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# GEOMORPHIC EVIDENCE AND RELATIVE AND ABSOLUTE DATING RESULTS FOR TSUNAMI EVENTS ON CYPRUS

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## ABSTRACT

For the Mediterranean area, almost 100 tsunamis were recorded in historical sources from Antiquity till present. Recordings often describe the consequences for human lives and buildings in coastal areas. However, little evidence for the geomorphic effects of tsunamis has been collected in this region.

Tsunami run-up may destroy soil and vegetation. Tsunamis may further move extremely large volumes of coarse clastic material including individual boulders weighing more than 20 t. Trottoirs, supra-littoral cliffs, and tafoni may also be destroyed. Deepwater foraminifers deposited on land also provide evidence for Tsunami action. Recently extensively dispersed tsunami deposits were observed in southwestern and southeastern Cyprus. Field collected evidence proves tsunami action for over 60 km of coastline and about 100 - 150 m inland. Coastal areas up to 15 m asl, sometimes up to a maximum height of 30 - 50 m asl, have been influenced by tsunami action on Cyprus Island. This paper describes these deposits, their morphologic characteristics, and possibilities of relative and absolute dating. Cues for relative age determination are provided by soil and vegetation, tafoning, karstification on displaced boulders, and by post-tsunami cliff and beach rock development. Field evidence suggests that tsunamis occurred during the last few centuries. This time estimate was also supported by the absolute $^{14}C$ dating of vermetids and calcareous algae crusts on displaced boulders, and by the dating of relocated wood and charcoal. Overall, strong tsunami action can be assumed for the time between 1530 and 1821 AD.

INTRODUCTION

The island of Cyprus is located in the eastern Mediterranean Sea off the Turkish coast and encompasses an area of approx. 9,300 $km^2$ (Figure 1). Numerous accounts of tsunamis in the Mediterranean region have been reported since Antiquity (Heck, 1947; Papadopolous and Chalkis, 1984; Dominey-Howes, 1996a, Perissoratis and Papadopolous, 1999; Soloviev et al., 2000; Matronuzzi and Sanso, 2000). However, Soloviev (2000) points out that the Island of Cyprus is an "interesting, but poorly studied, tsunamigenic zone". The Mediterranean is generally known as a region with high tsunami susceptibility, however, as Dawson described in 1994 "no detailed paper on the geomorphological effect of tsunamis" exists for this region, with the exception of the recently published papers by Kelletat and Schellmann (2001) focusing on coastal research on Cyprus Island and by Mastronuzzi and Sanso (2000) concentrating on tsunami deposits on the southern coast of Italy.

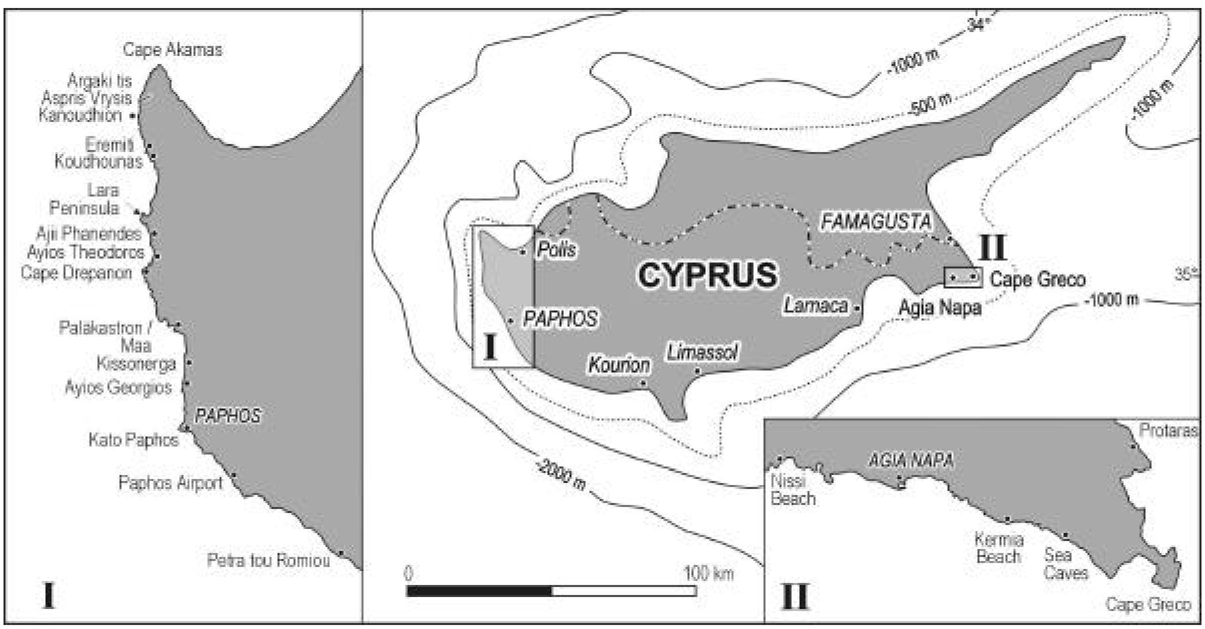


Figure 1: Map of Cyprus Island. Maps I and II display locations described in this paper (modified after Kelletat and Schellmann, 2001).

Despite detailed reports on the loss of lives and cultural landscapes, detailed geologic and geomorphic studies on the effects of these reported tsunamis on coastal landscapes in the Mediterranean region are still to be conducted. It was not until the last five to ten years that coastal research considered that tsunamis leave sedimentologic evidence in coastal regions (Dawson, 1999).

This is surprising since Papadopolous and Chalkis (1984) reported 119 earthquakes with a 6.5 magnitude or higher for Greece for the time between 479 BC and 1799 AD. These earthquakes were associated with 33 tsunamis. For the time period between 1800 and 1981, 130 of these earthquakes were reported, 34 of them were associated with tsunamis. 22 of these reported 67 tsunami events were catastrophic and destructive. Van Dorn (1965) reported 9 tsunamis till 1500, and 8 more tsunamis between 1500 and 1800. Based on Van Dorn (1965), 6 large tsunamis have occurred in the Mediterranean region since 1800. However, geomorphic evidence for these events has not been reported yet for the eastern Mediterranean region and sedimentologic evidence is mentioned in four sources only. Dominey-Howes et al. (1998) conducted research on the sedimentologic evidence of a tsunami in Falasarna (western Crete). The tsunami is likely to have occurred in 66 or 365 AD, based on the dating of foraminifers located above the beachline. Dominey-Howes (1996 a and 1996b) and Dominey-Howes et al. (2000) describe beach sediments that include gravel and cobble in locations up to 10 m asl for three localities on Astipalaea. These sediments have most likely been deposited by the 1956 tsunami that occurred in the southern Aegean. Heck (1947) and Mastronuzzi and Sanso (2000) are the only ones who reported boulder-size deposits as tsunami evidence. Based on Heck (1947), the 1908 tsunami, which occurred in the Street of Sicily with wave heights of 33 to 39 feet, transported a 20-ton boulder over a 20 m distance. Mastronuzzi and Sanso (2000) analyzed large boulders located on the Ionian coast (Italy).

It remains to be stated that, in contrast to regions in the Pacific Ocean, hardly any reports on field evidence of tsunami events in the Mediterranean region exist. This research observed field evidence for one or several tsunami events on Cyprus Island in younger historical time. Tsunami deposits and other evidence, including dating results, are described. This paper presents a detailed geomorphic study of the qualitative and quantitative effects of high magnitude - low frequency events on the costal formation in the Mediterranean region.

Neither the Geological Survey in London and in Nocosia (Dr. Xenophontos), nor written or oral reports, know of observations of tsunami evidence on Cyprus before the Amorgos tsunami of 1956. However, several tsunami events have been reported in literature for Cyprus and the surrounding region (Table 1).

| **Literature** | **Important tsunamis in Cyprus and the surrounding region** |
|---|---|
| Heck (1947) | 740, 1402, 1646 AD |
| Galanopoulos, A.G. (1957) | 1956 AD |
| Ambraseys (1960) | 479 BC, 426 BC<br>62 or 66, 365, 1650, 1821 AD |
| Ambraseys (1962) | 23 BC<br>76, 342, 1202, 1222 AD |
| Papadopoulos and Chalkis (1984) | 1410 BC<br>365 AD |
| Papazachos et al. (1985) | 1956 AD |
| Klug (1986) | 1956 AD |
| Soloviev (1990) | 92 BC, 26 BC,<br>1222, 1953, 76?, 342? AD |
| Dominey-Howes (1996a, 1996b, 1998) | 66, 365, 1956, 1650, 1956 AD |
| Perissoratis and Papadopoulos (1999) | 1956 AD |
| Dominey-Howes et al. (2000) | 1956 AD |
| Soloview et al. (2000) | 23 BC<br>76 (or 77), 342, 1202, 1546, 1822, 1953 AD |

Table 1: Tsunamis reported for the eastern Mediterranean.

This paper describes the sedimentologic and geomorphic evidence for tsunamis of younger historic age that has been observed on Cyprus. Tsunami evidence (Figure 2) has been observed on approx. 60 km along the western coast of Cyprus Island between the Aphrodite-rock Petra tou Pomiou, Paphos, and Cape Akamas. Tsunami evidence was also recorded on approx. 10 km of the southeastern coast of Cyprus Island, between Nissi Beach/Agia Napa and Cape Greco. Significant evidence for tsunamis has been found within these areas. Figure 3 depicts a profile of the typical morphology of a tsunami impacted low cliff on Akamas peninsula.

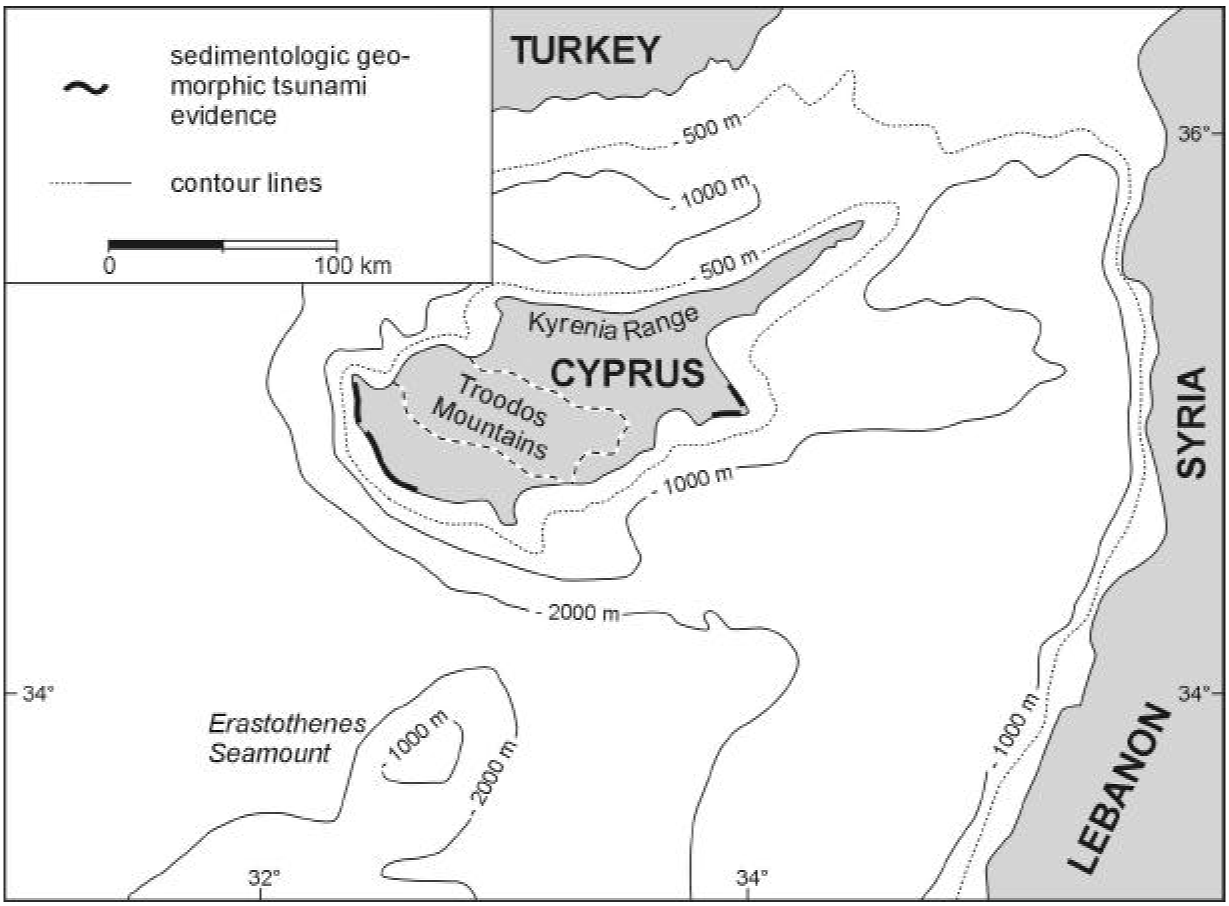


Figure 2: The location of coastal regions with sedimentologic geomorphic tsunami evidence (modified after Kelletat and Schellmann, 2001).

The coastal landscape on Cyprus is hilly with incised valleys. Pleistocene beach deposits such as cemented dunes or beaches, or foreshore-sediments are frequent. The coastline is predominantly rocky with cliffs of up to 50 m asl. Beaches are located in the Bay of Polis in western Cyprus and around Limassol in the south.

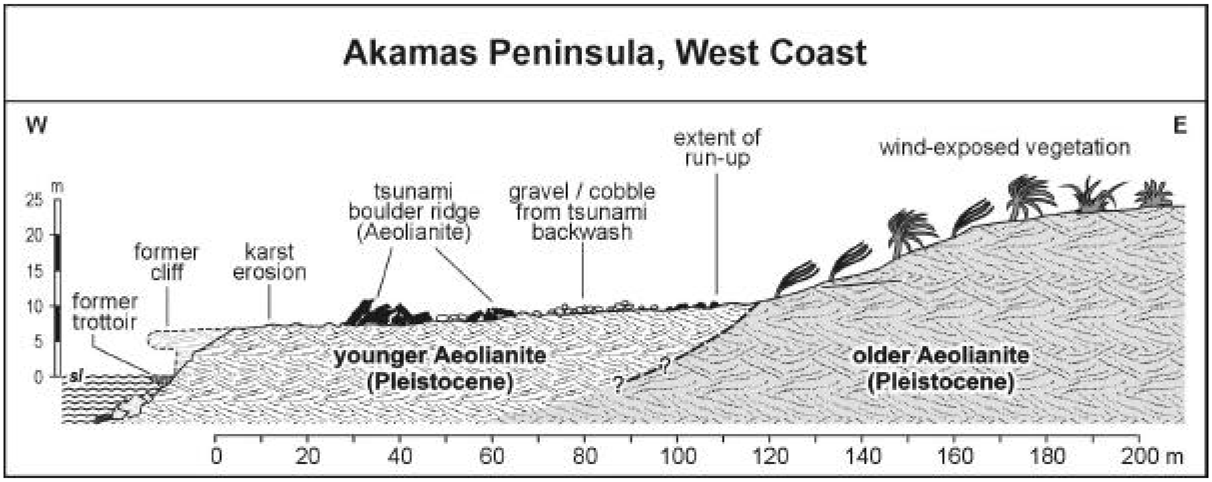


Figure 3: Profile of the typical morphology of a tsunami-impacted cliff on Akamas Peninsula (modified after Kelletat and Schellmann, 2001).

## GEOMORPHIC EVIDENCE FOR A TSUNAMI EVENT ON CYPRUS

### 1. Deposited Boulders and Boulder Ridges

Figure 2 marks coastal areas with sedimentologic and geomorphic evidence for tsunamis on Cyprus. Boulders and boulder ridges supply evidence for at least one significant tsunami event on Cyprus. They have been observed on numerous localities along the western and southeastern coast of Cyprus, in particular, along the 40 km long coastal region extending from the southern Akamas peninsula to north of Pahos. Figures 3 and 7 illustrate the location of these deposits on the western coast of the Akamas peninsula. The boulders are "strangers" in this coastal environment. They are separated from the present supra-littoral area and from wave impact and are located on bare rock surfaces several tens of meters away from present surf impact zone and several meters asl. Individual boulders reach weights of up to several tons and have edges and surfaces with a relatively fresh appearance. The deposits are located in areas stripped of any soil and vegetation. They have been observed as individuals, loosely dispersed over an area, and as boulder ridges (Figure 4). Figure 4 illustrates a more than 200 m long boulder ridge composed of Aeolianites located along the coast in the Bay of Eremiti on the Akamas peninsula. Boulders have been deposited at +5 m to +10 m asl. Tsunami run-up extended up to +15 m asl.

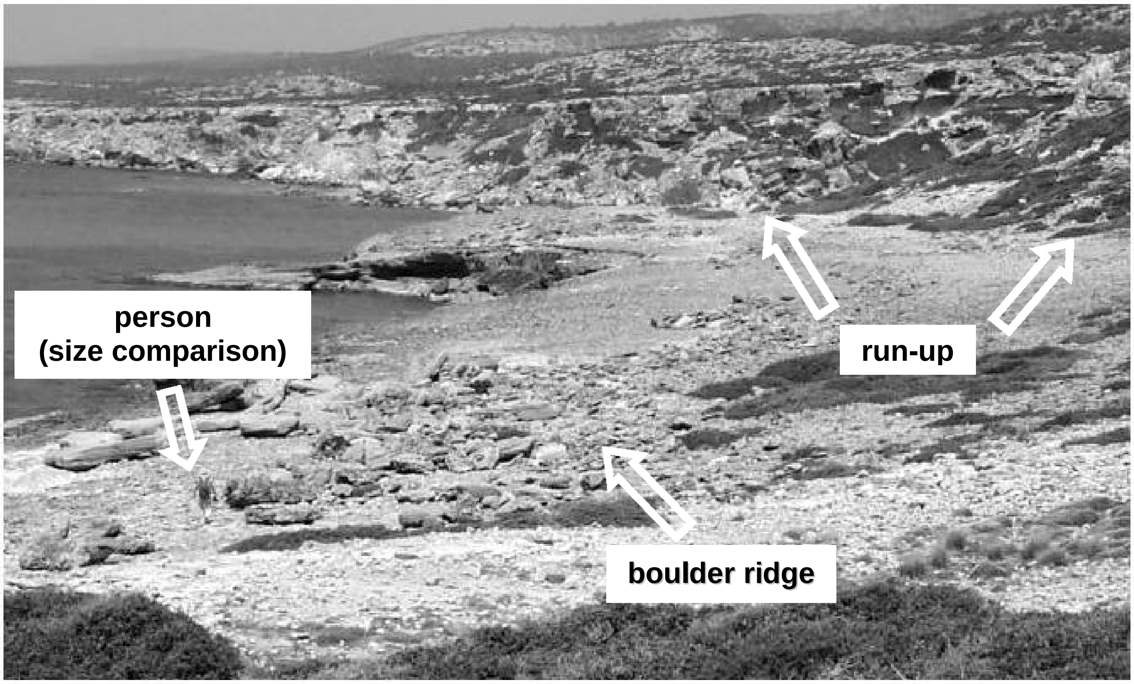


Figure 4: Tsunami deposited boulder ridge in Eremiti Bay on Akamas Peninsula. Boulders were deposited at elevations ranging from 5m to 10m above sea level. Tsunami run-up extended up to 15m (modified after Kelletat and Schellmann, 2001).

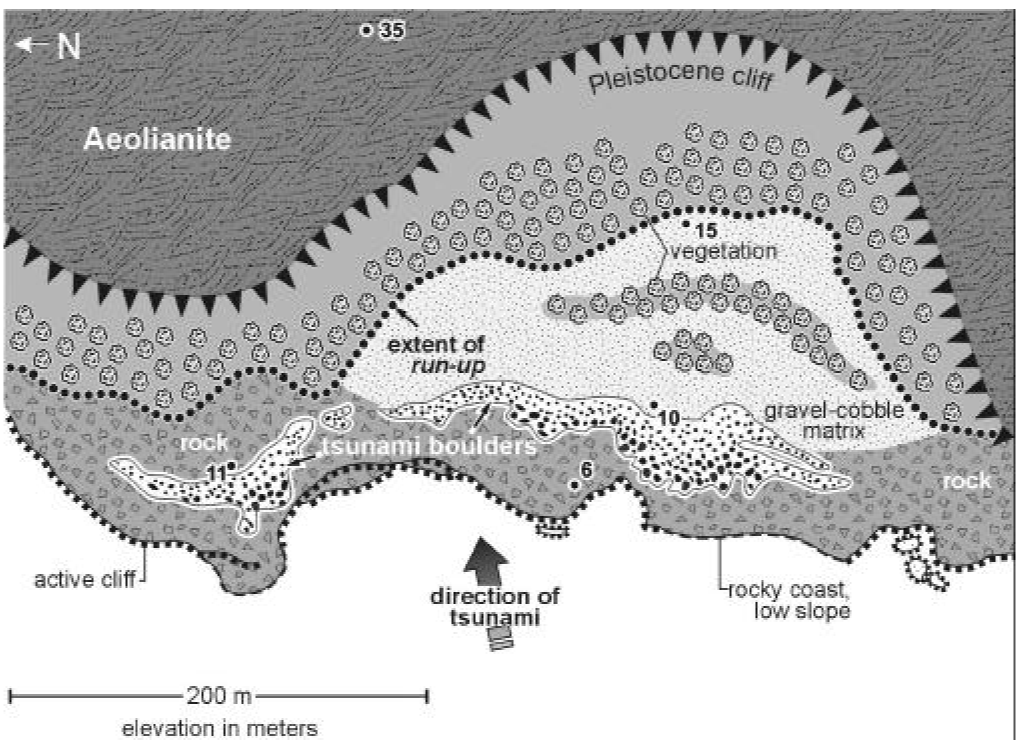


Figure 5: Geomorphic map of tsunami deposits in Eremiti Bay on Akamas peninsula (modified after Kelletat and Schellmann, 2001).

The area between boulder ridge and coastline is stripped of any sediment and characterized by rough rock surfaces with traces of erosion.  In contrast, littoral gravel and sand deposits have been observed in the area between boulder ridge and the coastal area not impacted by a tsunami.  Several patches of vegetation are also present in this zone.  Figure 5 provides a geomorphic sketch of the Bay south of Eremiti on the western Akamas peninsula.  A zone with thin sediment deposits and patches of preserved vegetation marks the run-up area of the tsunami wave.  The wavelike border of this zone marks the extent of the run-up.

Boulder ridges or boulder lines were also observed on other coastal areas on Cyprus Island, sometimes with dimensions of almost 1,000 m in length.  For example, boulders are lined up on young Pleistocene Aeolianites near Nissi Beach.  Boulder ridges have also been observed on Lara peninsula (Figure 6).  Figure 6 illustrates a tsunami boulder ridge on Lara peninsula, located in a distance of 100 m to the ocean and at 8.5 to 10 m asl.

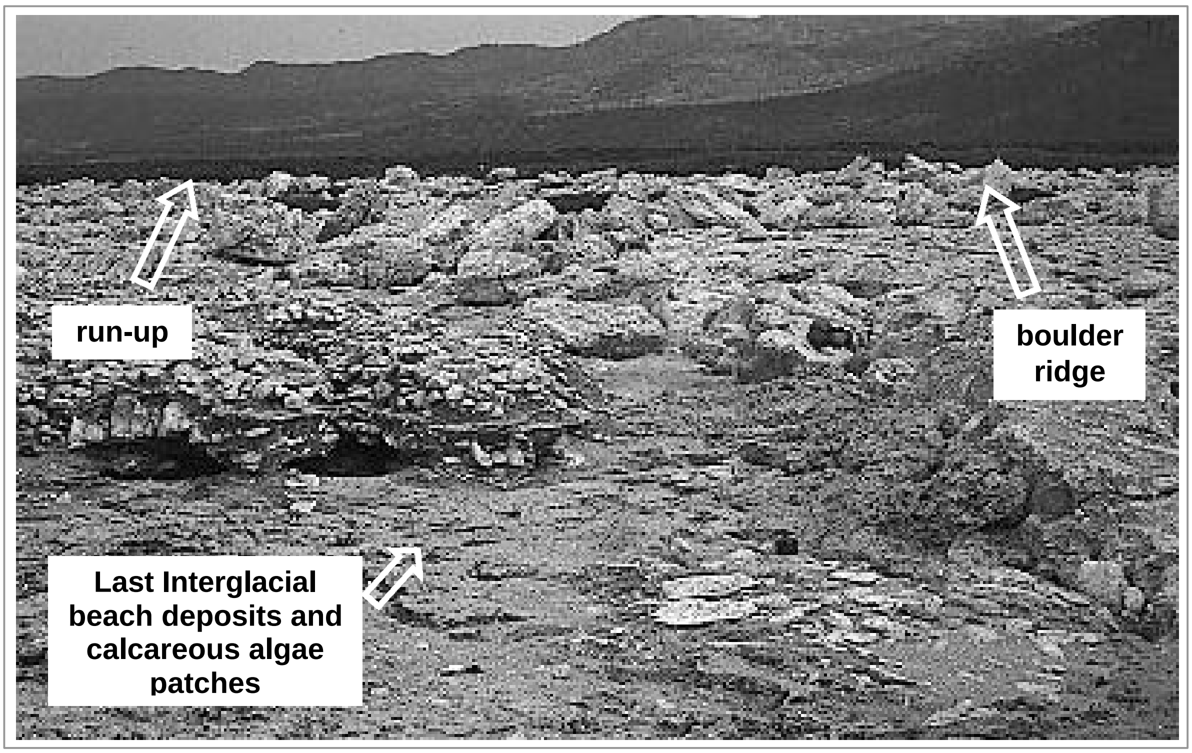


Figure 6: Tsunami-deposited boulder ridge on Lara Peninsula.  Boulders were deposited at approx. 10 m above sea level at a distance of approx. 100 m to the sea.

The individual weight of the deposited boulders within these tsunami deposited boulders, boulder lines, and boulder ridges is significant.  Several thousand boulders weigh more than one t, below Eremiti up to 20 t, on the Lara-peninsula mostly between two and seven t, and some more than 20 t.  Two individual deposits weigh approx. 50 and 55 t.  Near Sea Cave east of Agia Napa, boulders reach 10 to 20 t in weight, near Nissi Beach they reach up to 30 t.

The location of the observed boulders and boulder ridges is clearly separated through elevation and distance from the present surf and wave impact zone. Some deposits are located more than 100 m away from the present rock littoral zone. The boulder ridges are generally deposited in a wave like form and follow the contour lines of the coastline in a distance of several decameters (Figures 4, 5, 6). Boulder deposits are located at elevations up to 10 m asl and are out of the reach of waves generated by storms.

The abundance of boulders, their dimensions, their dispersion, and their separation from the littoral zone support the idea that these boulders were deposited by tsunamis and not by storm events. The deposits are present at a 40 km long stretch of coastline north of Paphos. Individual boulders have also been observed south of Paphos to Petra tou Romiou located 30 km south of Paphos. Figure 7 provides an illustration for the observed tsunami impact and the extent of the run-up on the northern Akamas peninsula.

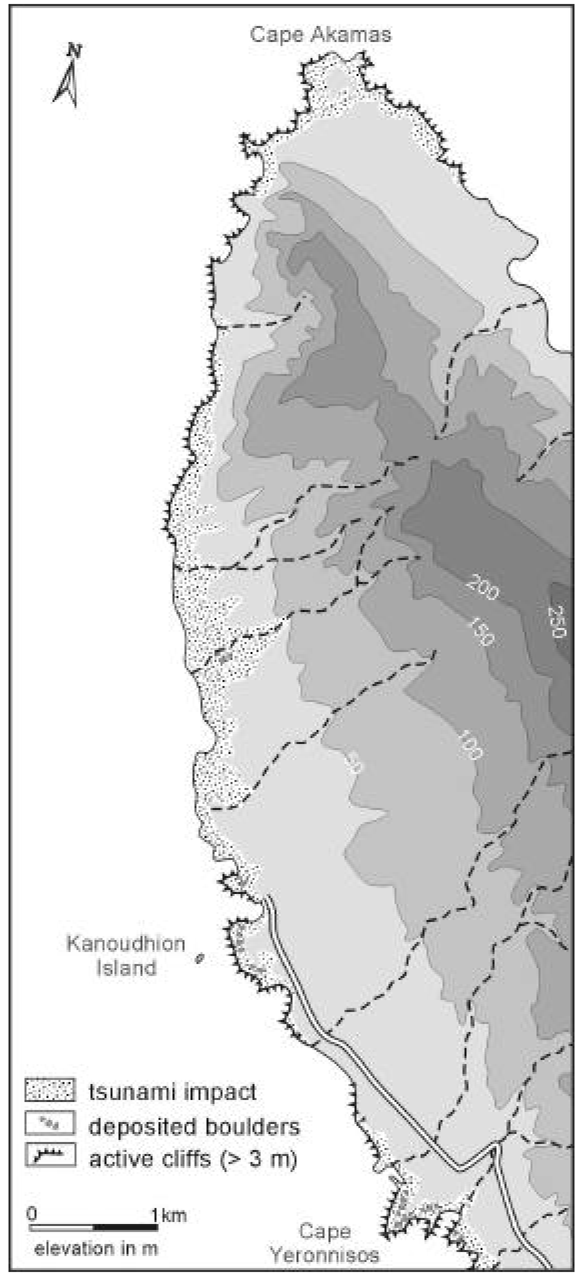


Figure 7: This map of the northern Akamas Peninsula illustrates where tsunami evidence was observed on the western coast of Cyprus Island (modified after Kelletat and Schellmann, 2001). The relatively soil and vegetation free surface provides evidences for the extent of the tsunami run-up and is visible in the field and on aerial photographs (see also Figure 11).

Tsunami deposits were also observed in the easternmost part of Cyprus near Sea Caves to the west of Cape Greco. There, boulders are located on an 8 m high cliff and along a one km long coastal area between Nissi Beach and Agia Napa. Low cliffs provide resistance to the tsunami wave and material to be broken off by the wave. No boulders and boulder ridges have been observed on cliffs higher than 10 m, and in areas where low cliffs are missing.

## 2. The Reconstruction of the Origin and Path of Transport of Deposited Boulders

Some boulders allow for the derivation of their origin and the reconstruction of the path of transport based on field evidence. For example, a beachrock boulder weighing approx. 0.5 t was deposited at +4 m on a small Aeolianite cliff south of Paphos airport (Figure 8). The boulder originated from the beachrock band located along both sides of the cliff. The boulder was moved at least 10 m sideways and 4 m upwards. Near that locality, an 8 t Aeolianite that originated from an Aeoliante cliff within a distance of 40 m, was relocated onto beachrock.

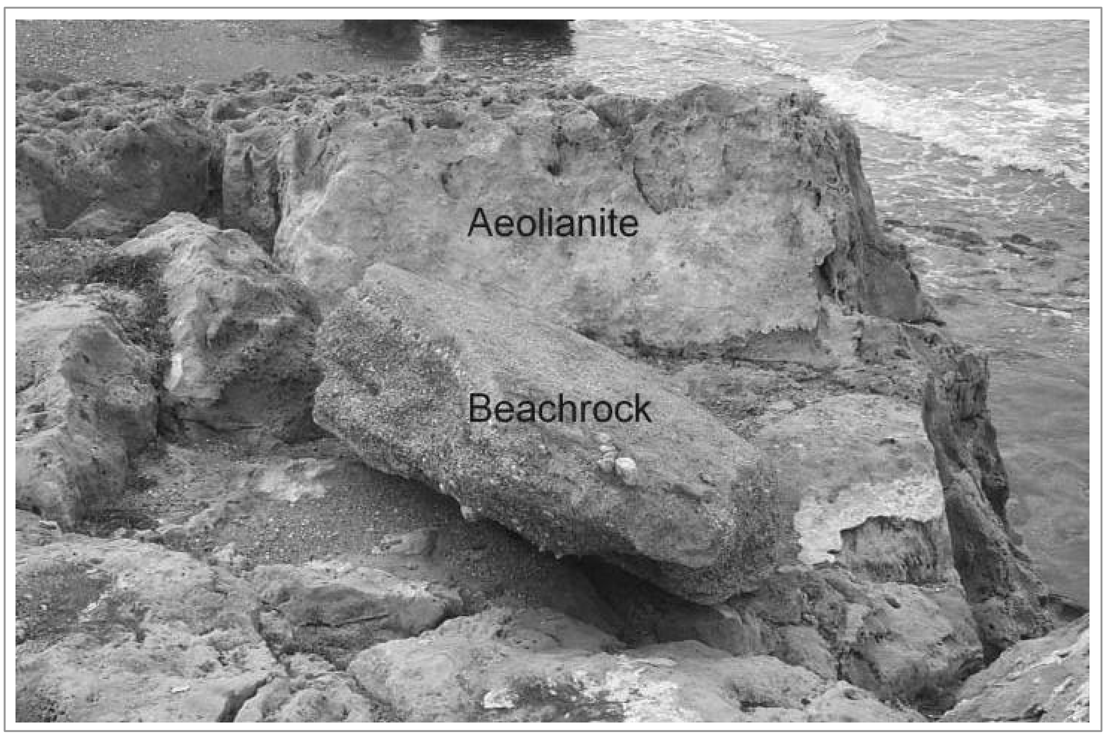


Figure 8: This beachrock boulder (length approx. 1m) was moved and deposited on a 4 m high Aeolianite cliff south of Paphos Airport (modified after Kelletat and Schellmann, 2001).

In some cases, the path of transport can be reconstructed based on textural properties of the dislocated boulders, attached sediments, or because the shape of a boulder matches its place of origin. Figure 9 illustrates an approximately 28 t boulder located on the present cliff with an elevation of +8 m asl in the southern Lara-peninsula. A rock pool at the bottom of the boulder provides evidence for the movement of the boulder. The boulder must have been turned upside down.


Figure 9: Large dislocated boulder of approx. 28 t on the southern Lara peninsula. Note the person in front of the boulder for a size comparison. A rock pool is located at the bottom of the boulder. A tsunami deposited boulder ridge is located in the background.

## 3. Cobble and Boulder Terraces

Cobble and boulder terraces in the coastal area may also provide evidence for tsunami impact. Tsunami terraces near Agios Theodoros south of the Lara peninsula show 3 to 3.5 m asl and 50 to 250 m wide cobble-boulder terraces that display little surface weathering and low vegetation density. The sediment matrix consists of chaotically layered large deposits of sand, gravel, cobble, and boulders with a boulder content of 80 to 90%. The chaotic layering clearly distinguishes these terraces from the well-layered sediment matrix of beach terraces deposited by numerous storm waves.

Tsunami impact may also be derived from the deposits of rounded gravel and cobble at elevation of 6 to 7 m and exceeding 10 m asl. These deposits have been observed above old beach lines and on top of weathered soil layers, as for example the gravel and cobble deposits on a Terra Rossa approx. 4 km north of Cape Drepanon. Since these deposits are located far beyond the reach of present storm waves, their origin can only be explained with the deposition through the run-up or backwash of a tsunami.

## 4. Other Geomorphic Evidence for Tsunami Impact on Cyprus Island

Several geomorphic traces provide evidence for at least one strong tsunami event on Cyprus Island. These include destroyed and newly forming tafoni in the coastal zone, partly destroyed weathering surfaces in rocky coastal areas, and evidence for the destruction of cliffs and notches. A tsunami tears off several boulders particularly from the upper cliff area and above notches, because these are the areas with the greatest resistance against the tsunami wave. There, the wave can access the area underneath the notch and break off the overhanging rock material. As a result, cliffs are heavily eroded with notches missing. Small notches generated through bioerosion and trottoirs build up by calcareous algae and vermetids were observed on a lower cliff located on Lara peninsula. Sharp edges on this cliff document the break-off of material. Several rock-pool were cut in half during tsunami impact.

Other significant evidence for tsunami impact on the west and southeast coasts of Cyprus Island in younger historic time includes the bare rock platforms stripped of any soil and vegetation (Figures 9,10). On the western Akamas Peninsula, individual boulders were deposited on a bare Aeolianite platform. Run-up extended up to 13 m asl at this location approx. 2.5 km north of Cape Drepanon. Figure 10 illustrates individual boulders deposited at an elevation of approx. 10 m asl on bare rock on Lara Peninsula.

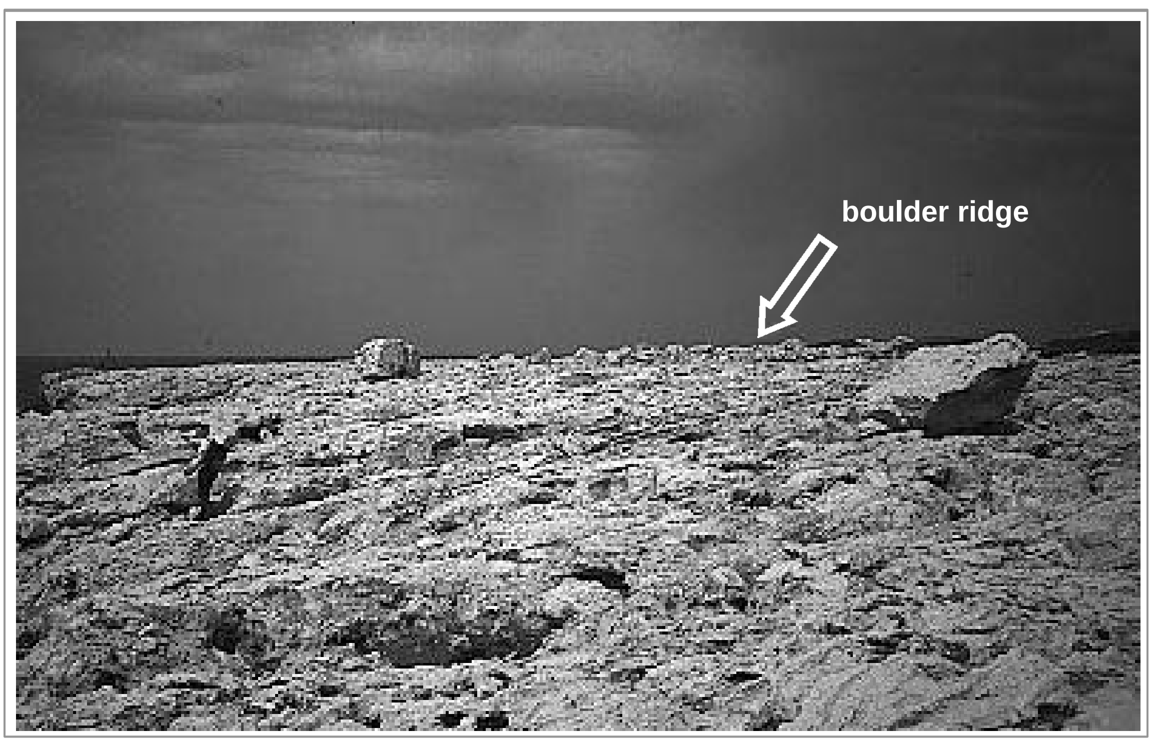


Figure 10: Individual boulders were deposited on bare rock surfaces on Lara Peninsula. Note the boulder ridge in the background.

The west coast of Cyprus Island is characterized by these bare rock platforms extending over 40 km along the coast with widths of several decametres to 100 m. The bare rock platforms are visible on aerial imagery taken from approx. 6,000 m above ground (Figure 11). The aerial photograph (Figure 11) displays the tsunami impacted coastal area with bare rock and vegetation and soil free areas. Argaki tis Aspris Vrysis is located in the lower part of the image and shows the extent of the tsunami impact reaching approx. 800 m inland. Aerial imagery was used to map the tsunami impact zones (see also Figure 7).

Figure 11: The tsunami impacted coastal region on Akamas Peninsula is visible on aerial photographs taken from 6,000 m above ground (modified after Kelletat and Schellmann, 2001). Note the vegetation and soil free coastal zone.

## RELATIVE AGE DETERMINATION OF THE TSUNAMI EVENT

Aerial imagery from 1963 displays the same areas stripped of soil and vegetation. This allows for the conclusion that soil formation and the recolonialization of vegetation at the coast of Cyprus occur very slowly. Therefore, the last great tsunami did not occur a few years ago, as one might assume based on the absence of any soil and vegetation, but it must have occurred more than several decades up to a few centuries ago. Similar relative ages have also been determined since new notches on destroyed cliffs have not been formed. The low degree of karst erosion and tafoning weathering, only individual tsunami deposited boulders experienced these processes, also allows for this conclusion.

As already stated above, neither historic records nor official authorities nor oral tradition hints on any tsunami event on the west and south coast of Cyprus. Therefore, the age of the tsunami event should be greater than the historic memory of the present population and it should be older than reliable historic records. The Amorgos earthquake of 1956 may be excluded as well as all other earth or seaquakes during the $20^{th}$ century and the time of British occupation back to 1878. The tsunami event must have occurred earlier. Due to the Greek wars in 1821, historic records are incomplete and unreliable. Therefore, the great tsunami of Cyprus must have happened before these wars, which were more than 180 years ago. The missing soil and vegetation layer, however, eliminate ages of many centuries.

## ABSOLUTE DATING

Radiometric age determination (Table 2) dated the tsunami event at the southwestern coast of Cyprus younger than 890 14C years BP (based on the dating of calcerous algae and vermetids) and older than 80 14C years BP.

| Sample Location | Laboratory No. | No. of Sample | Elevation (m asl) | Dated Material | $^{14}$C-Age years BP | time span AD |
|---|---|---|---|---|---|---|
| West of Kissonerga | Hd 20380 | 25-99 | + 3 m | vermetid | 890 ± 24 | 1070-1210 AD |
| 3 km west of Petra tou Romiou | Hd 29441 | 2a-99 | + 1 m | charcoal | 237 ± 42 | 1530 - 1950 AD |
| 4 km west of Petra tou Romiou | Hd 21254 | 11-00 | + 2.5 m | charcoal within tsunami deposited terrace | 125 ± 28 | 1680 – 1950 AD |
| | Hd 21260 | 12-00 | + 2.5 m | charcoal within tsunami deposited terrace | 90 ± 28 | 1685 – 1950 AD |
| approx. 3.5 km north of Cape Drepanon | Hd 20670 | 9*2-99 | + 5 m | wood | 112 ± 20 | 1680 - 1950 AD |
| | Ki 4597 | 9*1-99 | + 5 m | Juniper root | 155 ± 55 | 1660 - 1950 AD |
| Eremiti Bay | Hd 21261 | 9h-00 | + 10 m | Pistacia root | 137 ± 20 | 1680 - 1950 AD |
| | Hd 21095 | 9k-00 | 5 - 6 m | calcareous algae | 908 ± 31 | 1400 - 1470 AD |
| | Hd 21050 | 5a-99 | 5 - 6 m | vermetid | 1724 ± 39 | 620 - 730 AD |
| | Hd 21081 | 9v-00 | 5 - 6 m | vermetid | 2570 ± 46 | 380 - 170 AD |

Table 2: Selected absolute dating results. Ages in AD are calibrated ages (Calib rev. 4.3; based on Stuiver and Reimer, 2000). Age intervals are relatively large due to the large variability in atmospheric $^{14}$C-content.

Accounting for the reservoir effect of 300 to 500 years, C14 dating of calcareous algae and vermetids attached to dislocated boulders dates at 590 to 390 years BP. However, it is likely that the outer layer of calcareous algae and vermetids has been eroded and that older algae and vermetids were already dead when the tsunami occurred. The C14 dating results from relocated plant material and charcoal is more exact, but involves the risk that these were relocated or that it was not the youngest outer layer of the wood material that was dated. Therefore, the tsunami event may be younger than the dating results of 80 to 237 C14 years BP. However, due to the anthropogenic change of the atmospheric 14C level, the accuracy of radiocarbon dating for the time period since the early 19th century is poor. Calibration with dendrochronologic curves (Stuiver and Reimer, 2000) gives a broad time span for a tsunami event between approx. 1530 and 1950.

Absolute dating results also confirm the idea that the morphodynamically high impact tsunami event in western and southern Cyprus occurred before the Greek wars of 1821, most likely within the second half of the 18th century. More strongly weathered boulders and boulder ridges near Eremiti could have been deposited during a tsunami that occurred some hundred years earlier than the other tsunami event. It still remains to be researched, how many strong tsunami events occurred.

## CONCLUSION

This study correlated significant geomorphic evidence with tsunami activity on Cyprus Island. Tsunami evidence has been analysed using the deposition of large boulders, the physical characteristics of boulder deposits, including their dimensions, stratification, their spatial characteristics, the geologic characteristics of boulder deposits, attached fossil life forms, the displacement of large boulders, and was complemented by relative and absolute dating techniques. This study shows that high magnitude - low frequency tsunami events have a significant impact on the coastal landscapes of Cyprus Island. Similar evidence should be researched on other localities in the Mediterranean region.

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# TSUNAMI HAZARD MITIGATION
# AND
# THE NOAA NATIONAL WATER LEVEL OBSERVATION NETWORK

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## ABSTRACT

With the renewed interest in regional Tsunami Warning Systems and the potential tsunami threats throughout the Caribbean and West coast of the United States, the National Ocean Service (NOS), National Water Level Observation Network (NWLON) consisting of 175 primary stations, is well situated to play a role in the National Hazard Mitigation effort. In addition, information regarding local mean sea level trends and GPS derived geodetic datum relationships at numerous coastal locations is readily available for tsunami hazard assessment and mapping applications.

Tsunami inundation maps and modeling are just two of the more important products which may be derived from NWLON data. In addition to the seven water level gauges that are hardwired into the West Coast and Alaska Tsunami Warning Center (WC/ATWC), NOS has a significant number of gauges with real-time satellite telemetry capabilities located along the Pacific Northwest coastline, the Gulf of Mexico and the Caribbean. These gauges, in concert with near shore buoy systems, have the potential for increasing the effectiveness of the existing tsunami warning system.

The recent expansion of the Caribbean Sea Level Gauge Network through the NOS regional partnerships with Central American and Caribbean countries have opened an opportunity for a basin-wide tsunami warning network in a region which is ill prepared for a major tsunami event.

## Introduction

The Center for Operational Oceanographic Products and Services (CO-OPS), Silver Spring, Maryland, operates and maintains the National Water Level Observation Network (NWLON) which consists of 125 long term water level stations, located throughout coastal regions of the U.S., Hawaii and other administrative island territories, and an additional 50 long term water level stations operated in the Great Lakes. Most field units are fully automated data collection platforms (DCPs) equipped with acoustic water level and backup pressure sensors and satellite telemetry which transmits data via National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellites (GOES) allowing real-time access to tide and water level information. This network, with historical records dating back to the mid-1800s, supports a large and varied user community including; nautical charting and marine navigation, surveyors, engineers, and climate and global change research. In addition, the NWLON plays a critical role in the Nation's hazard warning system with the inclusion of storm surge and tsunami warning capabilities.

The U.S. Tsunami Warning System, composed of the Pacific Tsunami Warning Center (PTWC), headquartered in Hawaii, under the Director, National Weather Service (NWS) Pacific Region, Honolulu, responsible for the entire Pacific basin, and the West Coast/Alaska Tsunami Warning Center (WC/ATWC), responsible for Alaska and the U.S. West Coast, is supported by 43 NWLON stations configured to automatically revert to a high frequency tsunami data acquisition mode whenever tsunami waves are detected. Other NWLON stations are strategically located in coastal regions, bays, and estuaries that are most likely to be affected by tsunami hazards. Many of these stations are connected to the National Spatial Reference System (NSRS) which provides a tie to tidal elevations including local sea level and, as such, may be used for local GIS-based tsunami inundation mapping and modeling applications.

CO-OPS has been involved with the establishment of sea level observing stations in the Caribbean Islands as part of the Global Sea Level Observing System (GLOSS) and has also installed tide stations in Central America in response to the Hurricane Mitch disaster relief effort. These, as well as other regional sea level stations, could form the basis for expanded tsunami mitigation efforts and the first centralized tsunami warning network in the Caribbean.

This paper outlines the nature of CO-OPS operations and responsibilities regarding the National Tsunami Warning System, discusses NWLON data applications for tsunami hazard mitigation and explores opportunities for future expansion of a tsunami warning network in the Caribbean.

## NOS Tsunami Network

Of the 43 NWLON stations that have tsunami monitoring enhancements (triggers) in the Pacific basin, seven are hard wired into the WC/ATWC for real-time monitoring. At each station, an acoustic water level sensor takes a measurement every six minutes. Each measurement consists of a 181-sample average. These six minute measurements (ten points per hour) are then transmitted by GOES satellite every hour to CO-OPS, Silver Spring, MD via a satellite ground station at Wallops Island, VA.

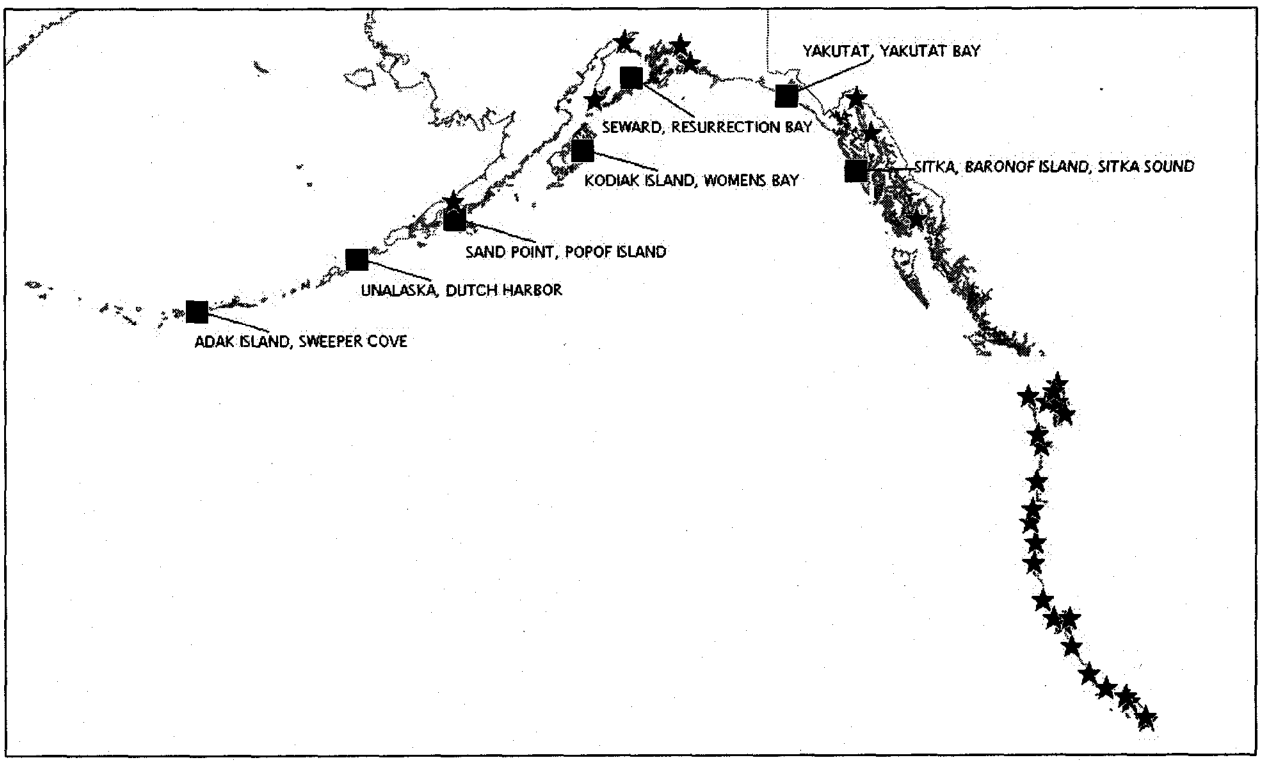


**Figure 1:** Map showing WC/ATWC NWLON stations equipped with tsunami triggers. The square icons represent stations that are hard-wired into the WC/ATWC.

Tsunami triggers can be activated manually through the following sequence: The watchstander at the WC/ATWC dials into the station's DCP via modem and enables the tsunami transmit mode. Once activated, water level measurements collected in one minute intervals are transmitted via GOES satellite telemetry every six minutes for a 24-hour period. The Warning Centers have direct links to GOES messages and begin receiving data just minutes after each station is enabled. There is also a high rate mode for storm surges as well. The triggering software is set in the same way as the tsunami transmit mode, except that rather than the NWS completing the operation, they telephone the Continuous Operational Real-Time Monitoring System (CORMS) watchstander in Silver Spring, MD with a list of stations to be activated. The storm surge data is accessed in six-minute intervals and transmissions are every 19 minutes rather than every six minutes when in tsunami mode.

The Alaska NWLON stations (Figure 1) that are hard wired for real time monitoring; Adak, Unalaska, Sand Pt., Seward, Kodiak, Yakutat, and Sitka use digital/analog converters connected to a phone line, through which water level elevations are changed from a digital signal to analog. The Warning Centers convert these signals into continuous water level heights which are displayed graphically for further visual evaluation. Sensors are also configured to trigger automatically should water level changes exceed a prescribed threshold rate of change. In the Pacific Northwest region, there are thirteen NWLON stations located between Washington and California and seven in Alaska. The Pacific Warning Center's operational procedures have continually been modified since its inception to meet the program and research requirements of both the NWS and the Pacific Marine Environmental Laboratory (PMEL). The 43 NWLON

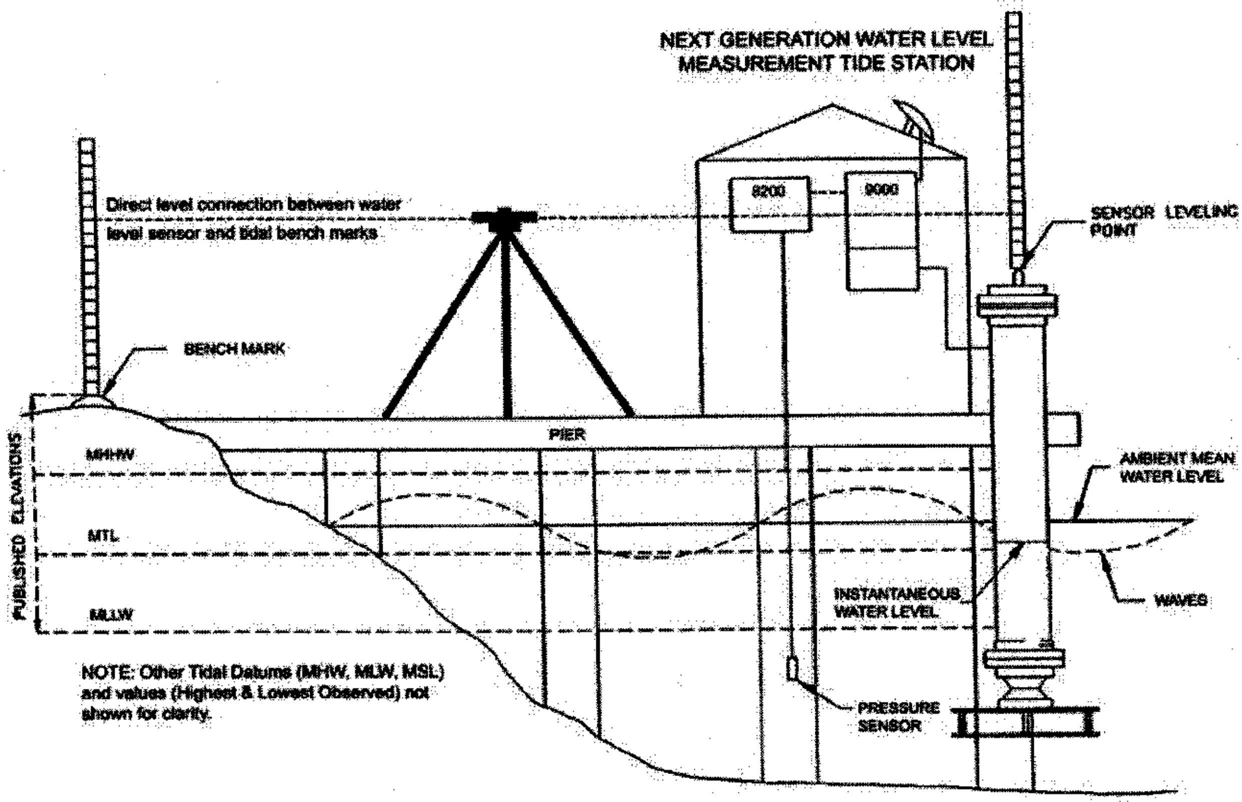


**Figure 3**: Depiction of NWLON station with leveling equipment and associated datums.

Stations that are closest to tsunamigenic events often prove most useful for post-event analyses. At most NWLON stations (Figure 3) geodetic bench marks, relative to the NSRS, have been tied into the local tidal datums determined from long term observations. This is most readily accomplished by traditional land surveying methods, but more recently, through the differential Global Positioning System (GPS). Ellipsoidal heights are becoming increasingly integrated into the NWLON, therefore, tidal elevations and extreme water levels may be compared in the same vertical reference system as modern GPS controlled bathymetric and topographic surveys. Other related information such as sea level trends, tide range and co-tidal time differences may also be used in supporting tsunami hazard mitigation efforts. It is through the integration of these tidal parameters with topographic elevations that tsunami inundation models will be best used to identify those coastal communities with high tsunami risk levels and provide up-to-date information for emergency response and evacuation planning.

## Tsunami Archives

Until the mid-1980's, physical analog marigram records, other than the standard six-minute measurements, were only available from the NOS archives for tsunami research and analyses. At that time, the National Ocean Survey, Oceanography Division, headquartered in Rockville, Maryland began a data loan program with the National Geophysical and Solar-Terrestrial Data Center (NGSDC), NOAA, Boulder, Colorado for the establishment of a tsunami stations that are operating in the Pacific region will continue to be an important element of future initiatives or programs designed primarily to improve capabilities in communications, data acquisition, and tsunami mitigation assessment.

## Recent Example of a Sequence - Lessons Learned

On June 23, 2001 at 20:33 UTC an 8.4 M earthquake struck near the coast of Peru. This seismic event created a tsunami wave that was detected across the entire Pacific basin. The effects were observed at 34 NWLON stations, 16 of which had considerable changes from their normal tidal signatures (Figure 2). NWS forecast modelers contacted the CO-OPS watchstander for the CORMS and requested that several NWLON stations be put into storm surge mode to initiate 19 minute satellite transmissions. The tsunami triggers were pre-empted by manual procedures for activating a station in storm surge mode, thus they could not be automatically transmitted in tsunami mode. However, both the one minute and fifteen second data series were recorded at the DCP's and the one minute data was downloaded remotely via modem. The fifteen second data was stored in memory modules that were later manually retrieved, so the data record was not lost.

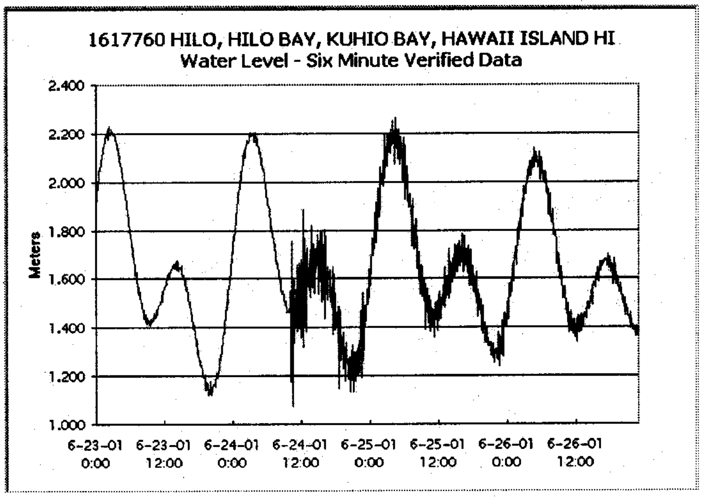

**Figure 2:** Plot of Tsunami signature at NOS NWLON station Hilo, HI.

Subsequent to this event, changes were made to the operational procedures and communications between the NWS and CORMS, ensuring that tsunami transmission mode would always have highest priority. It was also apparent from the large number of NWLON stations that had to be individually triggered, that TWC watchstanders would benefit from an upgrade in the existing software that would streamline the manual triggering process. CO-OPS is presently addressing the issue.

## Tsunami Mitigation and Hazard Assessment

The NWLON, is well situated to provide information for local tsunami hazard mitigation and assessment activities. Most of the 175 NWLON water level gauges have near-real time (hourly) satellite telemetry capabilities and the information is available via the Internet at the Tides Online website (http://tidesonline.nos.noaa.gov/). The Physical Oceanographic Real-Time Systems® (PORTS®) data are transmitted in real-time every six minutes. PORTS® is a NOS program that supports safe and cost-efficient navigation and includes centralized data acquisition and dissemination systems that provide real-time water levels, currents and other oceanographic and meteorological data. PORTS® are located in San Francisco, Los Angeles/Long Beach, Houston/Galveston, Tampa Bay, Chesapeake Bay, Delaware River and Bay (in progress), New York/New Jersey Harbor, Narragansett Bay, and Soo locks(Great Lakes). All data are accessible via the website (http://www.co-ops.nos.noaa.gov/). Monthly verified data and accepted station tidal datums are also available from this website.

record data base which would support the various national and international interests conducting tsunami research. Tidal analog records dating back to the 1850's were selected for tsunami events and microfiched over a 5-day event span. In addition, the NGSDC was provided with a wealth of tsunami damage photographs and descriptions and other effects of tsunami wave activity that were compiled and catalogued for public distribution.

The present day tsunami data base, with over 3000 microfiche tide records and 8000 digital records, is maintained by the NOAA, National Geophysical Data Center (NGDC), and World Data Center A for Solid-Earth Geophysics, National Environmental Satellite, Data and Information Service (NESDIS), Boulder, Colorado. The more recent high frequency records from post tsunami events are also accessible via the world wide web sites of NGDC and PMEL.

**Caribbean**

The potential for a major tsunami event in the Caribbean is well documented, ("Caribbean Tsunamis: An Initial History," James F. Lander and Lowell S. Whiteside, University of Colorado, Boulder,CO) and the need still exists in the Caribbean for expanding the National Tsunami Warning System to increase hazard warning and mitigation efforts. In addition to Puerto Rico, where NWLON tide stations located at San Juan and Magueyes support the Puerto Rico Tsunami Warning and Mitigation Program, there are a substantial number of other Caribbean Island stations operating in the GLOSS network. Together with sea level stations, installed under the Caribbean: Planning for Adaption to Climate Change (CPACC) initiative, a network of active stations now exists in the greater Caribbean region which will support a viable tsunami warning system. In order to build on the existing sea level network, it has been proposed by members of the UNESCO Subcommission for the Caribbean and Adjacent Regions (IOCARIBE), and others on the Tsunami Steering Group of Experts, that existing stations which transmit through GOES satellite links, and have acoustic sensors, should be modified with new software and water level pressure gauges for tsunami warning applications. CO-OPS personnel have been actively engaged throughout the Caribbean, providing field and technical support for the installation, and maintenance, of GLOSS stations and more recently, installing water level stations in the Regional Water Level Observation Network of Central America (RONMAC). With the recent emphasis on intergovernmental partnerships for disaster relief following Hurricane Mitch and the ongoing UNESCO activities in the Caribbean region, this is an opportune time for IOCARIBE member States to consider the establishment of a centralized Caribbean Tsunami Warning System.

**Summary**

A substantial subset of the 175 NWLON tide stations, operated and maintained by CO-OPS, form an integral part of the Nation's Tsunami Warning System and National Hazard Mitigation Program. Water level data and other associated information obtained from the NWLON may be readily applied to inundation, coastal flooding and evacuation maps through the seamless integration of tide elevations and datums with geodetic digital elevation models. The real-time access capabilities of tide stations along the Pacific Northwest coast, combined with detailed knowledge of local tidal characteristics and sea level trends derived from NWLON stations, adds another dimension to ongoing mitigation efforts made in response to near-shore seismic events. Modifications made to the automatic tsunami trigger system at NWLON stations and improved communications between NOAA regional offices have resulted in a more efficient tsunami warning operation. With the support of IOCARIBE, the opportunity now exists for the GLOSS and CPAAC observation networks, combined with select stations from Central America, to form the basis of a regional Caribbean Tsunami Warning System.

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# PALEOTSUNAMI EVIDENCES FROM BOULDER DEPOSITS ON ARUBA, CURAÇAO AND BONAIRE

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**Abstract**

The paleotsunami debris deposits of Aruba, Curaçao and Bonaire are investigated with regard to their geomorphologic characteristics, spatial distribution and their depositional history during the Younger Holocene. Differences between three distinctive formations – ridges, ramparts and boulder assemblages are highlighted and related to their origin within the coastal environment. Relative and absolute age determinations proved evidence for the occurrence of three paleotsunami events at 400-500 BP, 1500 BP and 3500 BP. The tsunamis approached the islands from a northeasterly direction leaving the most impressive geomorphic traces on Bonaire and due to shadowing effects reduced sedimentary effects on Curaçao and Aruba.

## Introduction

Since the first recorded tsunami occurred off the coast of Syria in 2000 B.C. far more than 2000 tsunamis have been reported and over 6500 runup locations are documented in the most comprehensive database of worldwide tsunamis maintained by the National Geophysical Data Center of the United States (NGDC, 2001). Nevertheless, the current state-of-the-art knowledge concerning the sedimentary and geomorphic imprints of tsunamis along the coastlines of the world is strikingly poor. Worldwide only about 60 academic papers related to tsunami sedimentation exist - most of them focus on fine sediments - and among them only very few discuss geomorphologic or geologic consequences of tsunami events. In addition, most studies investigate local tsunami evidences and systematic documentation of tsunami depositional traces on regional scales are rare. In contrast, Aruba, Curaçao and Bonaire, located north of the Venezuelan coast in the Caribbean Sea, exhibit several attributes that have permitted a detailed regional characterization of the morphology of tsunami deposits (Fig. 1). Their study allow conclusions of paleotsunami occurrence for the Southern Caribbean over a geographical distance of more than 200 km. Hitherto, tsunami impacts were unknown for the ABC-islands and the debris formations have been exclusively attributed to hurricane-generated waves (De Buisonjé, 1974).

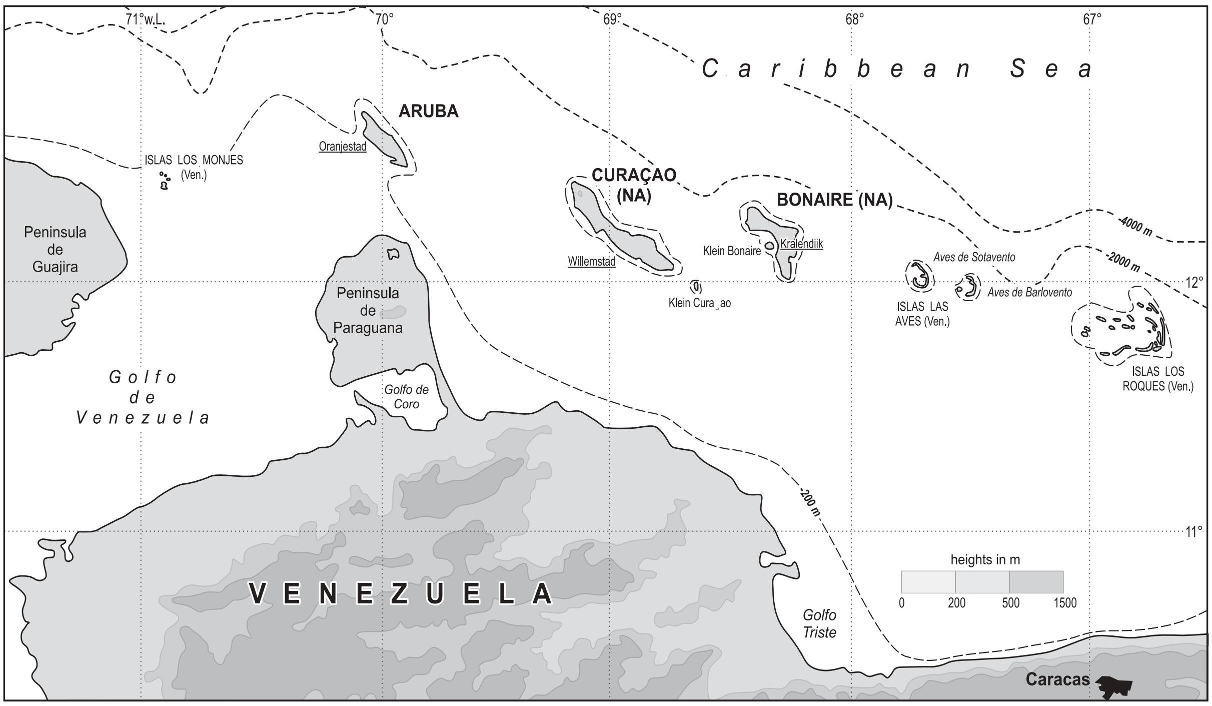


*Fig 1* The islands of Aruba, Curaçao and Bonaire in the Southern Caribbean.

## Methods

We choose an inductive approach to differentiate between the main debris types and document their spatial distribution with a dense field survey and the aid of aerial pictures and GIS on maps. In order to exclude tropical cyclones as a depositional force the critical wave heights necessary to overturn boulders according to the hydrodynamic formulas adapted from NOTT (1997) were calculated. A number of stratigraphic, morphologic and historical data allowed us to determine the relative age of the deposits, for absolute age determinations over 40 samples were dated with appliance of the radiocarbon method. To determine the source area of the debris within the coastal environment we analyzed with a statistical approach the shape and the material of the fragments in leeward and windward debris deposits on Curaçao and Bonaire.

## Discussion and Results

Some physio-geographical factors favor the study of paleotsunami relicts on the ABC-islands: During the Quaternary, the islands have undergone a relatively slow vertical uplift and no neotectonic dislocations in the interpretation of the deposits have to be considered. The wide occurrence of carbonate rocks is responsible for a variety of specific geomorphologic features like notches, benches or algae rims, which can be used for relative and absolute dating. Due to their geographical position at the southern fringe of the hurricane belt, major tropical storms or hurricanes only occasionally touch the islands. This results in an excellent preservation of coastal deposits. The limited hurricane impact causes an increased stability of biogenous fine structures of the coastal area with respect to conclusions concerning the relative age of the forms and the intensity of the forming processes.

The accumulations exhibit three main geomorphologic distinct types of paleotsunami debris formations, which have been distinguished as boulder assemblages, rampart formations and ridge formations (Fig. 2). Predominantly, the debris deposits have been accumulated on the northeastern sides of the islands, reaching from sealevel to a height of + 12 asl and extending up to 400 m inland. On a regional scale, the extent and amount of tsunami debris weakens from east to west with the highest energy impact on Bonaire in the east and a considerable lower impact on Aruba, the most westerly island.

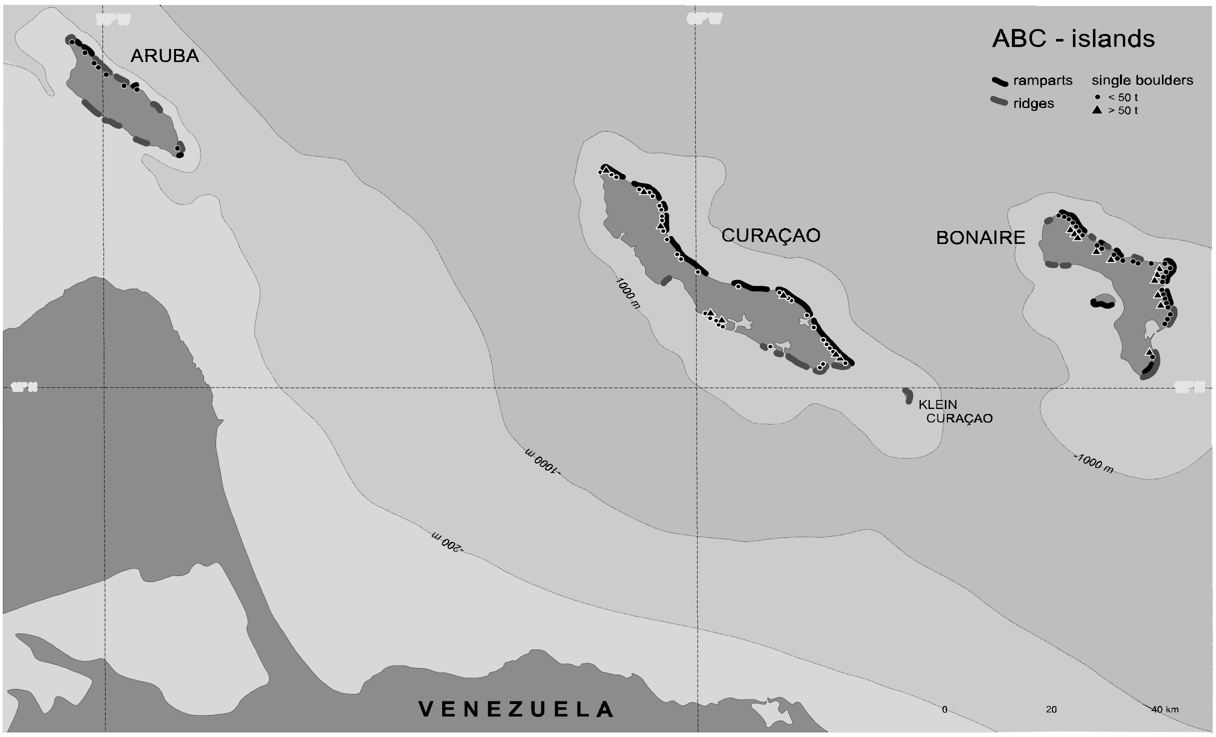


*Fig. 2* Overview of impressive paleotsunami imprints on the ABC-islands.

Each formation exhibits a distinct morphology and geographic distribution related to a certain coastal configuration. Boulder assemblages contain blocks of > 100 m$^3$ in volume and with a weight of up to 281 tons (Fig. 3). They occur on all islands with the most impressive evidences on Bonaire and Curaçao, but in general, they are coinciding remarkably often with coastal sections, where the cliff front is nearly perpendicular and the supratidal zone is rather narrow.

*Fig. 3* An impressive boulder field south of Spelonk Lighthouse, Bonaire, situated in rather dense vegetation more than 150 m apart from the shoreline.

*Fig. 4* Rampart formation at Dos Boka, windward coast of Curaçao, located at + 6 m asl and about 40 m distant from the cliff front.

If the coastal physiography leads to the development of a rather broad supratidal with a more convex cliff profile, the amount of debris increases significant as more material from the rugged rock pool zone can be derived by the tsunami. That coastal environment favors the development of rampart formations (Fig. 4). They occur likewise on all islands with the most developed ones in northeastern Curaçao and along the east-exposed coastal stretch on Bonaire. The ramparts are located with their seaward margin in distance of at least 40 – 50 m from the active shoreline, in cases up to 100 m, at elevations usually ranging from + 6.0 to + 10.0 m asl, and they are becoming more scattered and thin out with increased inland extent. They consist of small to medium sized fragments and show a thickness of some decimeters up to one meter with a planar gently land inwards sloping profile. Unfortunately, most of the rampart formations are massively disturbed or even completely removed due to intensive mining exploitations in the past.

The ridge deposits often follow subsequently to the coastline and surf zone and consist of mostly well-rounded platy and rod-shaped coral fragments with some rare limestone boulders present (Fig. 5). Imbrication is a common feature. Predominantly, the rounded material is derived from coral debris out of the subtidal environment. These ridges occur along the southern, southeastern and western leeward coastlines, where they may extend over several hundred meters with width from 10 – 50 m and relative heights from 1 - 3 m.

*Fig. 5* Subrecent debris ridge at Willemstoren, leeward coast of Bonaire.

In general, relating a geological deposit to a paleotsunami is in most cases a delicate exercise. One key problem concerns the differentiation between a storm-induced or tsunami-induced sedimentary record. For the ABC-islands, both - field observations and relative/absolute age dating - indicate clearly that a storm or hurricane-induced deposition can be definitely excluded and therefore the debris formations can be unambiguously related to tsunami events as the following arguments will highlight. During the time period 1605 – 2000 in total 14 hurricanes and 19 tropical storms, with maximum wind velocities between 100 – 120 mph (= 180 – 210 km/h) near the center, passed the islands within the 100 nm zone (Fig. 6).

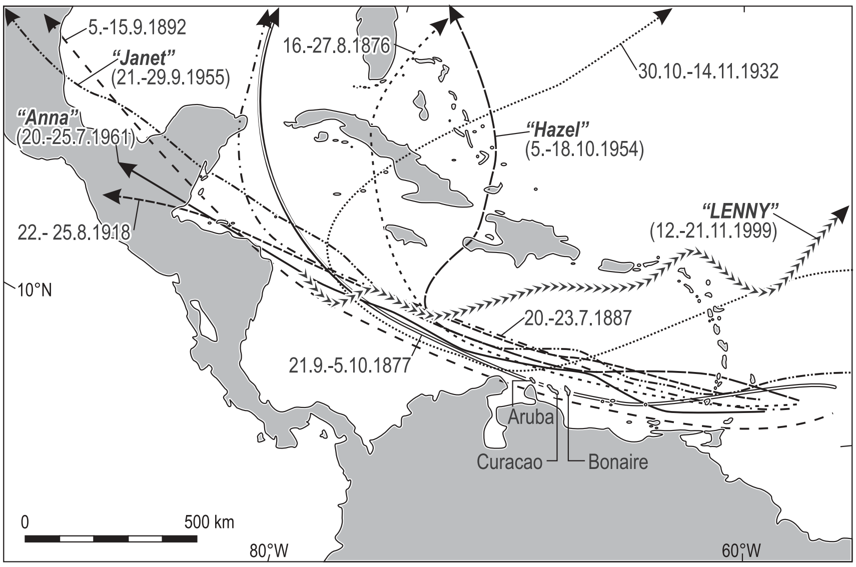


*Fig. 6* Only few hurricanes passed within 100 nm from Curaçao, Bonaire and Aruba over the time period from 1605 to 1998 (Source: Meteorological Service of the Netherlands Antilles and Aruba, 1998).

The most significant event in the past was Hurricane *Lenny* in November 1999, an extremely rare hurricane with wind speeds > 160 km/h, formed south of Jamaica and moved eastward toward the Lesser Antilles. This direction of travel for a sustained period, is the first reported in the entire 113 year hurricane record (Guiney, 2000). As a result of the rather unusual track, the islands of Aruba, Bonaire and Curaçao all experienced heavy surf conditions along their southwestern coastlines as *Lenny* passed 250 – 500 km north of the islands. The waves varied along the coasts, but were reported to be mostly in the range of 3 - 6 m. It can be clearly observed that the magnitude of the paleotsunami events exceeded the impact of hurricane *Lenny* significantly on all three islands. The storm-induced *Lenny* deposits are limited in spatial extent to the southwestern facing shorelines and their grain size distribution ranges only from centimeters to some decimeters, in no case larger boulders has been transported onshore (Fig. 7 and 8). Smaller fragments of *Acropora cervicornis* are the most common components in the accumulated ridges and spits.

*Fig. 7* Debris ridge (nearly 1 m high) consisting chiefly of rods of *Acropora cervicornis* branches with tongues of shingle. Pink Beach, leeward coast, Bonaire.

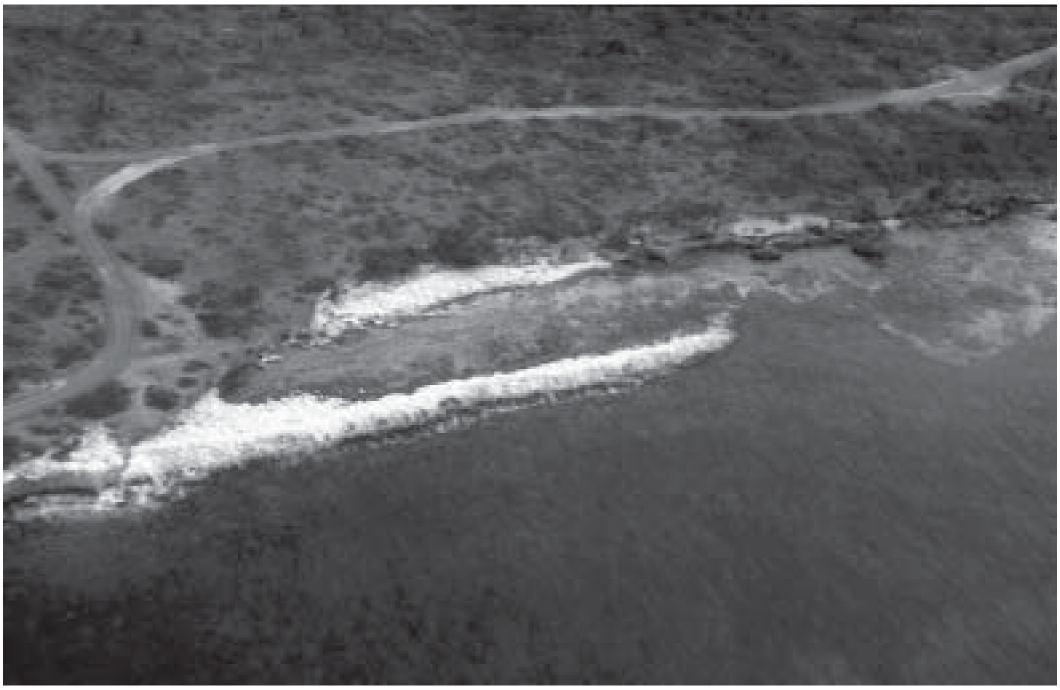

*Fig. 8* Aerial view of the recently formed coral rubble spit by hurricane Lenny.

In addition, the application of hydrodynamic calculations verifies this suggestion. The results demonstrate that the possibility remains that extremely large hurricane waves may have the capability to overturn boulders of an insignificant quantity, but considering their present position in cases up to 12 asl, it seems to be unlikely that such waves will deposit them into their present position. From the measured 76 distinctive boulders on Curaçao (weight >1t) - except very few - all require storm wave heights, which never have been observed at any coastline of the world (up to 125 m!). For the 42 measured boulders on Bonaire none could be moved by storm surf regarding the required waves height of 14-89 m. Even on Aruba, where the boulders usually are much smaller, waves of 13 - 56 m would be needed. In contrast, the wave height calculated for tsunamis are well in the range of observed events.

Geomorphologic relationships between the debris formations and coastal features, e.g. rockpools and bench development, illustrate that at least a time period of some hundred years since the youngest tsunami event must have expired. Especially a closer look at the rockpool zone characterized by sharp, irregular limestone peaks with depressions of up to 60 – 80 cm depth and located between the debris deposits and the coastline confirms that suggestion. This rough sculptured zone reaches often up to 30 m inland and is strikingly completely free of sediments, although the rockpool depression would represent an excellent sediment trap for coarse material. In general, dating of coarse sediments is a difficult task since no stratigraphical sequence can be interpreted and no analysis methods of sedimentology can be applied in coarse sediments. Nevertheless, relative age indications allow a good estimation of the time range for the minimum and maximum age of the deposits. One important relative dating possibility of a tsunami impact is related to the preservation of bioerosive and bioconstructive coastal features (KELLETAT & SCHELLMANN, 2001 a, b). Estimations of the time period needed for the forming processes (bioerosion: ~1-2 mm/y; bioconstruction: ~2-5 mm/y) can limit the time range for the event relatively accurate. Transferred to the ABC-islands, it can be stated, that no signs of fresh outbreaks of limestone material either in the cliff front, the bench or the supratidal zone were found, so that the origin of boulders could be unambiguously identified. Subsequent bioerosive processes made the breakouts unrecognizable, indicating a minimum dislocation and depositional age of at least some hundred years. Limited bench development along coastal stretches with major tsunami impact point to several centuries without further impacts of tsunamis, again suggesting an age of some hundred to thousand years. Overall we can limit the maximum age range to the Younger Holocene as evident in particular by chemical and biological weathering processes and the spatial relation of the debris formations to the recent sealevel highstand, which reached the present level between 5000 and 6000 BP in this part of the

Caribbean, since when it remains very stable (RULL, 2000). Beside geomorphic imprints of tsunami occurrence the historical record has to be considered. On the ABC-islands no written or oral sources describing a tsunami impact exist, pinpointing also to a time span of minimum 350 – 400 years without the occurrence of any severe tsunami event, presumably since the Dutch occupation in 1634 AD or even the occupation by the Spaniards in 1527 AD.

However, the resolution of relative age dating is insufficient to establish a more detailed chronology of the tsunami impacts, so that radiocarbon age determinations from 43 samples were performed from different geomorphologic units (boulders, ramparts, ridges) and on different material (vermetids, corals, gastropods). These conventional radiocarbon datings supplied a non-calibrated age range from 370 ± 32 to 4222 ± 49 years BP. The uncalibrated age data show a clustering in three main time units around 500 BP, 1500 BP and 3500 BP with intermediate periods of only infrequent or no age values (Fig. 9).

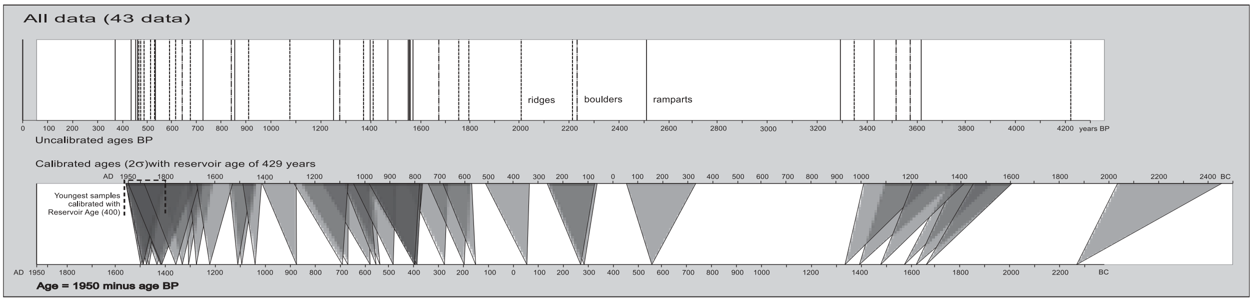


*Fig. 9* Age distribution of all 43 dated samples. The conventional radiocarbon ages are visualized as single line, the calibrated (2σ) ages are presented in form of triangles. Reservoir age = 429 years.

The distribution of the age values supports the interpretation of the coarse debris deposits as tsunamigen, and is inconsistent with a hypothesis of a storm-induced origin. If storm events would have contributed at least partly to the depositions, we could expect an even distribution of the data samples over the time period, when the Holocene sealevel reached more or less the present height around 5000 BP (RULL, 2000).

The generating mechanisms of paleotsunamis of the described magnitude is unknown, but most likely they are related to seismic activity in the northeastern part (0 - 90° sector) of the Caribbean along the faults of the Caribbean Plate boundaries (Fig. 10). Another potential source region is the Southern Caribbean Plate Boundary Zone along the northern Venezuelan continental margin with clear evidence of neotectonic right-lateral strike-slip deformation including uplift and subsidence of large fault blocks along the fault zones.

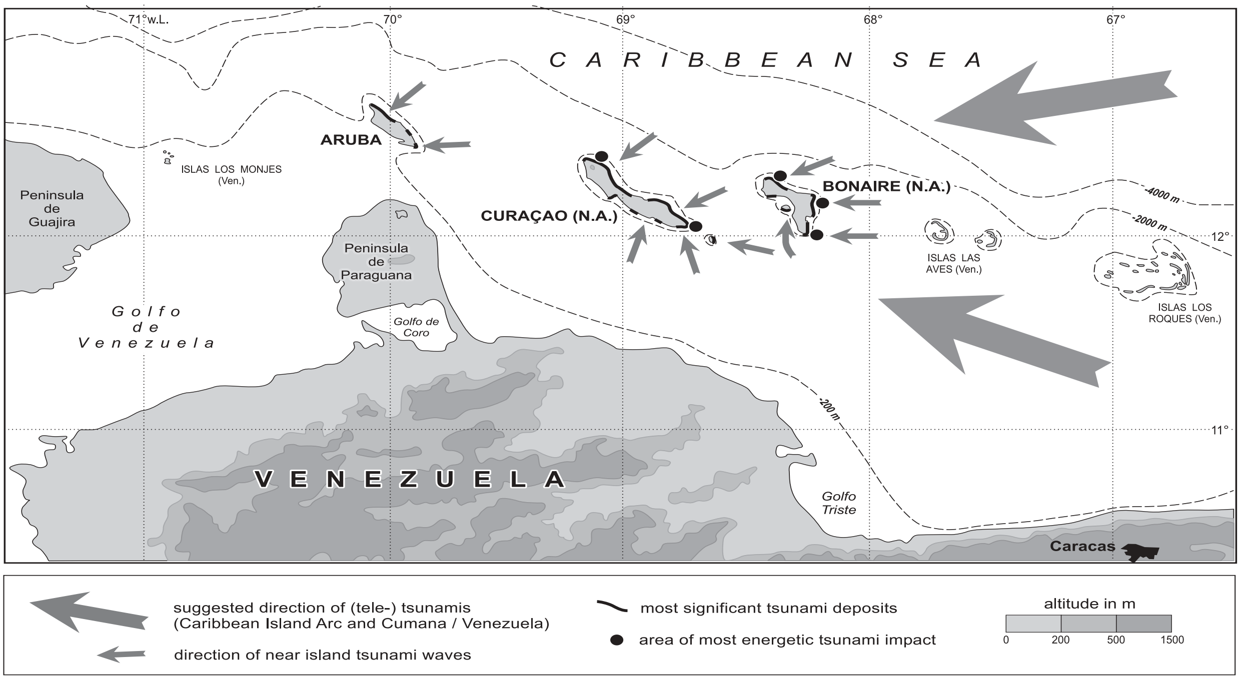


*Fig. 10* Suggested direction of paleotsunamis impacting the ABC-islands.

**Conclusions**

From this new, but still limited knowledge of the occurrence of paleotsunamis with severe magnitudes in the Southern Caribbean, we can derive that potentially catastrophic tsunamis may represent a much higher risk than at present recognized by the governmental organizations and the inhabitants of the Caribbean islands. The risk of severe tsunamis anywhere around the Caribbean is still largely unknown as geomorphologic observations of tsunami evidences are yet very rare and many presumed imprints of tsunamis have not yet been found, studied and mapped in appropriate detail. In the near future further efforts should concentrate on geomorphologic field studies on a Caribbean-wide scale to understand the nature of tsunami deposits and to precise and extend the existing Caribbean Tsunami catalogue comprehended so far by LANDER & WHITESIDE (1997). With regard to the results of this study it must be stressed with great emphasis that the establishment of a feasible and effective Intra-Americas Sea Tsunami Warning System as it is visualized by the Intergovernmental Oceanographic Commission of the UNESCO is an important step to mitigate future disasters. We hope to encourage with this study the governmental institutions on a local and a Caribbean-wide scale to intensify activities in tsunami related education, warning, management as well as research.

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# THE MOMENTUM OF TSUNAMI WAVES

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## ABSTRACT

In the generation and propagation of tsunamis, it seemed like the momentum might be a quantity of some usefulness. In many tsunami generating situations the source mechanism might impart significant initial velocity to the water in addition to surface displacement. In the cases of pyroclastic flow and landslides from land into the water this is surely the case. The property of momentum that is especially noteworthy is that, unlike energy, the momentum of a body of water is affected only by external forces and not by internal forces associated with turbulence or laminar flow. These latter aspects of wave propagation dissipate energy and have disappeared from the distant wave motions in which principally irrotational flow remains. The impulse, $Fdt$, where $F$ are external forces on the body of water, result in a change of momentum, $d(Mv)$ of the body of water. The momentum density of a column of water of dimensions $dxdy$ and from the bottom to the surface corresponding to particle velocities $v(z)$ is the quantity discussed in this paper.

## INTRODUCTION

Some years ago I had an Indonesian student who was going to take a look at the tsunami associated with the eruption of Krakatoa (as referred to in English.) There were at least three tsunami-generating mechanisms there: an explosion, a pyroclastic flow, and the displacement of the top of the mountain into the adjoining lagoon. The displacement of solid matter into the ocean and the over-pressure from the explosion are clearly wave generating phenomena that are traditionally handled. But how about the pyroclastic flow? I haven't seen the pyroclastic part of it specifically treated in wave generation. It seems like the horizontal velocity of the flow should be important in determining the wave generation in addition to just the surface displacement caused by the flow. The horizontal momentum produced by the flow might be a major part of its effect. Later in mentioning these ideas to Charles Mader, he said the steam generated when the pyroclastic flow hits the water should be substantial blasting the water in every direction.

Also, momentum would be a factor to consider in any landslide that is producing a tsunami and, in fact, in any earthquake which has a lot of horizontal displacement, as do most of the earthquakes that generate tsunamis. So, it seems like momentum might be a factor in many, if not most, tsunami generation situations. Anyway, the details of it work out in an interesting way.

## MOMENTUM PHYSICS

The physics of momentum for shallow-water long waves turns out to have an interestingly simple and useful form.

Newton's second law is basically the momentum equation. Namely that the force times time equals the change in momentum.

$$Fdt = d(Mv).$$

The M is the mass of any element of matter large or small that we choose to isolate. The $F$ is the total external force on that element and is a vector as is the velocity, $v$. We could think of the momentum of total ocean as $Mv$ , and $F$ as the sum of all the external forces on this volume, or we could concentrate on smaller elements of water and the external forces on these elements. The sum of the partial momenta add up to the total momentum. The symbols are not well defined here, as this is at the moment a verbal discussion to introduce the concepts.

Initially I just want to think about the total horizontal momentum delivered to the water by the earthquake, the landslide, the pyroclastic flow, and the overpressure from the explosion. We have to add up the external horizontal forces, $Fdt$, from every source and over some period of time in which the tsunami is generated. The displacement of the earth produces a horizontal force along the bottom of the ocean. The landslide may push some water horizontally all along its path of descent. The pyroclastic flow hits the water with considerable momentum at the surface and for some distance below that, and the explosion delivers a moving pressure field along the surface that, insofar as it moves the water, creates horizontal momentum. These sources certainly do not produce waves with irrotational flow, but in considering momentum it doesn't matter. The change in momentum is determined only by the external forces during the generation period and thereafter! This same momentum during the generation period is conserved throughout the propagation of the wave except for the external forces $Fdt$ of friction which has minor effect as discussed later, and some unbalanced forces related to the bathymetry and to the wave patterns. Note that the internal forces connected with laminar or turbulent flow have no effect whatsoever on the net horizontal momentum.

Once the momentum is delivered to the ocean it is delivered to distant shores by wavelike motions. Henceforth $M$ will stand for the momentum density. That is the momentum of a column of water of dimensions $dxdy$ extending from the bottom to the surface.

Suppose there is a slightly irregular undulating wave train moving to the right and diminishing to the left. For a wave traveling in the positive direction, the particle velocity is positive under positive crests and negative under negative surface elevations. Let $\eta$ be the water level as measured from the undisturbed level. Once the water motions are organized into shallow-water long waves, the velocities are almost uniform in the column of water from $\eta$ to the bottom and, in fact, are proportional to $\eta$ according to the rule

$$v(x, y) = \eta(x, y)\sqrt{(g/d(x, y))},$$

where $d(x, y)$ is the water depth. In other words, the momentum density (per unity length and width) will be (the density is left out and mass/unit volume is taken as 1.)

$$M(x, y) = \eta(x, y)d(x, y)\sqrt{(g/d(x, y))},$$

or

$$M(x, y) = \eta(x, y)c(x, y)$$

or just $\eta$ times the *celerity*, $c$, since

$$d\sqrt{(g/d)} = \sqrt{(gd)} = celerity$$

of a long wave in water of depth $d$.

The proportionality of momentum density to wave height times celerity is pretty handy. After you have started a tsunami with generating equations you can look at the distribution of wave heights that result and see if they account for all of the displacements and the momenta that were judged to be part of the generation.

What does friction do to momentum? Internal friction - nothing. Bottom friction, not much. In the direction of the advancing wave, where the momentum density is positive and the particle velocity is positive, the frictional force $F$ opposes the particle velocity and $Fdt$ is negative reducing the momentum. Under negative water levels, the particle velocity is negative and $F$ is positive since it opposes the particle velocity which is in a negative direction, therefore the negative momentum density under the negative crests is increased by a positive number $Fdt$ and negative momentum density is diminished in absolute value.

Compare this with the effect of bottom friction on energy. The work done by the bottom frictional force $F$ is $Fds$. This term is negative under the positive crests and also negative under the negative crests. Writing this as $Fvdt$, the expression $Fv$ is always negative and the extra factor $v$ will be small in deep water and larger in shallower water so one expects the frictional dissipation of wave energy to be larger in shallower water (naturally) but to have little effect on the momentum.

Consider a tsunami generated across a segment of displacement so that it has well defined horizontal momentum in a given direction pretty much in just a segment of the ocean corresponding to the generating area. What happens to this momentum as the water wave spreads? The initial momentum in the direction of travel remains the same, but the unbalanced gravitational forces at the two ends of the wave segment cause some spreading. This additional momentum is at right angles to the direction of travel and the vector sum of the momenta due to spreading on the left side and the right side would be zero. As long as there is no net horizontal force in the direction of travel, the momentum in that direction remains constant except for the minor effect of bottom friction. In addition the differences in water depth that refract the waves also refract the momentum because the refraction is caused by net external forces of the variable bottom on the water in the ocean.

And finally, what happens to the wave momentum? Well, this is what we really want to know because some part of it results in damage in the inundation zone. Some of it is transferred to the ocean bottom and the land over which it floods. Every positive $Fdt$ of the wave on buildings or man-made structures, or on a bottom irregularity or against vegetation or against hills takes some momentum from the wave and transfers it to either the bodies themselves if they can move or to the ground itself. A fair amount of momentum is bounced back to the ocean in various directions. When the wave runs up a sloping beach, the force of the bottom (both the frictional force and the horizontal component of the weight vector) on the water has a horizontal component reflecting the momentum back towards deeper water.

**REVIEW OF THE 1994 SKAGWAY, AKASKA TSUNAMI AND FUTURE PLANS**

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## ABSTRACT

On November 3, 1994 a nine meter amplitude submarine landslide-created tsunami with a resonate wave train lasting about 30 minutes struck the Skagway, Alaska, waterfront causing extensive damage and loss of one life.

Numerous scientists and engineers have studied the 1994 tsunami and at a workshop on the subject in Seattle, Washington, on October 30-31, 2001, have generally concluded that large down inlet submarine landslide(s) created the tsunami. A general plan under the National Tsunami Hazard Mitigation Program was developed to start a study, which could lead to mitigation measures at Skagway with possible adaptability to other parts of the world with similar problems.

This paper briefly overviews the events preceding the tsunami, reviews findings following the event and outlines plans relating to similar future expected tsunamis.

**Introduction**

The City of Skagway, Alaska is located at the head of a fjord in northern Southeast Alaska (the panhandle) and situated on a river delta landform resulting from Skagway River sedimentation (Figure 1). Founded in 1897 by miners heading for the Klondike gold fields, Skagway soon experienced river flooding problems necessitating river training dike construction, which has continued sporadically to the present. This dike construction causes river sediment bed loads to deposit in an unnatural and concentrated fashion on the river's submarine delta.

Mining is no longer a major economic factor for Skagway, but tourism via large tour ships primarily, brings many people to the city. Presently up to five large tour ships, the state ferry and other vessels can be in port at one time, thus any hazard involving the waterfront becomes much more important than in the past. Thousands of tourists can be scattered along the waterfront and throughout the city during the time ships are in port.

In 1972, the U.S. Geological Survey issued an open-file report (Yehle & Lemke 1972) addressing tsunami hazard potential at Skagway, Alaska. They predicted the possibility of up to an 18-meter amplitude event as a result of submarine landslides. Subject to tide stage they predicted such an event could pose a major hazard to the Skagway waterfront and other parts of the city. They further recommended that the area be studied in detail to better understand the Skagway River delta front stability and tsunami hazard potential.

Response time for local tsunamis can be a matter of minutes or less; thus responsible officials apparently concluded that nothing could be done in the way of warning, thus nothing has been done, including the recommended studies. The 1972 USGS report was apparently filed with no attempt being made to mitigate the problem or to educate the people of Skagway, visitors, workers or others about the tsunami hazard.

During the first week in October, 1994 the Skagway River experienced a violent flood, nearly reaching top of dike levels and serious consideration was given by officials to evacuate some areas of the city. A large bed load was carried by the Skagway River as evidenced by resident reports of noise and high water velocity on the 0.8 percent river gradient.

On the evening of November 3, 1994 during one of the lowest tides of the year (extreme tide range at Skagway is El. +23 to El. –6 or 29 feet) a submarine landslide occurred producing a tsunami with an estimated amplitude of nine meters. Extensive waterfront damage resulted and one life was lost.

Following the tsunami, various legal teams presented arguments supporting each client's position, many without technical merit (Nottingham 2000). Visible ongoing dock construction was the main litigation target as a triggering mechanism for the submarine landslide and ensuing tsunami. This legal activity delayed the important task of identifying and mitigating the continuing tsunami hazard identified as early as 1972.

In 2001, Alaska Congressman Don Young recognized the government's responsibility in this matter and working with the National Tsunami Hazard Mitigation Program organized a workshop on October 30-31, 2001 in Seattle. Interested scientists, engineers and officials were invited to discuss the 1994 Skagway tsunami and other related issues. The workshop resulted in an initial one year work plan and budget basically similar to that recommended in 1972 by the U.S. Geological Survey.

**Summary of Workshop Proceedings**

Dr. Frank Gonzalez (NOAA/PMEL) acting as workshop chairman provided an opening welcome and outlined the workshop schedule and expected work products. Attendees were given the opportunity to present their interests, affiliations, findings or other information relating to the subject.

Technical summary notes taken at the workshop are as follows:
Dr. Costas Synolakis (USC) presented a series of case histories of various past tsunamis world wide including landslide created events. This presentation helped to outline potential serious risks of tsunamis, many of which had some relationship to Skagway.

A general discussion of past historical tsunamis at Skagway disclosed three large events probably creating waves with amplitudes from three to nine meters pus numerous potential smaller events. Detailed information was contained in a 1972 USGS report on Skagway where significant space was dedicated to discussing tsunamis and tsunami potential relating to submarine landslides at Skagway. Potential submarine landslides along the east shoreline, and off the Skagway River delta were mentioned. A technical discussion primarily related to the 1994 tsunami centered on potential locations of submarine landslide frequency and impact of these events.

Bruce Campbell (Consultant) discussed the need to utilize and explain every shred of evidence in arriving at forensic conclusions about the 1994 event or any event. He located three primary potential submarine landslides using available survey information and discussed slide cross-sections and volumes (Figure 2). He also spent time discussing eyewitness reports and tide gage action with the conclusion that effects from offshore slides directed down the inlet could only fit all the evidence. He showed that Skagway River diversion was concentrating river sediments in an area with future landslide potential. Sediment thickness increases of over 30 meters had been found for about a 50-year time interval.

Dr. George Plafker (USGS) verified Mr. Campbell's findings of potential past landslide locations. He chose to investigate the easterly shoreline slide south of the rail dock because of recent slide evidence found during submarine dives. This slide was so large in volume that he concluded the small volume of material involved with dock construction was inconsequential and thus not a factor. In fact, the slide retrogressively ended at dock construction instead of starting at dock construction.

Dr. Synolakis presented modeling results of the east shoreline slide identified by Dr. Plafker with results closely matching most evidence including eyewitness reports, except time length of the measured wave train was not discussed. An exceptional video animation clearly demonstrated the event.

Dr. Zygmunt Kowalik (UAF) discussed the unusual nature of the tsunami and exceptional time length of the wave train. He found it necessary to nearly simultaneously use the three slides found by Campbell to reproduce all the evidence. These included the east shoreline slide (about three million cubic meters), a central delta slide (about four million cubic meters) and a westerly delta slide (in excess of eight million cubic meters). Note that large areas of surface gas bubbles verifying submarine slide locations were seen by engineers immediately after the November, 1994 event at the location of the easterly and westerly slides and about a week later near the center of the inlet (Figure 2).

Dr. Kowalik also investigated known movement of the floating Alaska Marine Highway System Ferry Terminal under various slide scenarios but found the three slide down inlet modeling most nearly produced results consistent with the evidence. His work also identified tsunami related inlet current activity most important to moored ship response.

Dr. Charles Mader (Consultant) was unable to attend the workshop, but provided information that supported the conclusion that a very large submarine slide volume progressing down inlet would have been required to produce the observed and recorded (tide gage) tsunami on November 3, 1994.

Investigators generally concluded that one or more down inlet submarine landslides must have been involved to create actions consistent with the evidence. The slide(s) were very large and produced initial drawdown at the rail dock probably creating slope instability. The returning crest wave was nearly coincident with the progressing slope failure near dock construction.

Discussions centered around potential for future tsunamis and need for additional investigation. General conclusions based on documented recurrence of tsunami activity at Skagway were that there is a need for more investigation and potentially some form of mitigation.

USGS, in their 1972 report, provided in part to the workshop, recommended future study involving site investigation, seismic evaluation, bathymetry, sediment analysis and Skagway River delta front stability analysis. These recommendations were essentially followed by the workshop in drafting a future work scope with a first-year budget.

Before conclusion of the workshop, participating State and Federal representatives and City of Skagway officials discussed how they might participate and presented their general impressions. The consensus was that a much better understanding had been gained during the workshop and that a pilot tsunami investigative project for Skagway would be an important step for Skagway and the other parts of the world.

The following workshop summary statement was issued following completion or the workshop.

**Workshop Summary Statement**

Skagway, Alaska has a history of deadly and damaging tsunamis caused by landslides. The most recent, on 3 November 1994, killed one person and caused an estimated $21 million in damage. The risk increases each year with the arrival of cruise vessels that dock at Skagway; this seasonal tourism can swell the Skagway annual population by 800,000 – many of whom live on-board dockside vessels during visits.

> There is no question that future landslides and tsunamis will occur – they are expected, even inevitable. This is because the causative physical processes that generated past events will continue to be active in the future – earthquakes, sedimentation, extremely low tide levels, delta accretion and failure, coastal slope failures. The appropriate questions are:
> 1. What is the level of the hazard (Hazard Assessment)?
> 2. What could/ should be done to reduce or eliminate this hazard (Hazard Mitigation)?

An Action Plan for Hazard Assessment to address the first of these questions was developed at the "Workshop Relating to Potential Tsunami Hazards at Skagway, Alaska." This workshop brought together Skagway elected officials and Twenty State, Federal and private scientists and engineers. The working sessions were held in Seattle, Washington on 30-31 October 2001 at the Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Administration, the lead Federal agency for the U.S. National Tsunami Hazard Mitigation Program.

Essential components of the Action Plan were identified, and preliminary budget estimate was drawn up for the proposed work in Year 1. The Year 1 Action Plan proposes both the exploitation of existing data and new data acquisition to estimate fundamental indicators of risk – background delta accretion rates; flood history and its influence on sedimentation rates and delta loading; Landslide history from paleosedimentology; assessment of coastal slope stability; ship response hazardous scenarios; tide, seiche and wave measurements; acoustic detection and characterization of landslides; measurement and characterization of the earthquake environment. We expect that lessons learned and technologies developed by this effort will be exportable to other Alaskan and U.S. sites.

NOAA's Pacific Marine Environmental Laboratory (NOAA/ PMEL) under Dr. Eddie Bernard, Director will provide overall management and administration of the Skagway project.

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Nottingham, Dennis, "Investigating the Skagway, Alaska 1994 Tsunami," Proceedings of the Second Congress on Forensic Engineering, American Society of Civil Engineers, San Juan, Puerto Rico, May, 2000.

"Workshop Relating to Potential Tsunami Hazards at Skagway, Alaska, Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Administration, Seattle, Washington, October, 2001.

Video and DVD disk documenting the 2001 workshop produced by In Progress Media Productions, 1319 Cornwall Ave. #200 Bellingham, WA 98225, (206) 752-1384.


## TSUNAMI INFORMATION WEBSITES

Los Alamos National Laboratory
http://t14web.lanl.gov/Staff/clm/tsunami.mve/tsunami.htm

Tsunami Society Journal and Symposium
http://www.sthjournal.org/
http://www.mccohi.com

National Tsunami Hazard Mitigation Program
http://www.pmel.noaa.gov/tsunami-hazard/

More information:
The Tsunami Society
P.O. Box 37970
Honolulu, HI 96817

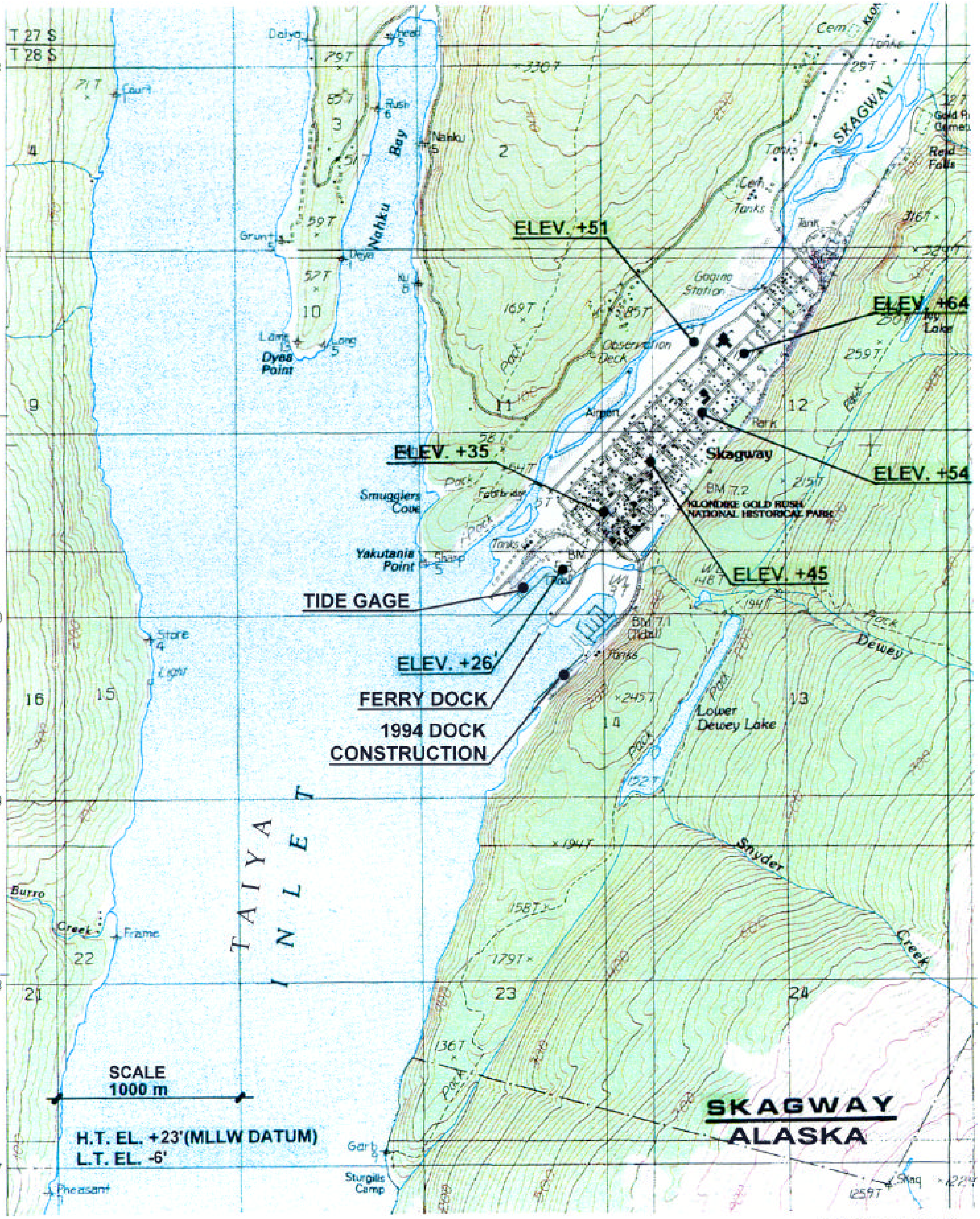
ELEV. +51
ELEV. +64
ELEV. +35
ELEV. +54
ELEV. +45
TIDE GAGE
ELEV. +26'
FERRY DOCK
1994 DOCK
CONSTRUCTION
SCALE
1000 m
H.T. EL. +23'(MLLW DATUM)
L.T. EL. -6'
SKAGWAY
ALASKA
Skagway
KLONDIKE GOLD RUSH
NATIONAL HISTORICAL PARK
Smugglers
Cove
Yakutania
Point
Dyea
Point
TAIYA
INLET
Lower
Dewey Lake

FIGURE 1

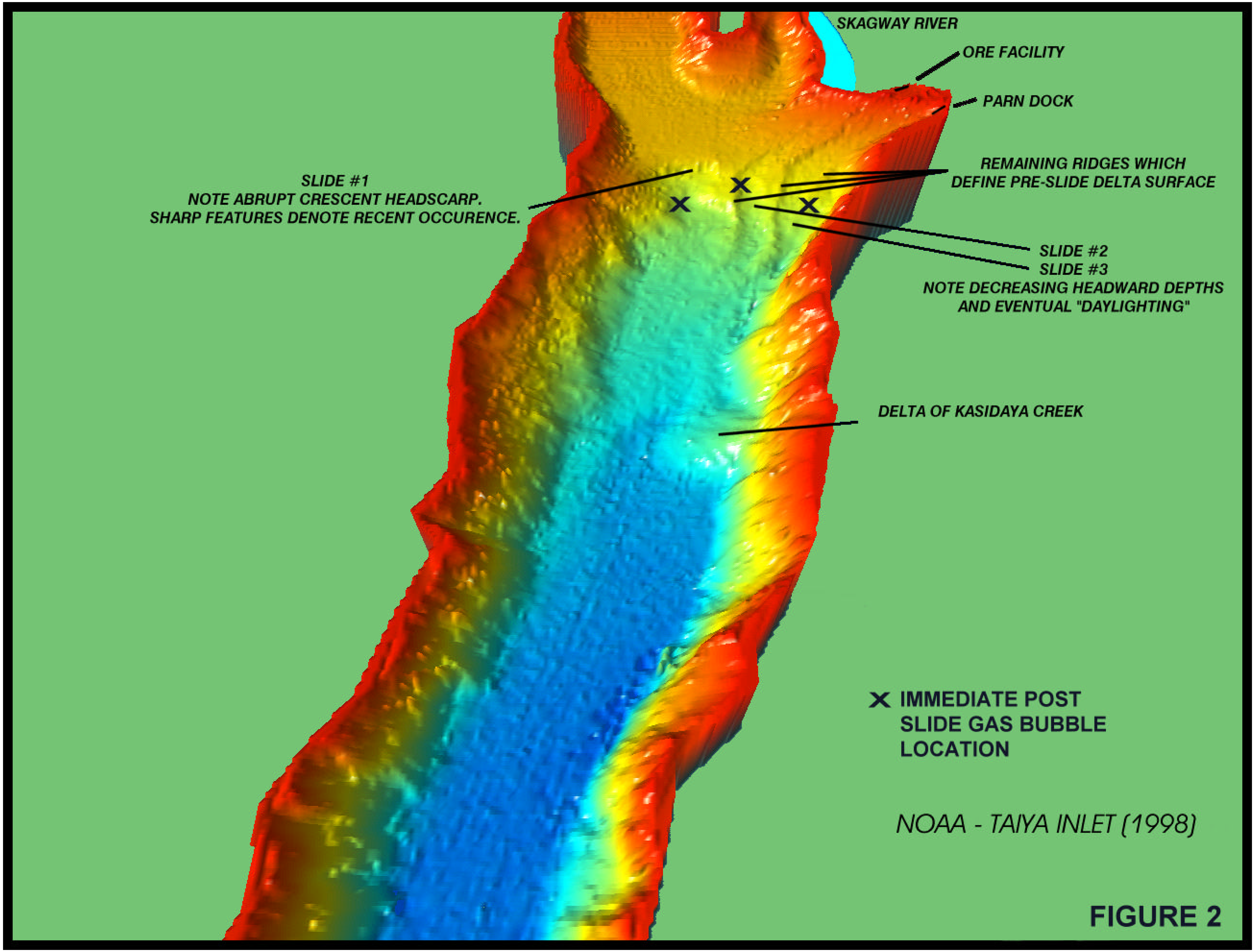
SKAGWAY RIVER
ORE FACILITY
PARN DOCK
REMAINING RIDGES WHICH
DEFINE PRE-SLIDE DELTA SURFACE
SLIDE #1
NOTE ABRUPT CRESCENT HEADSCARP.
SHARP FEATURES DENOTE RECENT OCCURENCE.
SLIDE #2
SLIDE #3
NOTE DECREASING HEADWARD DEPTHS
AND EVENTUAL "DAYLIGHTING"
DELTA OF KASIDAYA CREEK
X IMMEDIATE POST
SLIDE GAS BUBBLE
LOCATION
NOAA - TAIYA INLET (1998)

FIGURE 2

# TSUNAMI BOOK GIVES A BETTER UNDERSTANDING OF ANCIENT FLOODS ON MARS

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## ABSTRACT

During 2001 Dr Edward Bryant from the University of Wollongong published a book "Tsunami: The Underrated Hazard". He proposes that the best explanation for a range of odd geological features along the south east coast of Australia is that at least one large tsunami struck the coastline around 1500 AD. The book describes these geological features and the mechanisms by which they can be produced by tsunami. The book also covers historical accounts around the world, the physics of tsunami, causes of tsunami and a review of the risk to coastal populations.

After reading the book I was keen to visit Wollongong (just two hours drive south of Sydney) and see the evidence myself. By a fortunate coincidence Dr Vic Baker from the University of Arizona was visiting Wolongong at the time. Dr Baker studies evidence of mega-floods on Mars and related features on Earth, such as the Washington Scablands. Early in 2002 I joined Dr Bryant and Dr Baker on a tour of the coast. This informal report describes that fascinating experience.

## INTRODUCTION

This article was originally planned as a review of the book "Tsunami: The Underrated Hazard" by Edward Bryant (Cambridge University Press, 2001) [1]. However, a review by Japanese tsunami expert Kenji Satake appeared in the journal Nature [2] so I decided, instead, to describe my own investigations to verify some of the phenomena that are described in the book.

Ted Bryant is an Associate Professor at the University of Wollongong, on the south east Australian coast. He is a geoscientist with an interest in geomorphology. Bryant had studied the coastal features of the area since the late 1960s. Some things did not add up. He remembers the day in 1989 when he was examining fresh boulders jammed into a crevice in a cliff well above the height of any possible storm waves. After eliminating all other explanations he and his colleague, Bob Young, "were left with the preposterous hypothesis that one or two tsunami waves had impinged upon the coast". Bryant began to gather other evidence of these mega-tsunami, including the overwashing of a headland 130m high.

Many researchers were (and some remain) sceptical about Bryant's claims. They picked on isolated items of evidence and provided alternative explanations for the unusual features. It seems, however, that none of the critics have actually visited the dozens of interesting sites and considered the convergence of evidence which leads to the conclusion that mega-tsunami have struck the south east Australian coast in recent times.

Eventually Bryant decided to set out his research in a book. As well as describing the mechanisms of alteration of coastal landforms he comprehensively covers a wide range of topics concerning tsunami: historical accounts around the world, the physics of tsunami, causes of tsunami and a review of the risk to coastal populations.

Sakate's review in Nature is mostly complimentary but cautions that "the quality and depth varies greatly from chapter to chapter" and that "parts of the book lack vigour and consistency". I do not have the knowledge to make such judgements but I found the book fascinating and it certainly triggered my curiosity. The description of bedrock scouring, in which large chunks of rocky headland are torn away in a matter of minutes was amazing. Sakate commented that "a modern example of bedrock scouring would also have made Bryant's arguments more convincing". I had the same thoughts, and set out to investigate this phenomenon.

## SOURCES OF INFORMATION

An internet search led me to an unlikely source - the Creation Research Society. It seems that members of this Society are keen to demonstrate that modern eroded landscapes, such as the Grand Canyon, could have been formed in a few thousand years. Fortuitously they have gathered together recent examples of bedrock scouring by catastrophic floods. A paper by Dr Glen Wolfrom [3] describes sudden erosional effects at three locations. Wolfrom reports that water from a spillway "acted like a chisel, a drill, a grinder and a thousand bulldozers all in one". Pictures illustrate where huge chunks of bedrock are missing from the streambed below dam spillways.

Another potential source that arose from an internet search was research on Martian geology. I have a long-standing amateur interest in Mars so this source caught my attention. The Viking spacecraft that orbited Mars in the early 1970s took pictures of Martian channels that had signs of catastrophic flooding. Dr Mary Bourke from Oxford University in the UK has studied the geomorphology of ancient floods in Central Australia as an analogue for those features on Mars. In one paper she describes erosion of bedrock including "scour holes generated by macroturbulent vortices" - evidently a similar process to that which generated the whirlpool features at Bass Point [4].

Dr Vic Baker from the University of Arizona also studies the Martian features and has compared them with the strange landforms of the Washington Scablands in the USA [5]. I contacted Dr Baker by email and, to my surprise, he told me he would be visiting Ted Bryant in Wollongong the following week.

A quick call to Dr Bryant confirmed that I could tag along while Dr Baker was shown the tsunami signatures of the area. Fierce rainstorms and dense fog on the two hour drive from Sydney to Wollongong could not deter me from joining the tour.

Now if you intend to visit Wollongong yourself and want to experience that moment of realisation that a mega-tsunami is the only logical explanation for the coastal landforms then I suggest you read no further because I am about to reveal some of Ted Bryant's tantalising evidence.

## GEOLOGICAL SIGNATURES OF TSUNAMI NEAR WOLLONGONG

The northern side of Bass Point is covered by a thick, jumbled layer of sand, crushed shells, pebbles and boulders - clearly subjected to severe mechanical action. Bryant's explanation is that they have been dumped there when a mega-tsunami swept over the opposite side of the headland, from the south east. We then crossed to the rugged, exposed south east face of the headland. Here, carved into the rock, are two giant donut-shaped whirlpool features some 50 metres across. One is complete and has a central plug (Figure 1). The other is about three-quarters complete and looks as if it was being quarried when work suddenly ceased (Figure 2). Bryant's explanation is that when the tsunami overwashed the headland giant whirlpools were formed. The outer edges of the whirlpool started to form secondary vortices ("kolks") that were highly erosional and tore out chunks of bedrock in a circular path. For the second whirlpool feature the tsunami finished before the full circle could be completed.

This mechanism is still regarded as speculative by Sakate. I was unable to find a modern example of such an action (that is, where before and after pictures of the changes to bedrock are available). There are however, several other examples of these erosional whirlpools in the Wollongong area. They do not appear to be associated with any localised weakness in the rock. They are similar in topography and aspect - suggesting they were conducive to the formation of vortices during overwashing by a mega-tsunami.

I tend to think of the whirlpool mechanism as being similar to a rock-face tunnelling machine that has a large rotating head with smaller rotating bits on the circumference. However, the hydraulic forces generated by water flowing in excess of 20m/s at depths of, perhaps, tens of metres are much more efficient at excavating rock than these machines.

Bryant then showed us the clinching evidence. We clambered over the rock formations to a valley that had a group of boulders at one end. The boulders were imbricated (stacked like a pile of fallen dominoes). He explained that the boulders had been carried from the seaward side of a ridge that was more than six metres above sea level. He pointed out that one of the boulders had oyster shells attached - it had been scooped up from the shoreline by a tsunami, carried over the top of the ridge and dumped against the other boulders (Figures 3 and 4). The shells had been dated to 1500AD, just 270 years before Captain Cook sailed up the east coast of Australia!

After Bass Point we travelled to several spots along the south coast to see other examples of strange erosion, imbricated boulders and huge sand deposits in odd places. Mega-tsunami are the simplest, most logical explanation for this wide range of features.

**POSSIBLE CAUSES OF THE MEGA-TSUNAMI**

What could have caused the mega-tsunami that struck the south east coast of Australia five hundred years ago?

Bryant's book describes the four causes of tsunami: earthquakes, undersea landslides, volcanic eruptions/explosions and cosmic (asteroid or comet) impacts with the ocean. Of these cosmic impacts and giant landslides are the most likely causes of mega-tsunami.

Landslides are a possible cause of the Australian mega-tsunami. The shallow continental shelf extends tens of kilometres from the coast then drops off steeply to depths of 4 kilometres in some places. Major rivers such as the Shoalhaven and Hawkesbury deliver sediment to the edge of the shelf and this might periodically tumble down the continental slope. Apparently a thorough survey of the continental slope that might pick up signs of past landslides only recently got underway.

Bryant refers to the work of Ward and Asphaug [6] when considering the possibility that cosmic impacts might have caused mega-tsunami. Their work suggest that for Sydney the average interval between 10m+ tsunami caused by cosmic impacts is about 80,000 years (based on Bryant Figure 9.10). My own investigations of tsunami from cosmic impacts led to a paper in the Science of Tsunami Hazards [7]. In that paper I pointed out major differences between researchers in the estimates of long range wave heights from impact-generated tsunami. Using the more conservative estimates of Crawford and Mader [8] I estimate that, for Sydney, the average interval between 10m+ tsunami from cosmic impacts is about 1 million years.

Even the most pessimistic frequency derived from the work of Ward and Asphaug would not account for frequency of large tsunami established by Bryant - perhaps every 500 years. There remains, however, the possibility of an unusual series of impacts such as a barrage from the breakup of a comet. There are signs of such an event occurring several thousand years ago [9] but it does seem unlikely that "frequent" ocean impacts large enough to devastate the coast of Australia were not accompanied by similar large impacts in the northern hemisphere, including some that would have left impact craters on land.

On the other hand the last major Australian tsunami event, that evidently occurred around 1500AD, has some historical coincidences. The largest recorded death toll from a meteorite fall occurred in China in 1490AD - more than ten thousand died in the city of Ch'ing-yang Shansi [10]. There is also evidence of impact generated fires and tsunami in New Zealand at this time (Bryant's book).

Finally there is speculation about the enigmatic Balls Pyramid rock outcrop near Lord Howe Island, between Australia and New Zealand. It is a stunning sight in the middle of the ocean and looks to me like a giant stone tool that has had shards flaked off to give a ragged edge (Figure 5). The odd thing is that the vane-like island is aligned in the same direction as the mega-tsunami that hit Bass Point and possibly the South Island of New Zealand. In discussions during our tour, Bryant pointed out that a tsunami tens of metres high could cause the strange features observed on Balls Pyramid.

My recommendation is that people living near the coast read Bryant's book and go out looking for some of the tsunami signatures that he describes. You may discover unsettling evidence that our populated coastlines are surprisingly vulnerable to these giant waves.

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An interactive map of the New South Wales tsunami features, with many new photographs, is now available at: http://www.uow.edu.au/science/geosciences/research/tsunami/tsunami_nsw.htm

Picture credits: All pictures by Michael Paine. Email for copies: mpaine@tpgi.com.au


Figure 1. Complete Whirlpool Formation at Bass Point

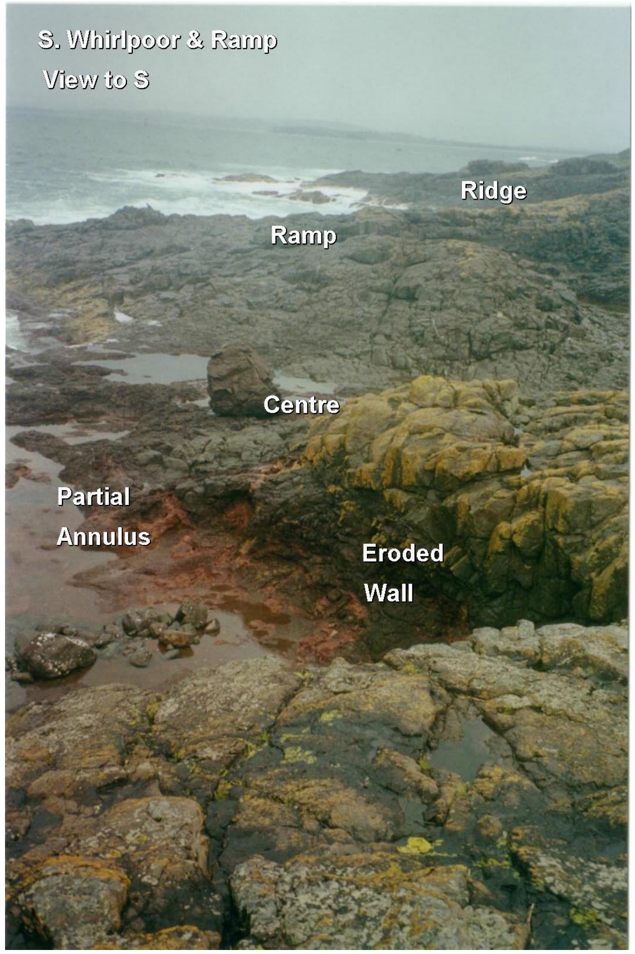


Figure 2. Incomplete whirlpool and the ramp that faces the direction of approach of the tsunami.


Figure 3. View of valley behind ridge (a wall of the incomplete whirlpool is in the foreground)


Figure 4. Vic Baker, Ted Bryant and Gerald Nanson (left to right) examine the boulder with oyster shells. The boulder has been carried over the ridge by a tsunami.

Figure 5. Balls Pyramid near Lord Howe Island in the Tasman Sea. The ragged ridgeline and scalloped surfaces are difficult to explain by conventional geological processes. It is speculated that a mega-tsunami could tear away pieces of rock to produce this type of formation. Interestingly the vane-shaped island is aligned towards the south east - the same direction as the mega-tsunami that apparently struck Bass Point in 1500AD.