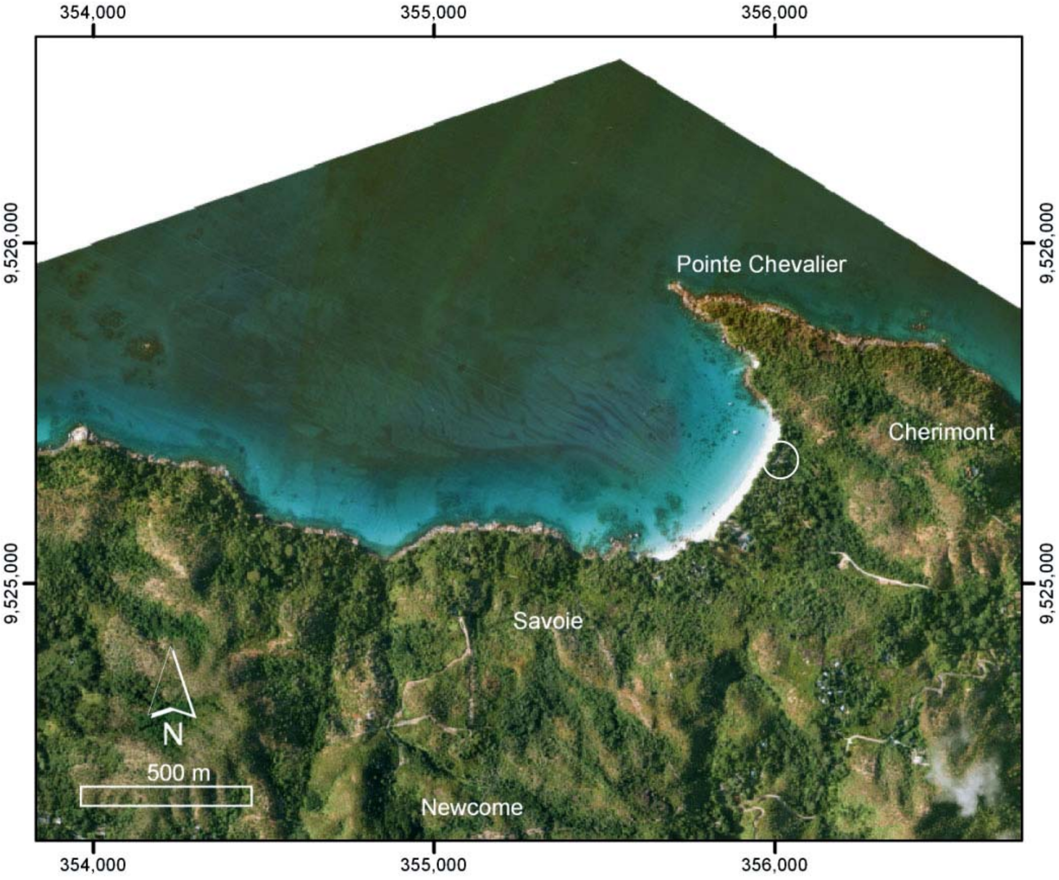

Fig. 54: Chevalier bay (Anse Lazio) with the Bon Bon Plume restaurant circled.

The sea drained from Chevalier Bay at about 12:00 local time (08:00 UTC) on December 26. The rocks on the floor of the bay were well exposed. Three columns of 'boiling' water emitting a 'ghostly sound' were sighted coming around Chevalier Point from the northeast some minutes later. They were clearly advancing from the northeast. That was the first of three waves counted by Mr. Verlaque. The first rose above the beach and slightly flooded the restaurant. The second wave struck the restaurant 2 to 3 minutes later flooding it waist deep. People, at this point, were swimming for their lives and tables and chairs were being rolled by the surging water. A third wave apparently arrived on this flood. A woman acquaintance of Mr. Verlaque was clinging to a coconut palm and counted five waves in all before she lost her grip and was carried out to sea where she was rescued next to her floating car. The Anse Lazio area had completely drained within about 45 minutes of the arrival of the first wave. There were no subsequent waves large enough to cause flooding beyond the beach. However, Mr. Verlaque noted that the largest subsequent wave occurred at about 16:45 local time. The wave reached the top of the beach berm adjacent to the restaurant but did not spill beyond it.

Dual frequency GPS and Emery pole surveys of the Anse Lazio area determined that water traveled up to 140 m inland and reached an elevation of 3.1 m above MSLD.

Site 15: Anse Possession (Paul Turcotte residence)

Location: On the north coast of Praslin exposed to the northeast (04°18.727'S, 55°43.611'E). This site is located on a narrow coastal terrace just across the road from the beach in Anse Possession (Fig. 55). The bay is protected from the north by Curieuse Island. A steep slope rises immediately behind the house.

Description: This site experienced significant flooding that ruined household items, floated a car some distance, and caused minor structural damage. The tenant, Paul Turcotte, is the Canadian consular representative in the Seychelles. Mr. Turcotte reported that the first wave (flooding the home) was at 12:24 local time (08:24 UTC) (Figs. 56 and 57). His wall clock stopped at this time after falling into the flooded interior of the house. There were four or five waves between 13:00 and 17:00 local time. Another very big one came about 40 minutes after the first. However, Mr Turcotte was not sure of times. Water stayed a long time in the house (probably due to the fact the house is 60 cm below the beach berm). There was a series of at least five static water marks visible outside the house, and water marks inside as well. Mr. Turcotte claimed that his two puppy dogs ran up the adjacent hill prior to the tsunami. In reviewing field notes, it is not clear whether this happened before the first wave arrival or during the events. Mr. Turcotte was confused and lost track of time. He also mentioned that his neighbours told him that their tortoises sought high ground, but the same comments re: the dogs, apply.

Damage: Flood damage to household items and a car, and settlement of the foundation of the house causing cracking of walls. This was apparently due to consolidation of the uncompacted sand on which the house was constructed.

Maximum run-up and flood level: 3.0 m MSLD (Fig. 58).

Maximum run-up distance: Approximately 35 m.

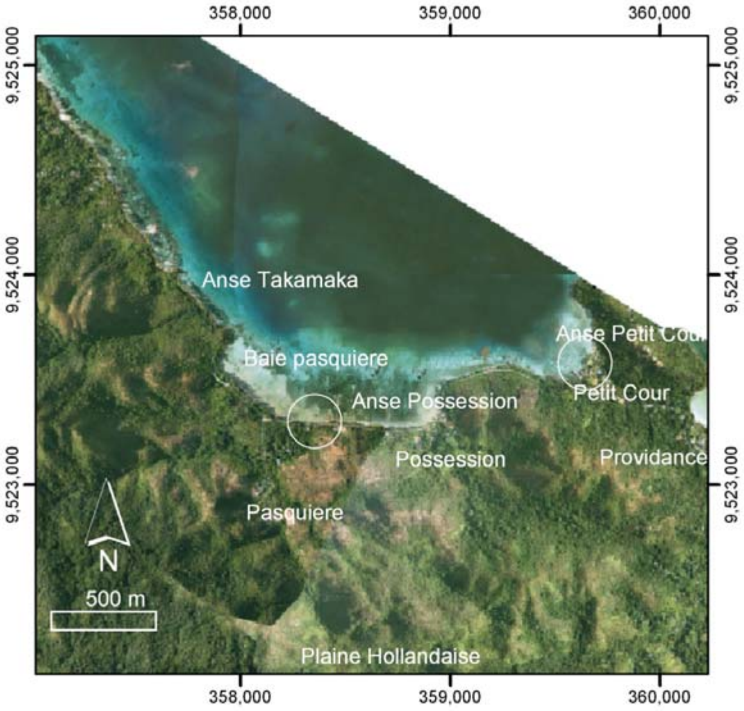

Fig. 55: North coast of Praslin, showing the locations of Anse Possession (Turcotte home) and Anse Petite Cour (La Reserve Hotel).

Fig. 56: Photo supplied by Paul Turcotte showing tsunami waves crashing on the beach scarp across the road from his house, 26 December 2004.

Remarks: The site is an unfortunate location for a house: not only is it close to a beach that appears to be eroding (limited sediment supply?), but also it is at a very low elevation that would tend to trap flood water (Figs 58 and 59). Boulders placed along the road in front of the house were rolled toward the house by the surging tsunami waters. The largest of these had an intermediate diameter of 57 cm. The minimum flow velocity (***U***) required to initiate movement of this boulder can be estimated from empirical equations used in civil engineering. Estimates for flow velocity based on an intermediate diameter of 57 cm and specific gravity of 2.5 are given below:

equation	**estimated *U*** (m/s)
Mavis and Laushey (1949):	3.3 (bottom velocity)
Perterka et al. (1956):	3.7 (bottom velocity)
Torpen (1956: equation B):	5.1 (mean velocity for rolling)

Fig. 57: Tsunami floodwaters surround the Turcotte house. Photo by Paul Turcotte, 26 December 2004.

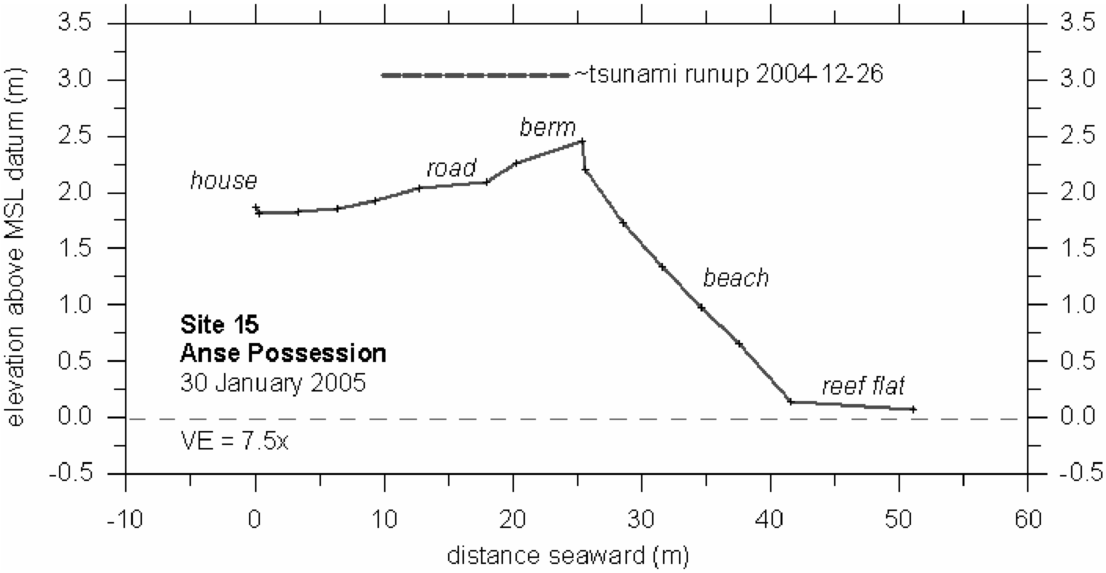

Fig. 58: Profile at Anse Possession. The line extends from the corner of the Turcotte residence across the road, berm, and a low scarp to the beach and intertidal flats (at right). The ground at the corner of the house is 1.87 m MSLD and the highest water mark on the outside of the house was 1.14 m above ground level. Thus the maximum flood level was 3.01 m MSLD. Inundation was facilitated by the landward slope of the ground surface.

Fig. 59: View of Turcotte residence at Anse Possession from the adjacent intertidal flats. Photo: JS (GSC), 30 Jan 2005.

Site 16: Anse Petite Cour (La Reserve Hotel)

Location: Anse Petite Cour, northern coast of Praslin (04°18.626'S, 55°44.147'E).

Environment: Anse Petite Cour is a semicircular cove that faces northwest (Figs. 60 - 62). It is sheltered to the northeast and east by Pointe Zanguilles, a rugged promontory that rises to 80 m above sea level. The bay is underlain by a coral reef. A small pocket beach occurs along the southernmost part of the bay. La Reserve Hotel adjoins the beach and consists of a complex of hotel buildings (one block is directly adjacent to the beach and was protected by a sea wall). Next to this, a pier restaurant has been constructed, one of the biggest attractions of the resort.

Description: La Reserve Hotel was one of the most impacted sites on Praslin Island. The first indication of the impending tsunami was the draining of Anse Petite Cour between 11:00 and 12:00 local time on December 26. Coral heads at the bottom of the bay were completely exposed. A photograph taken by a guest documents the draining of the bay (Fig. 62).

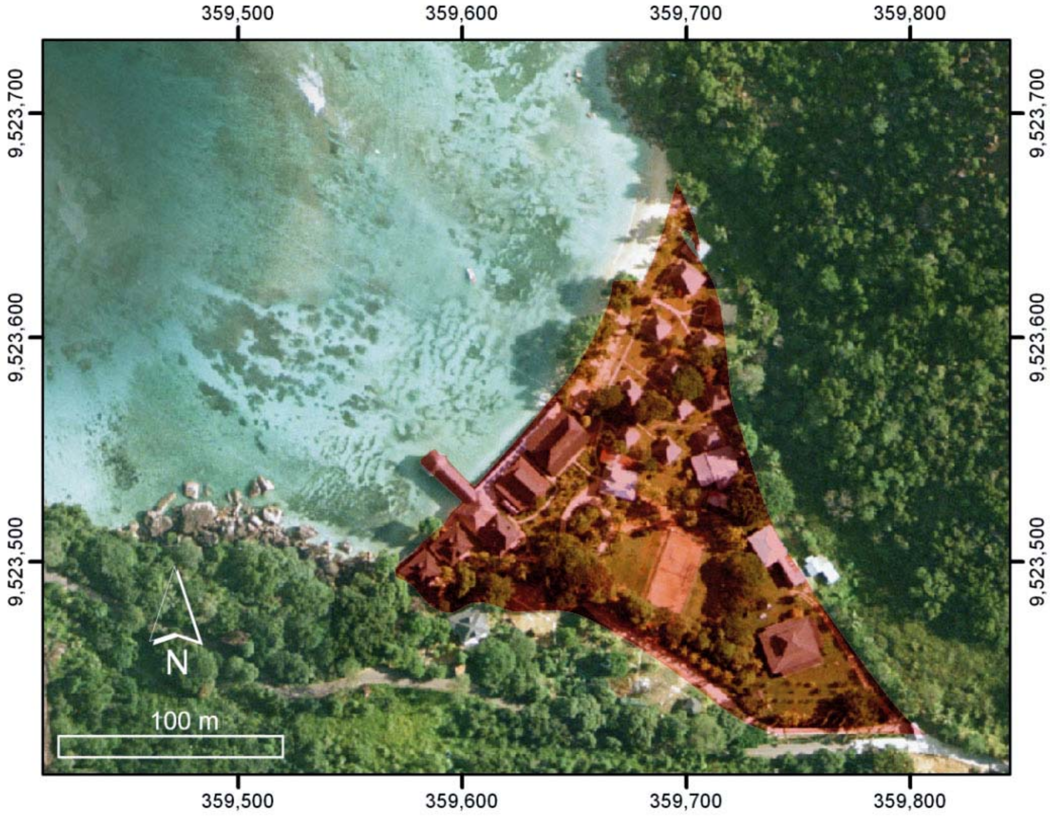

Fig. 60: An overview of the La Reserve hotel complex in Anse Petite Cour. A prominent feature is the hotel restaurant that projects into the bay. The red overtone indicates the triangular-shaped inundated area on 26th December 2004. The boundary of the flooded area is somewhat uncertain, but we have good evidence - both geological and oral - that the flood waters reached the apex of the triangle at the bottom right of the image.

The bay filled with water from lowest ebb to flooding the grounds of La Reserve Hotel to an elevation of 2.5 m and reaching 225 m inland in about five minutes. The force of the water smashed doors and windows of beach-front hotel rooms. Choppy waves traveled along the surface of the flood. The hotel grounds were flooded for about one hour. There were minor recessions during that time. The water began recession at about 13:00 local time. The receding water caused severe erosion of the sediments underlying the foundations of three beach-front buildings, including the landward end of the pier restaurant. It also undermined some of the piles supporting the pier restaurant causing causing them to rotate from vertical. These structures were extensively cracked and distorted as a result and will have to be demolished (Fig. 63).

The receding floodwaters left the grounds covered in fish that later putrefied. A ray was found at the upper limits of the flood.

Following the recession of the flood, the bay was noted to drain and fill with a period, recalled by witness Peter Pomeroy, estimated at 10 to 15 minutes (not timed by a timepiece). In addition to structural damage, extensive damage was done to the hotel's electrical system from salt water flooding including the destruction of a bakery that supplies bread to much of Praslin.

Another effect noted was a scouring of the bay and the deposition of a gravelly bar of coral detritus normal to the shore (previously, a bar was present parallel to shore according to Mr. Pomeroy).

Fig. 61: A- La Reserve Hotel. All of the buildings between points A and B will have to be demolished because of structural failure due to undermining of their foundations by the draining tsunami flood. The pier restaurant is midway between the two letters. North is toward the right. Virtually the entire property was inundated by the tsunami. Photo from http://www.mauritius-seychelles.com/la-reserve-hotel-seychelles.html).

Fig. 62: Brain corals exposed on the floor of the completely drained Anse Petit Cour ca. 08:00 UTC, 26 December 2004. La Reserve Hotel is seen in the background. View to the southwest. Photo courtesy Peter Pomeroy, La Reserve Hotel.

Fig. 63: Southwest side of pier restaurant showing erosion of foundation and partial collapse. Several of the piers of the structure in the background have rotated out of plumb. Photo: LEJ (GSC), 29 Jan 2005.

Site 17: Anse Volbert (Paradise Sun Hotel)

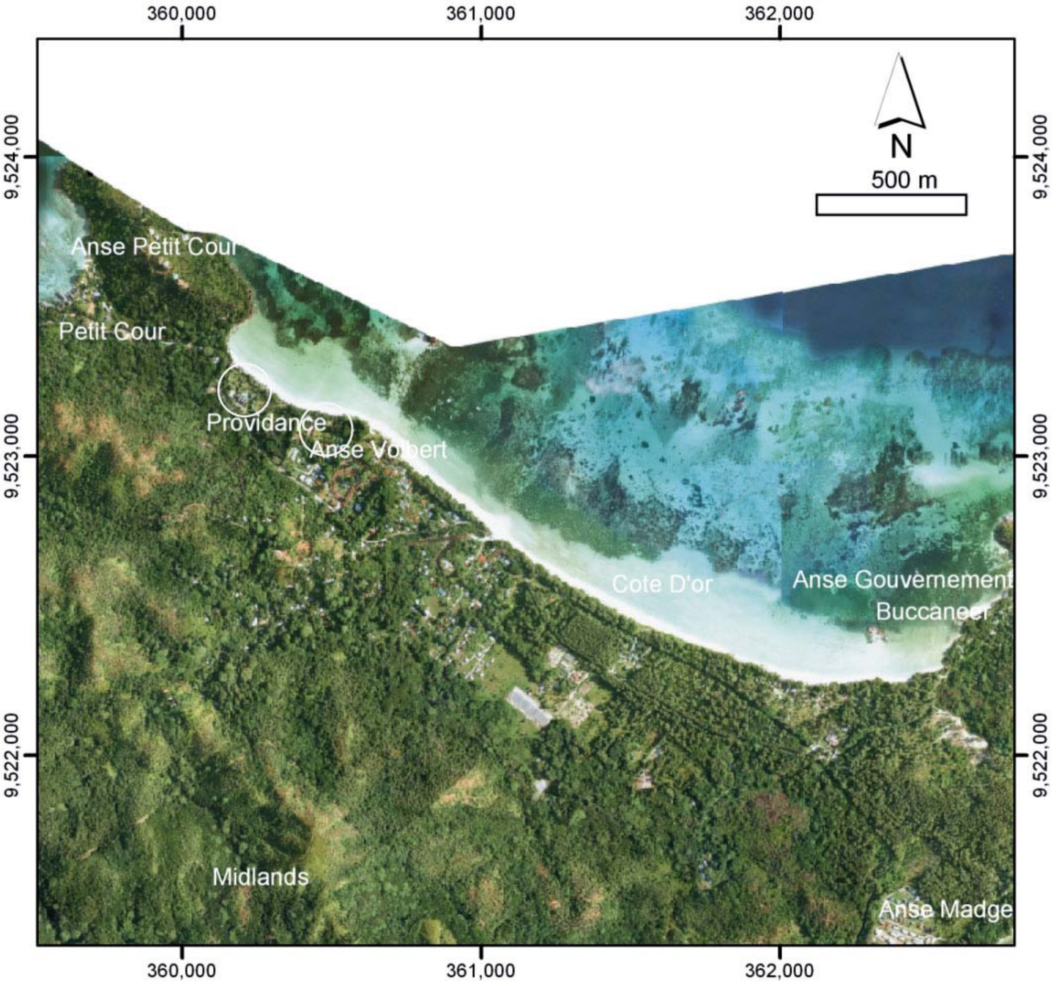

Fig. 64: Anse Volbert, with circles showing locations of Paradise Sun hotel (left) and Berjaya Praslin Resort (right).

Location: Extreme northwest end of Anse Volbert, north coast of Praslin.

Environment: The Paradise Sun hotel is located on a narrow coastal terrace behind a sandy beach; beyond the beach lies a wide reef flat (Fig. 64). When we visited the area between here and the next site we were struck by the large amount of coast protection work that has been done (Fig. 65). Because this stretch of coast is highly developed for hotels, beach armour and groynes have been installed to stop erosion. Now, of course, natural processes of coastal retreat and berm building have been halted, resulting in collapsing palm trees lining the eroding beach front.

Damage: The hotel was closed during our visit. The entire electrical and air conditioning systems had been put out of action by floodwaters that crossed the wooden rampart behind the beach and occupied the grassy terrace on which the chalets were built. We observed and surveyed well-defined flood marks in the grounds of the hotel. We interviewed Gilbert Gendron (security guard) and the manager Phil Pickering, who was not at the site when the first wave arrived. He claimed that the water retreated initially, and the time of first wave arrival was 11:00 local time. This was a very forceful wave. There may have been many waves but the interviewee talked only of two big waves, one at 11:00 and one about 16:00 local time. There was a high water level overnight, which they did he not observe, but saw the debris and water mark evidence in the morning. The first strong wave at about 11:00 carried heavy beach beds up into the car park but did not get into the swimming pool. The second wave got into the swimming pool. The beach level has been down since the event. However, beach levels are known to fluctuate over the years resulting in the installation of coastal protection (wooden pilings) to stop erosion. He claimed that 80 people went to the hospital seeking attention, one of who was a woman hurt on his property (Paradise Sun).

Fig. 65: The waterfront of the Paradise Sun hotel, showing the erosion of the beach has been an ongoing concern. The beach beyond looks undeveloped, but in fact this is one of the most developed stretches of coast on the island: hotels lie just to right of the fringing palms. Photo: JS (GSC), 28 Jan 2005.

Maximum run-up level: 1.9 m MSLD.

Maximum run-up distance: Approximately 100 m, the distance to the higher ground behind the hotel.

Remarks: This was an example of a hotel completely disabled by the tsunami due to destruction of its electrical system rather than structural damage.

Site 18: Anse Volbert (Berjaya Praslin Restaurant)

Location: On the northeast-facing coast of Anse Volbert, Praslin.

Environment: The hotel lies on a low, flat-lying coastal terrace (Fig. 64). The hotel restaurant - the pizzeria - is the most seaward part of the hotel.

Fig 66: The Berjaya Praslin hotel complex. The grassy area immediately northwest of the pizzeria is circled. This area was flooded and received a tsunami deposit of well-sorted medium to fine sand (Figs. 67 - 69). The run-up in this area reached the seaward part of the semi-circular hotel complex. The limit is about 175 m from the top of the beach or about 200 m from the MSL shoreline.

Description: Churchill Gill, our informant, was in the pizzeria during the event. A wave came beyond the high tide level then retreated. The water was ankle deep. It was dry out to the island of Chauve Souris (sea floor not normally exposed at low tide). The water rose and fell many times. The biggest wave was at 14:30-15:00 local time (10:00-11:00 UTC). The water became knee deep and flooded landwards into the grounds of the hotel.

Fig. 67: Restaurant on the beach, Berjaya Praslin Hotel. Photo: JVB (GSC) 28 Jan 2005.

Fig. 68: Discontinuous sheet sand deposited by tsunami in park beside restaurant (in background). Photo: DLF (GSC), 28 Jan 2005.

Fig. 69: Sand deposited beside speed bump 175 m inland (looking seaward to beach beyond buildings in far distance). Photo: DLF (GSC), 28 Jan 2005.

Damage: There was no structural damage. Some of the low berm at high tide level – near the fence – was eroded. However, a tsunami deposit of well-sorted fine to medium sand (maximum thickness of 7 cm) was deposited over the grassy area beside the pizzeria (Figs. 67 and 68) and up to approximately 175 m inland (Fig. 69).

Maximum flood level: Higher than 2.0 m (water was knee-deep in pizzeria).

Maximum run-up distance: About 175 m.

Site 19: Grande Anse (Palm Beach Hotel)

Location: Southwest coast of Praslin (04°19.930'S, 55°43.185'E).

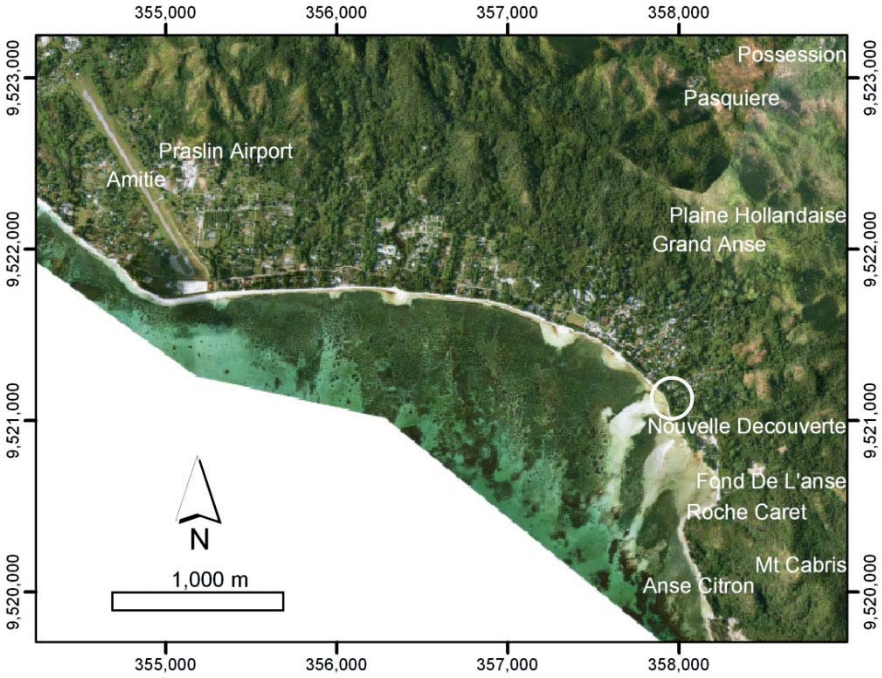

Fig. 70: Grand Anse, with the location of the Palm Beach hotel circled

Environment: The hotel is located in Grand Anse Bay, on the southwest coast of Praslin (Figs. 70 and 71), on and behind the berm of a sandy beach backed by coastal lowland. Like many properties that experienced damage, the natural berm is absent, and some continuing erosion problems are evidenced by the presence of granite rip rap. A groyne is located just to the south. The bay is unusual in that the reef flat is very wide (3 km) and is capped by large shore-transverse sand bars that are shore-attached in the vicinity of this site.

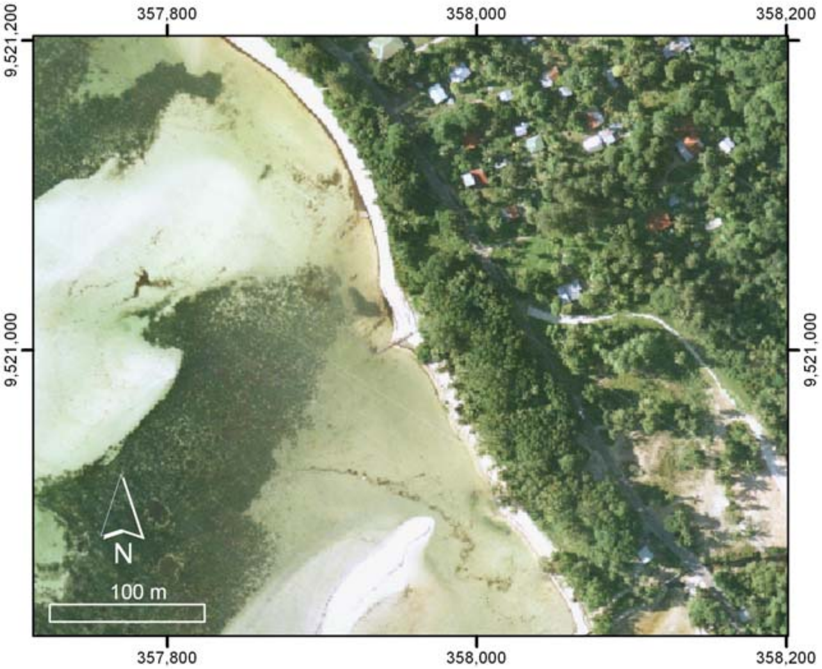

Fig. 71: An enlarged view of the beach near the Palm Beach Hotel. The groyne just south of the hotel is visible, as are the large shore-attached sand bars.

Description: The owner related a detailed account documented by photographs and video showing the tsunami surging through the hotel's bar. Timing of events was from memory. It had been a fine day and he planned to go boating later. The first wave came up to the normal high water level at perhaps 10:30 local time. The water withdrew and a second wave at about 11:00 (local time) came to the top of the sand berm at the hotel, in front of the terrace. After a retreat, a wave came in about 12:00 local time, seemingly quicker than previous waves. It flooded the terrace to a depth of about 20 cm, and flowed towards the land. The water rose and fell many times. The witness lost count as the situation deteriorated. One wave was reported to have approached the hotel from both directions along the shore, meeting at the hotel. The biggest wave was perhaps at 13:30 local time. It reached the top of the square parts of the stone pillars of the hotel. The witness thought that the highest wave was about 21:30 local time that evening. His video shows what is probably the 13:30 wave.

Damage: Mostly damage to stock, equipment, cars, and movement of the decking of the terrace.

Maximum run-up level: 2.8 m MSLD on one wave and 3.63 m MSLD on a later one.

Maximum run-up distance:. ~50 m (Fig. 72).

Remarks: Almost invariably damage occurred where hotel structures have been sited directly on beaches (Fig. 73), and where natural beach processes have been restrained by roads, structures, and in this instance, groynes. The rip rap is a clue to an existing problem. The manager was very forthcoming and provided photographs and also a dramatic video showing the floodwater rushing through the bar.

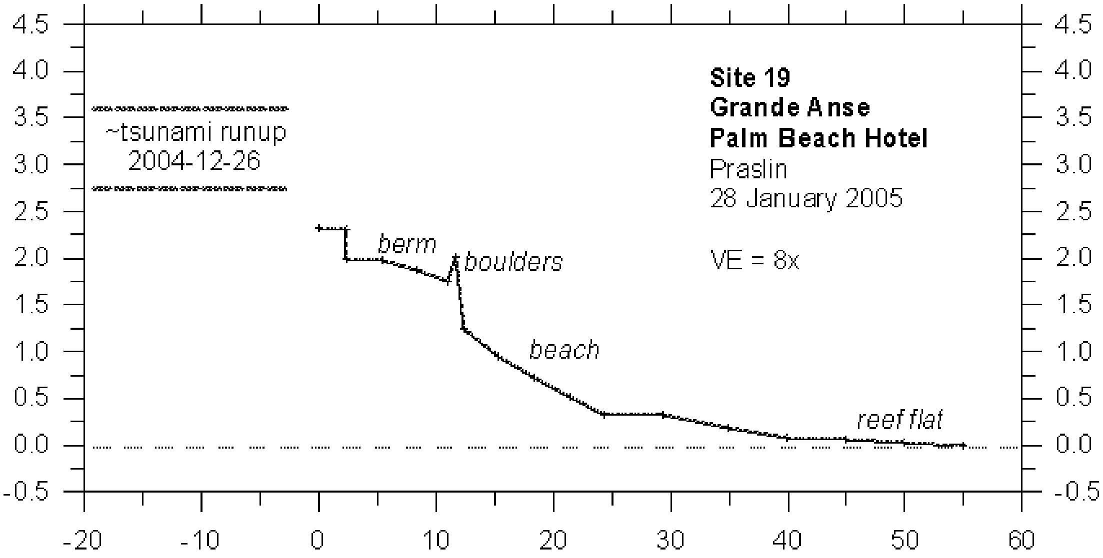

Fig. 72: Profile at Palm Beach Hotel, Praslin. Witness said the water (at 13:30) reached 43 cm up the pillar, the base of which is the start of the profile at left, giving an inundation level 2.75 m MSLD. However, he also indicated that it went through some windows at a level 130 cm above the terrace (flood level therefore 3.62 m MSLD). Seaweed debris was thrown a further 40 cm above this level.

Fig. 73: Palm Beach Hotel, Grand Anse, Praslin. Note the low granite rip rap that supposedly provides defense against waves. The natural berm is gone and the coast is constrained. Photo: JS (GSC), 28 Jan 2005.

Site 20: Baie Ste. Anne

Location: Southwest coast of Praslin.

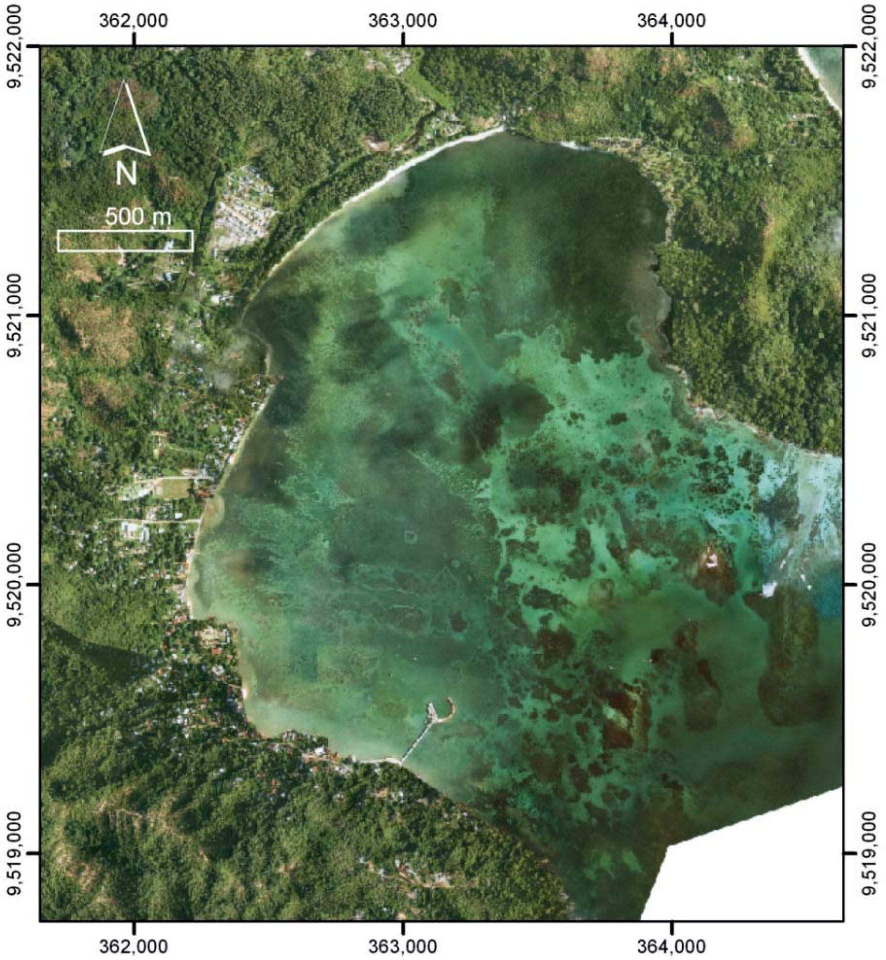

Fig. 74 Baie Ste. Anne, on the southeast coast of Praslin. This shallow bay is floored by coral reef. The pier at the south side of the bay is the location of the Mahé ferry terminal. Some land has been reclaimed at the west side of the bay, site of the main settlement.

Environment: Baie Ste. Anne comprises much of the eastern coast of Praslin. It is a southeasterly facing horseshoe-shaped bay protected by high headlands to the northwest and south (Fig. 74). Much of the population of Praslin Island as well as most of its businesses are located around the Bay.

Description: The events in Baie Ste. Anne during the tsunami are based on an interview with Paul Turcotte who owns a photography and film production business situated along the western shore of the bay. During the tsunami, water levels within the bay only rose to the high tide level. No flooding occurred. Strong currents were generated in the bay as evidenced by coral blocks that were swept through constriction created by recent artificial fills (Figure 74 predates fills).

Damage: none

Maximum run-up level: to high tide level ~1.8 m

Maximum run-up distance: within normal high tide

Remarks: Baie Ste. Anne is remarkable in that it experienced minimal tsunami effects compared to other areas on Praslin Island such as Chevalier Bay that were impacted by maximum run-up levels approximately twice as high. It illustrates the significant effect that orientation and bathymetry played in mitigating or exacerbating the effects of the tsunami. However, if the tsunami had struck during higher tide, there would have been extensive flood damage to homes and businesses in the area.

DISCUSSION

The effects of the tsunami can be summarized in terms of a hierarchy of effects, as follows. At the first level, refraction on the shelf around the granite islands brought the tsunami waves to leeward coasts.

At the second level in the effects hierarchy the tsunami waves approaching shore were funneled into embayments such as Anse à la Mouche. It was also apparent that reflection by headlands may have accentuated the funneling. It is not clear whether or not intensive land reclamation in the form of artificial islands on the east coast of Mahé provided a beneficial protection from the incoming waves.

At the third level, damage was incurred by inappropriately located infrastructure. Most of the recorded damage to infrastructure occurred where hotels are located at the coast. Obviously most of the attraction of a hotel in the islands lies in a coastal setting, so there is a tendency to locate buildings very close to the water. On Praslin, one hotel had a restaurant actually located on pylons projecting into the ocean. The most extreme example of capitalizing on a coastal setting is the location of chalets on stilts within reefs, as is done on the Maldives. This is presently not practiced in Seychelles.

While observing damage to hotels, where natural berms had been removed, or at places where coasts had been constrained by roads and walls, we also that observed adjacent stretches of coast with natural berms were undamaged. While we have not been directed to comment on coastal zone management practices, we nevertheless feel that the vulnerability of infrastructure to the tsunami has been increased by inappropriate practices.

The Seychelles provided an excellent natural laboratory in which the tsunami phenomenon could be studied from a location proximal enough to the tsunami source so that waves, run-up and inundation had sufficient impact to arrest the attention of many observers. However, it is distal enough so that coastal areas escaped with generally superficial damage and witnesses, with two unfortunate exceptions, lived to share their observations. There are many phenomena recorded in this report that will require further investigations in order to more completely understand them. For example:

- Refraction on the shelf around the granite islands brought the tsunami waves to leeward coasts. This, in retrospect, is not unexpected. Modeling of this refraction would be a useful scientific follow-up to our efforts and could be employed in further predicting particularly vulnerable areas around the granitic Seychelles islands in the event of a future tsunami. Modeling would explain the anomalous occurrence of sites immediately adjacent to one another such as Baie Lazare (site 9) and Anse á la Mouche (site 10) that experienced dramatically different degrees of inundation.

- How many tsunami wave trains struck Mahé and Praslin? The first destructive wave arrived shortly after 08:00 UTC. In many areas, waves had diminished to within the high tide range within an hour of this wave. However, an exceptionally large wave, which did extensive damage locally on the west coast of Mahé and flooded Victoria, was recorded on both islands at ca. 13:00 UTC. Was this the first wave of a separate wave train triggered by an aftershock or was it an anomalously large wave in a generally decaying single wave train?
- The oscillations recorded on the Mahé tidal gage continued through several tidal cycles. The highest water in the Victoria harbour and at the adjacent tide gage came at about 01:00 UTC in conjunction with high tide. Was this a tsunami wave or were most of these oscillations by that time due to seiching induced by the passage of the tsunami wave train during the previous day?

These points and other phenomena remain to be addressed with the context of Seychelles and the larger context of the cumulative record of all of the tsunami survey data collected around the Indian Ocean and beyond.

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INTERVIEWS

Transcripts of interviews referred to in the site descriptions will be made available upon written request to the authors.