THE TSUNAMI HISTORY OF GUAM: 1849-1993

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ABSTRACT

The great (Mw 8.1) tsunamigenic earthquake of August 8, 1993, about 50 km to the east of Guam, has created renewed interest in the tsunami hazard for the island of Guam. We examine this hazard from two perspectives--historical and mechanistic. Guam has had only three tsunamis causing damage at more than one location--in 1849, 1892, and in 1993, and only two to six other locally-generated tsunamis which were observed on the island in the past 200 years. Five of these six events have low validities and may not be reports of true tsunami. On the other hand, dozens of storm surges related to typhoons have caused millions of dollars of damage on Guam. The island of Guam is located west of the Marianas Trench. The trench is caused by the subduction of old, cold, and dense lithosphere of the Pacific plate under the Philippine plate. Steeply dipping old material is unlikely to trigger tsunamis because (1) the two plates are decoupled and (2) the motion is too slow to allow large amounts of stress to build up before earthquakes occur, resulting in less violent earthquakes. A small section of the Marianas Trench near Guam, however, has shallow subduction. This is where the 1993 event occurred, and a quiet area south of this may be the site of a similar future tsunamigenic earthquake. Most of the damage from a local tsunami would occur on the relatively unpopulated east coast; the likelihood of a local tsunami from the west is minimal. However, a repeat of the 1848 tsunami with a southern source could affect both the east and west coasts. The 1993 earthquake occurred coincident with the passage of Typhoon Steve. We show that this may not be coincidental as there is a substantial statistical correlation between earthquakes and typhoons at Guam. The close encounter of a typhoon with Guam doubles the probability of an earthquake with magnitude greater than 5.0 occurring on that day.

INTRODUCTION

Guam, located about 50 km west of the axis of the Marianas Trench, one of the world's deepest at 9650 m, has a history of strong seismic events. Major earthquakes were reported in 1809, 1822, 1825, 1834, 1837, (Degraz, 1838) 1849, 1892, 1902, and 1909 (Repetti, 1939). An unconfirmed tsunami has also been reported from the late 18th Century as having caused severe damage in Agana and Umatac with several fatalities. This event has been reported as having occurred in 1767 (Farrell); 1769 (*Guam Reporter*, Jan. 1929, p 217); 1779 (?) and 1799 (Maso 1910). Degraz (1838) reported that in the month of October 1837, an extraordinary movement of the sea was experienced. A type of tempest disturbed it and it flooded raised portions of the banks, caused landslides and considerable damage. This was also a year of a reported major earthquake. He also reported similar movements for the 1809 and 1825 events where some ships experienced violent shocks near Guam. The 1837 event caused four of the Caroline Islands to disappear and only parts of two to remain above water level. Survivors emigrated to Guam and settled on Saipan. Surprisingly, Guam has a history of directly and clearly observing only a few tsunamis, including those local tsunamis in 1849, 1892, 1990 and 1993 and teletsunamis from the 1952 Kamchatka earthquake and the 1960 Chile earthquake. Only minor damage has resulted from these tsunamis with the 1849 event being the largest event. There is a report of a possibly observed local tsunami in 1903 but this given a low validity event.

Storm surges are also an urgent problem in Guam, reaching several meters in height, often coming unexpectedly, and occasionally causing extensive damage. For example, Soloviev and Go (1984) cite Dumolin (1940) that in October of 1837, just 12 years before the tsunamigenic earthquake of 1849, a strong storm surge did considerable damage on Guam and caused four low-lying islands in the Caroline group to be submerged. Two islands later reappeared and the other two became banks. The earthquakes of 1849 and 1993 produced similar intensities, although it is difficult to make direct comparisons due to different construction practices over time. The main reference for the 1849 event is Professor Marjorie G. Driver's translation of Governor Perez's report of the earthquake and tsunami effects to his superiors in the Philippines. The main reference for tsunami effects for the 1993 event is report of interviews by Judy Flores for a University of Guam class project in 1993. The resulting tsunamis affected the eastern and southern coast, with the 1849 event being the larger. This event caused Guam's only reported tsunami fatality. There are reports of the 1849 event strongly affecting the Caroline Islands of Satawal and Lamotrek that were completely overrun by large waves resulting in many casualties. There is also a report that the earthquake was felt aboard a ship 1000 kilometers from Guam. As the 1993 Mw 8.1 event was not reportedly observed in the Caroline Islands, the effects reported from the Caroline Islands in 1849 may be a separate tsunami or storm surge. The report of a remote earthquake felt on shipboard may also have been a separate event. The 1892 tsunami report mentions only a drop in water level in Agana Harbor and flooding of the San Antonio quarter that probably was caused by a submarine landslide inside the harbor.

The limited reports of the 1990 and 1993 events raises a question of the completeness of the history, but it is unlikely that an unreported destructive tsunami could have happened on Guam since the Spanish era beginning with contact in 1565 and settlement in 1668. The United States took over the administration of Guam in 1897. The marigraph was first installed in Apra Harbor in 1950. The Mw 8.3 earthquake at Hokkaido, Japan, in 1952, produced a tsunami which was recorded in Agana with an amplitude of 10 cm. Waves of 1.5 m were reported observed in Ylig Bay. All other recorded tsunamis had heights of 10 cm or less except the great 1960 Chile tsunami which had a height of 20 cm. The 1960 event was not reported observed on the eastern coast but this may reflect the frequent under reporting of tsunami observations at Guam. The lower heights may reflect that Agana is a sheltered harbor on the western coast and that instrumental measurements are usually significantly lower than the actual waves amplitudes. The 1993 event produced waves observed all along the eastern and southern coasts with a maximum height of about 2 meters and it was recorded in Agana and Apra with heights of only 10 and 15 cm respectively. However, the earthquake damage (more than $267 million per Hattori, 1995) was so severe that tsunami effects were largely unreported in the scientific community until a year later. Much of the damage occurred in structures damaged by the earthquake and then soaked by 1.9" of rain from Typhoon Steve that passed near Guam on the date of the 1993 earthquake.

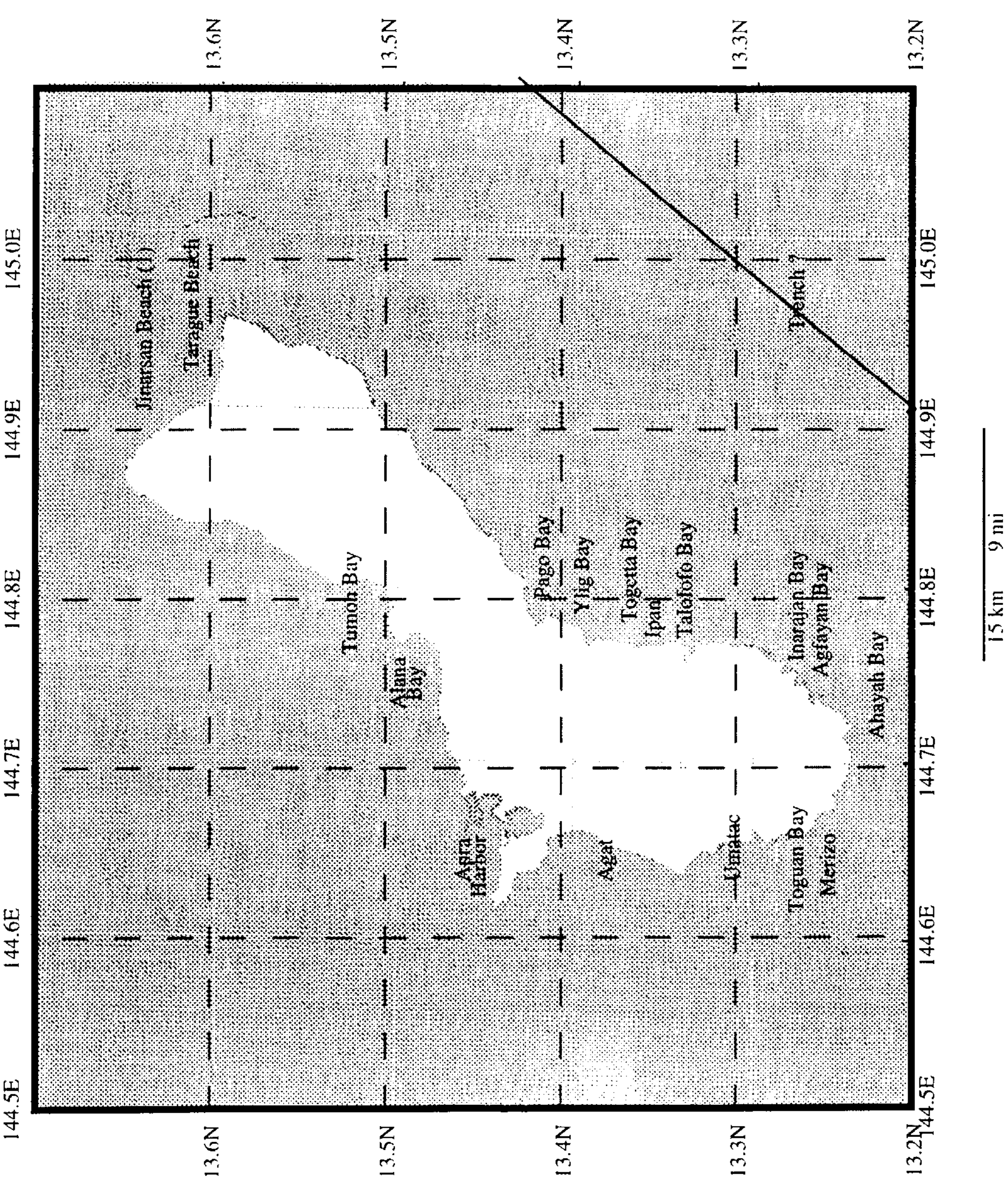

Figure 1. A simplified map of Guam, showing major bays.

TSUNAMI HAZARD FOR GUAM

To understand the potential hazard to the Island of Guam from tsunamis of local origin, it is necessary to understand the tectonics and seismic history of the region. Unfortunately, seismic history is available only from the early portion of the 19th Century, and is probably considerably under-reported until the advent of the WWSSN system and usable teleseismic catalog in the mid-1960s. The known tsunamis that have been observed and their effects on Guam are tabulated in the Appendix.

The Island of Guam (Figure 1) is located at the southern portion of the Mariana Islands arc. The Pacific plate is subducting beneath the Philippine plate with the Marianas Trench marking the boundary between these plates. This boundary is located about 50 km to the east of Guam. The Pacific plate in this region is among the oldest subducting plates in the world (age of about 200 million years). Because of it's age, it is thicker, denser, cooler and more brittle than most subducting material. Its high density with respect to the upper mantle causes the material to sink rapidly into the mantle once subduction has begun. This, in turn leads to a steep angle of subduction (>50 degrees) and the great depth of the Marianas Trench (Wortel, 1980). Because the Pacific plate is so dense, and therefore sinking rapidly with respect to the Philippine plate, the Mariana Islands arc is generally regarded as the archetype of a seismically decoupled subduction zone (Ruff and Kanamori, 1983). Furthermore, Ruff and Kanamori (1980) have demonstrated that in decoupled seismic zones, large (Mw>=7) earthquakes are rare and that great earthquakes (Mw>=8) should not occur. For most of the Mariana Islands arc this has been the case. While earthquakes in the magnitude range 5-6 occur at a rate of 5 to 8 per year within 400 km of Guam, earthquakes in the magnitude range 6-7 occur only on average once in ten years and quakes greater than 7 occur about once in 100 years. Figure 2 shows that when the dip of a subduction zone is between 45 and 90 degrees, the chance of tsunami generation is small. We define the efficiency of producing tsunamis defined by (1):

(1) $Et = Nt*100/N7$

where Et is the efficiency of producing tsunamis, Nt is the number of observed tsunamis and N7 is the number of regional events with Mw>=7.0. Et is quite low in the Mariana Islands region. In other words, decoupled subduction zones (with high dip and relatively low subduction velocity) are unlikely to produce significant tsunamis. We have used the regionalization of Wortel (1980) and his numerical dip, and age data for plates and subduction zones, the Preliminary Determination of Epicenters (USGS, 1993) for magnitudes and locations of earthquakes and the listing of historical tsunamis (Lockridge, 1996) from the NGDC database found on the Seismicity CD-ROM (Whiteside et al. 1996) to produce Figure 2.

However, in the region of Guam, the tectonic situation is slightly different from that in the rest of the Marianas arc. Figure 3a shows the historical seismicity (Whiteside et al. 1996) for the region of Guam. Several patterns can be seen in this figure. To the east of Guam and running on a line SW-NE there is a pattern of shallow seismicity extending from the trench toward Guam for about 50 km. Between this shallow seismicity band and a second band of seismicity to the north of Guam is a region about 50 km wide of little or no seismic activity. This is followed by a third band of seismicity, extending for about 50 additional km. This seismicity is composed of deep or intermediate focus earthquakes. An additional region of seismic quiescence can be seen between 12.2N 144E and 13N 144.6E (approximately the location of the August 1993 event).

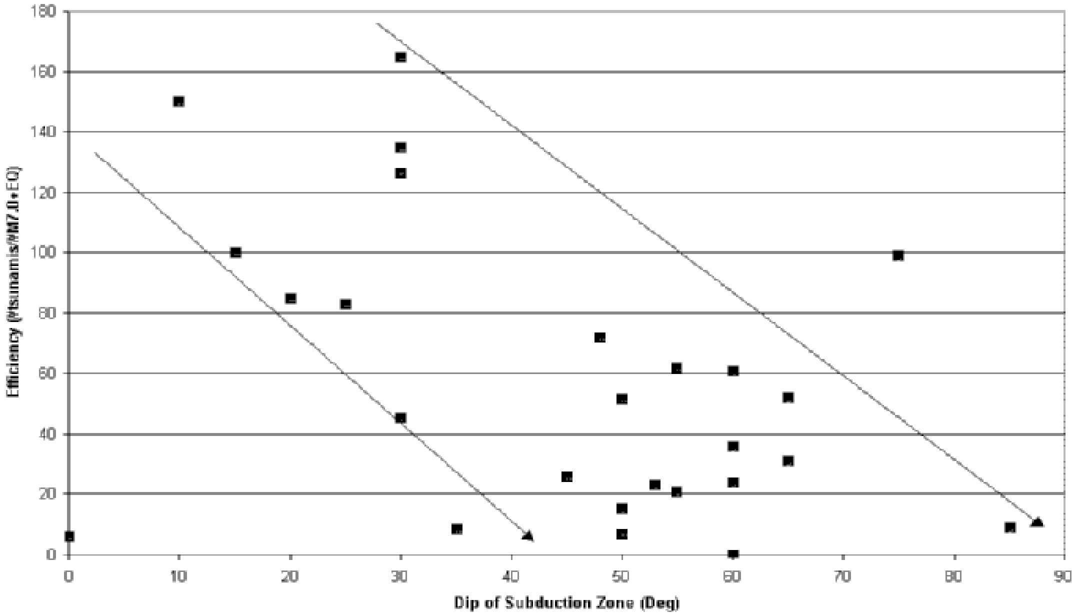

Figure 2. Subduction Zone Dip compared with calculated tsunami efficiency for tsunamigenic earthquake of Mw>=7. Tsunami efficiency is defined as the number of occurring tsunamis divided by the number of earthquakes of Mw>7 times 100.

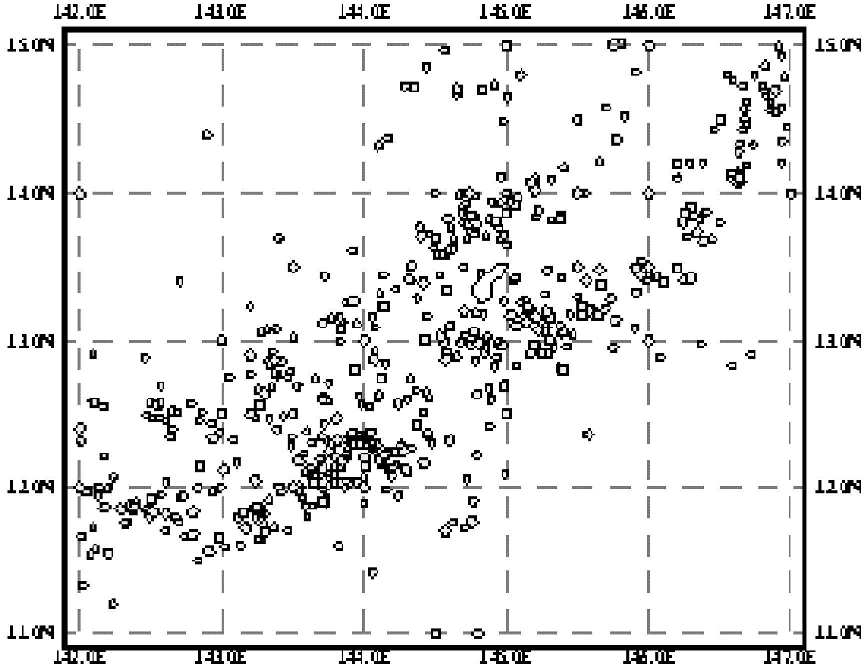

Figure 3a. Historical seismicity for the region of Guam, 1900-2001.

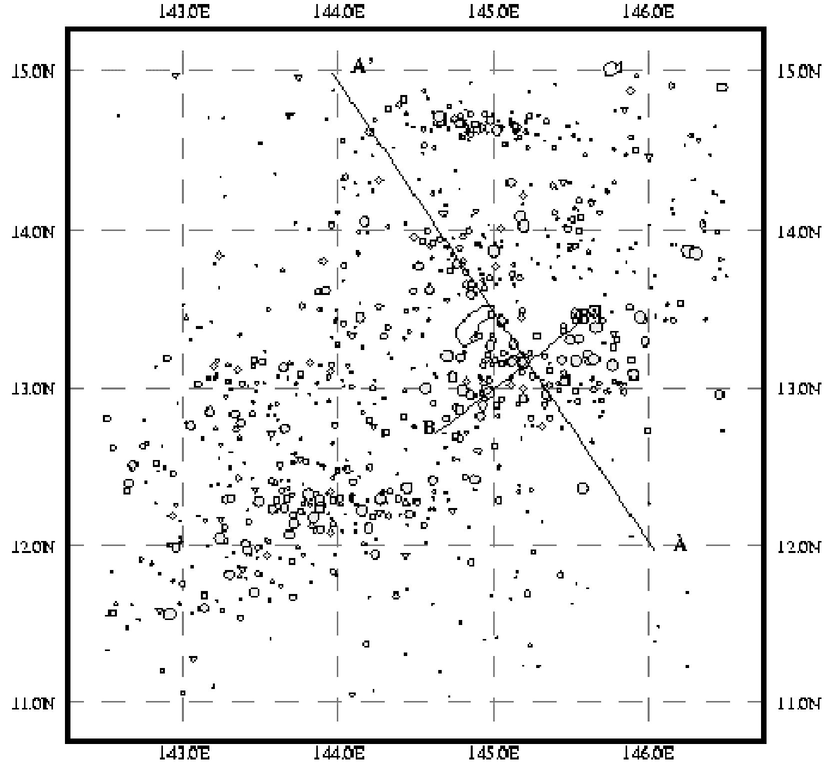

Figure 3b. Aftershocks and other seismicity near Guam following the earthquake of August 8, 1993 (1993-2001).

The 1993 event appears to have begun at 12.9N 144.8E and ruptured northeast with two subsequent events about 15 km to the NE and about 100 km to the NE (Campos et al. 1996). Li and Nabelek (1996) found that the CMT mechanism showed a time delay of 24 seconds with long period Rayleigh wave arrivals from the PDE epicenter. This is consistent with a rupture propagating at 3 km/sec to the CMT solution location about 70 km distant. Aftershocks of the 1993 event are shown in Figure 3b. The complex nature of this earthquake is confirmed by the observations of damage at the Seismological Observatory in Guam (Hattori, 1995) who noted that the pattern of breakage and fallen objects was consistent with "'two different mechanisms' … two different events close together, one from the SSE and the other from the SSW."

The 1993 earthquake hence appears to have filled a portion of a seismic gap between 13N and 14N and 145E and 146E. The seismically quiet section between 12 and 13N and 144 and 145E, however remains unruptured and may represent a significant threat of a tsunamigenic earthquake in the future.

Figure 4a shows a cross-section of seismicity within 150 km of either side of cross-section line AA'. The seismicity seen as bands on Figure 3a is shown as a change in subduction style in Figure 4a. The Pacific plate moving at about 3 cm/year encounters the Philippine plate about 50 km east of Guam (from direction A, Figure 4a). For about 50 km the subduction is shallow and with a low angle thrust. Near Guam, the direction of subduction changes dramatically. This change occurs in the region underlying the aseismic band on Figure 3a. To the west of this, the plate subducts at an angle between 60 and 80 degrees. Because of the aseismic nature of the bend, it is possible that the plate is broken at this section with two portions to the west and east of Guam detached from each other. If this is the case, large earthquakes directly under Guam are highly unlikely and this breakage in the plate may be the conduit for volcanic materials to rise through, creating the Island arc, including Guam. Figure 4b examines the eastern portion of the subduction more closely. The 1993 mainshock is marked by a triangular symbol. The approximate extent of the Pacific plate is outlined by arrows.

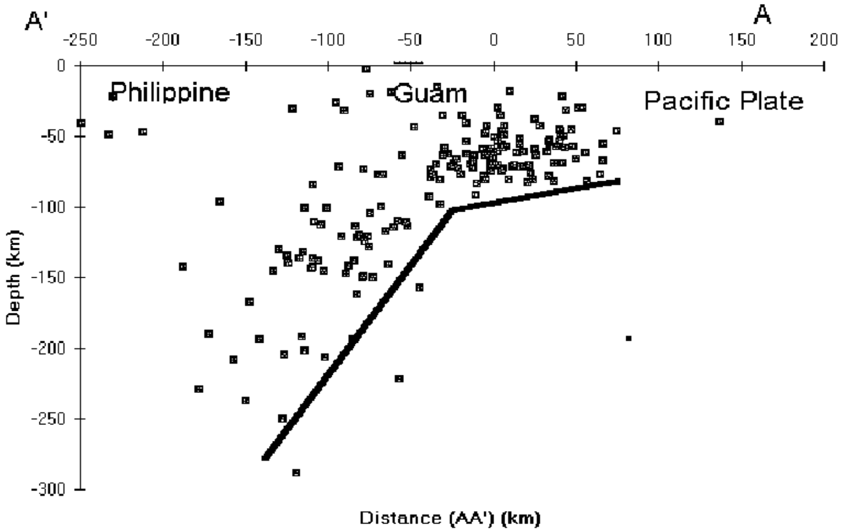

Figure 4a. Cross section of seismicity along line AA' from Figure 3b.

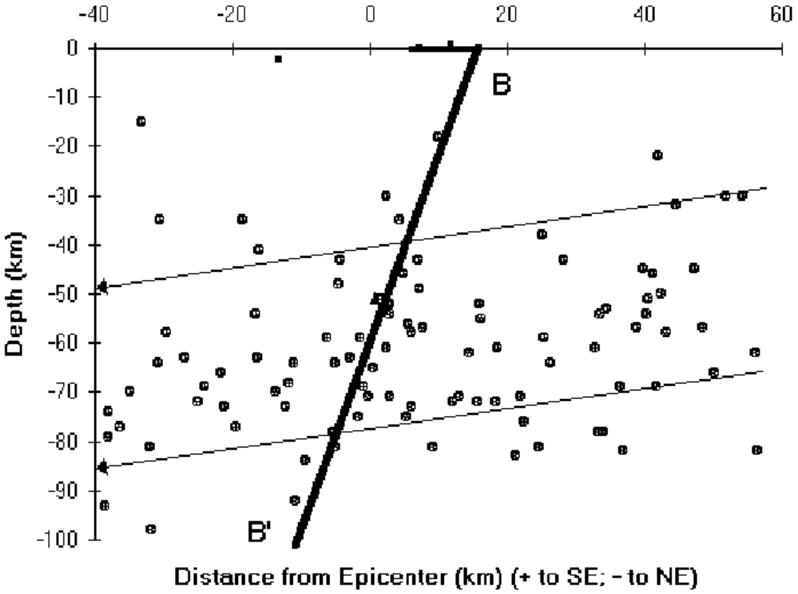

Figure 4b. Cross section of seimicity along line BB' from Figure 3b.

We find that the empirical dip of this plate in this region is about 13 to 15 degrees to the northwest. This observation confirms the modeling of Campos et al. (1993) who find that the dip of the fault plane was 13.77 degrees dipping to the NW. However, it is in sharp contrast with work of Tanioka et al. (1995) who modeled tsunami waveforms and proposed a steeply dipping fault plane cutting through the subducting slab. There is, however, some evidence in Figure 4b for an auxiliary fault plane similar to that modeled by Tanioka et al. at an angle of about 70 degrees with the vertical and passing through the hypocenter of the mainshock.

In general, the Campos et al. model provides the better match with the GPS data from Beaven (1994) that showed a 25 cm horizontal movement while the Tanioka et al. model reproduces the tsunami more accurately. Both are based to some extent on the Beaven GPS data. We, however, feel that since the Island of Guam (where the GPS data was obtained) may not be directly connected to either the westerly deeply subducting slab nor the easterly shallow subduction, the data may not describe the actual motion that is required to understand the earthquake or tsunami mechanism.

Most models of the mainshock of August 8, 1993 have determined a relatively deep hypocentral depth for the event. Depths range from Harvard CMT (59.3 km); USGS (68.0 km); Caltech (57.0 km) and Campos et al. (41.0 km). Depths around 60 km seem unlikely to be capable of producing a sizable tsunami, especially if they do not break through to the trench. To produce a tsunami, some differential motion of the ocean bottom must occur either directly from the event or from landslides secondary to the earthquake. A number of landslide and liquefaction events did occur in the coraline soils surrounding and on Guam (Mejia and Yeung, 1995), so the possibility exists that the tsunami was induced by mass motion of materials in the trench. The depths may also be in error. Both BJI (Beijing, China) and PDE report an earthquake on August 3 of Mb 5.1 - 5.3 whose epicenter is less than 2 km from the mainshock on August 8.

On the other hand, the epicenter of this moderate foreshock is listed as having a depth of 46 km by PDE and 37 km by BJI. These are in the depth range where a tsunami might be expected. If the mainshock nucleated at the epicenter of the foreshock, as might be expected, then it's depth would be shallower than that commonly modeled. The models are probably in error because they find the depth as a function of the average hypocenter given all first arrivals from the initial and sub-events of the mainshock or they locate the centroid not the hypocenter. If the initial rupture occurred at the top of the deeply dipping plane along line BB' on Figure 4b, then the average depth in the slab would be around 60 km as the models suggest. Nevertheless, earthquakes on the deeply dipping plane (BB') can be seen as shallow as 15 km +/-10 km. In this case motion at the surface could easily have triggered a tsunami. This mechanism is further supported by the difficulty of triggering a tsunami by horizontal motion of the ocean floor (Tanioka and Satake, 1996). While tsunamis can be generated by horizontal motion they are about ten times smaller than an equivalent tsunami generated by vertical motion. The nearly vertical fault plane hitting the surface at about 15 km to the SE of the mainshock would be an ideal candidate to trigger the observed tsunami.

We propose that both the Beavan and the Campos models are correct. The GPS data at Guam reflects the fact that the motion of Guam is mostly influenced by the dominant motion of the shallow slab pushing during the earthquake towards Guam. During the earthquake, however, a secondary fault ruptured (this is line BB' on Figure 4b). The tsunami was caused by this deeply dipping fault. This could be checked by examining the arrival times at various locations in Guam of the tsunami (if accurate times were available).

It appears that local tsunamis are not likely to be damaging to Guam because they will be generated to the east, while most of the settlement on Guam is on the western side of the island and because any generated tsunami is likely to be small because of the tectonics of the regions. The only likely area to produce a tsunami in the near future is in the seismically quiet region to the south of Guam.

THE TYPHOON CONNECTION

The earthquake of August 8, 1993 in Guam was closely associated with Typhoon Steve which dropped 1.89 inches of rain on Guam on the same date. Winds from Typhoon Steve measured more than 40 m/sec (Joint Typhoon Warning Center, 1994). Dunbar and Whiteside (1994) have proposed that the winds and microseisms from hurricanes can trigger nearby earthquakes when stresses are appropriately high in the earthquake region. An alternative hypothesis suggests that pressure changes associated with the extreme low pressures associated with typhoons and hurricanes causes the land to rise under a reduced load. This is a reasonable hypothesis when the earthquake occurs under land, but over the ocean, a change in pressure in the atmosphere is generally compensated for by an increased elevation of the water level, but the total column of air plus water retains a relatively constant mass because both the air and water are fluids. The resulting pressure on the sea floor and the subduction zone would remain unchanged. While the study by Dunbar and Whiteside examined hurricanes off the west coast of Mexico and the central Atlantic Ocean, the mechanisms are equally appropriate for typhoons in the region of Guam. The eye of Typhoon Steve passed about 80 km to the north of Guam on the 8th of August. Winds were pushing on Guam (and the Marianas arc) from the southeast. The resulting stresses would have pushed Guam and the Philippine plate to the northwest and reduced the normal stress between subducting Pacific and the overriding Philippine plates. This reduction in normal stress results in a loss of friction, which can trigger an earthquake.

We have examined the history of the association of typhoons and earthquakes in the region of Guam. Figure 5 shows the number of earthquakes of Mb>=5 in the region as a function of the time delay between the earthquake occurrence and the closest approach of a typhoon which ultimately passes within 500 km of the island of Guam. The delay time is the difference in time between the date of the closest approach of the typhoon and date and time of the earthquake. Numbers of earthquakes are summed over one-day intervals. Figure 5 shows that far more earthquakes occur within one day of the arrival of typhoons than on any other day in the 20-day interval shown (10 days before and 10 days after the closest approach of the typhoon). Data are from the annual "Typhoons of the Western Pacific Ocean" tabulations and typhoon paths (Joint Typhoon Warning Center, 1959-1994) for the time period 1959-1993 (data from 1960-1962 are missing). Earthquake data is from the Seismicity Catalog CD-ROM (Whiteside et al. 1996).

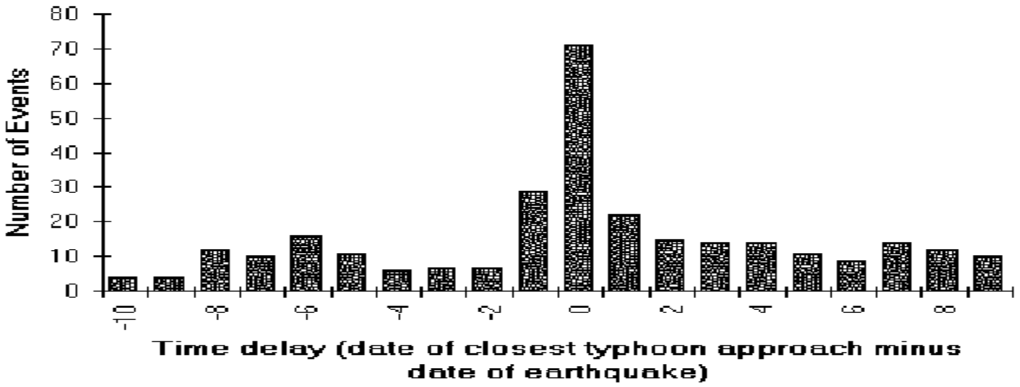

Figure 5. Comparison of number of earthquakes (M>=5) occurring at delay times of closest approach of typhoons to Guam.

The strong peak at zero time difference corresponding to coincidence between magnitude 5+ earthquakes and closest approach of typhoons to Guam is somewhat overstated on Figure 5 because when aftershocks of M 5+ occur they are included in the count. Therefore, when there are a number of aftershocks on a particular day, the count for that day may be more than one. This can be corrected by counting the total number of typhoons that are associated with an earthquake within a day of their closest passage to Guam. There were 107 coincidences between typhoons and earthquakes during the period 1959 to 1993. During this same time interval there were 582 earthquakes of M>=5.0 recorded in the area and a total of 185 +/- 10 typhoons passed within 500 km of Guam of which 109 were associated with an earthquake near Guam which occurred within 1 day of the closest passage of the typhoon.

The statistical analysis of the coincidence between earthquakes and typhoons in Guam is summarized in Table 1. Statistics are based on 34 years of earthquake and typhoon data (1959-1993) (12418 days), M>=5 in the area defined by Figure 1. Due to missing data and errors in both the earthquake and the typhoon catalog statistics are approximate only.

Table 1. Coincidental statistics for typhoons triggering earthquakes in the Guam region.

Total number of earthquakes vs. total number of typhoons:

	# Observed	Interevent Time	Daily Probabilities	Coincidences/Tsunami/Earthquake	
Q	582	21.3	0.015/0 .045	Expected # /34 years	Observed #
T	185	67.1	0.047/0.140		
				81.8	123

Total number of Earthquake Days vs. total number of typhoon days:

	# Observed	Interevent Time	Daily Probabilities	Coincidences/Tsunami/Earthquake	
Q	477	26.0	0.038/.115	Expected #/34 years	Observed #
T	185	67.1	0.015/.045		
				54.9	109

Q: Number of quakes or in the second instance the number of days on which quakes were observed in the time period
T: Number of typhoons observed to come within 500 km of Guam during the time period.
Interevent time: Average number of days between quakes or quake days or typhoons.
Daily probabilities: Probability that a quake or quake day or typhoon will occur on a given day or after the slash during a given 3-day interval (+/- 1 day)
Expected #: Number of coincidences between typhoons and earthquakes expected during the 34 year period.
Observed #: Number of observed coincidences between typhoons and earthquakes expected during the 34 year period.

From Table 1 we see that 1.5 times as many quakes are coincident with typhoons as are expected and that 2.0 times as many days on which quakes occur are coincident with typhoons as expected. This means that of the 123 observed coincidences about 41 are probably triggered by stresses induced by the typhoon, and that of the 109 days on which both typhoons and earthquake occur, in about 54 there is probably a causative relationship between the typhoon and the earthquake. It should be noted that since 1985, some of the best coincidences are the result of earthquakes reported by NAO (the NORSAR array) but by no other teleseismic network. It is possible that NAO is misidentifying arrivals from the microseismic activity due to the typhoon as earthquakes. This would reduce the significance of the above results, but there are too few of these events (10) to reduce results to insignificance. The results would still require 31 triggered earthquakes and 44 excess earthquake days.

CONCLUSION:

Guam is located near the Marianas Trench, a subduction zone of high seismic activity. While several M>=8.0 earthquakes have occurred near Guam in recorded history, none have produced the devastating tsunamis often associated with great earthquakes in other subduction zones, such as Chile or the Kuril Islands. We have shown that this is probably due to the age of the subducting Pacific plate and slowness of the subduction. This decouples the plates to the extent that large earthquakes in the deeply dipping subduction zone are unlikely. The large tsunamigenic earthquakes of 1849 and 1993 occurred to the east of Guam in the shallow dipping region of the subduction. Because the extreme depth of the trench, large tsunamis do not occur between the epicenters of these quakes and the island itself, even when they occur.

In addition to the protection offered by the location of Guam the harbor at Apra is a natural barrier to large tsunamis. The tsunami of 1993 was probably caused by a triggered earthquake on a secondary fault at a steep angle to the horizontal which ruptured towards the surface during the mainshock as proposed by Tanioka et al. (1996) and may have been related to the close passing of Typhoon Steve on the same day. The mainshock occurred at the upper

Pacific/Philippine plate interface in the shallow portion of the Pacific plate subducting at about 13 degrees dip under the Philippine plate (Beaven et al. 1994).

Nevertheless, Guam needs protection from the sea, as storm surges from typhoons and other tropical storms can cause major damage. In the past 35 years nearly 200 typhoons have brushed Guam. For example in 1990, Typhoon Hattie caused $1.7 million in damage to Guam. In 1991, Typhoon Yuri, the largest in 33 years, inflicted losses of $33 million to Guam. In 1992, Typhoon Omar devastated Guam with losses estimated at $457 million. We have found that not only do typhoons directly damage the island, but probably also trigger earthquakes which cause indirect damage, as was apparently the case in the earthquake of August 8, 1993, with total losses to Guam of $267 million.

APPENDIX: TSUNAMIS REPORTED AT GUAM

Reported Observed and Recorded Local Tsunamis

Date	Description
late 1700's	Unconfirmed report 1767, 1769, 1779 or 1799. A tsunami probably occurred.
1809	A violent earthquake occurred. Ships at sea experienced shocks near Guam. **Validity 1.**
1825, April	Terrible earthquakes caused great damage. (Repetti, 1939) **Validity 2**.
1837, Oct.	Extraordinary movement was experienced at sea. A type of tempest disturbed it and caused flooding, landslides and damage. Four islands in the Caroline Islands were over-washed and only parts of two remained above the water level. Survivors migrated to Guam and settled on Saipan. Degraz (1838). Terrible earthquakes caused great damage. (Repetti, 1939) **Validity 2**
1849, Jan 25 5:10 UT	Major earthquake damage and tsunami effects reported by the governor including the only fatality due to tsunamis in Guam's history. Villages flooded, homes destroyed, bridges washed away. Runup of at least 6.1 m at Agat and inundation of at least 402 m at Umatac Bay. Evidence of submarine landslide in Apra Harbor. **Validity 4**
1892, May 16 11:31 UT	A strong earthquake caused the sea to recede in Agana Harbor. Only in San Antonio did the sea return and cause flooding. (Maso, 1910) **Validity 4.**
1903 Feb.	Earthquakes in Guam and a 15 cm rise of the sea. Location not given nor was the rise identified as water or land level. **Validity 2.**
1909 Dec. 10	Destructive earthquake. Several fissures opened in the ground. A large flow of water came from one of the fissures. A passing wave could be seen as it crossed the plaza, and the station ship in the harbor felt the shock. (Maso, 1910) **Validity 1.**
1990 Apr. 5	A magnitude 7.5 earthquake near Saipan caused 3 to 4 m waves at Saipan and Tinian and a 1.5 to 1.8 m wave at the Talofofo River going up the river to a settlement. This was just recently reported because eyewitnesses were found. Since there were no initially reported runup data, no survey of effects was conducted for this tsunami that probably affected Guam's northern and eastern coasts. **Validity 4.**
1993 Aug. 8	A magnitude 8.1 earthquake caused $200 million in damage. The tsunami was recorded at 15 cm at Apra, and 10 cm at Agana Harbors. Waves about 1.8 m high washed cars into the ocean on the east coast where an initial withdrawal was reported. A wave 2.4 m high went up the Talofofo River carrying debris 400 m upstream. A wave reported in Tumon Bay would have been due to a local slump**. Validity 4.**

DESCRIPTION OF LOCAL EVENTS

1810. Events similar to the 1837 event were reported by Degraz (1838). A violent earthquake occurred. Ships at sea experienced violent shocks near Guam. These were probably were sea quakes. **Validity 1.**

1825, April. An event similar to the 1837 event occurred (Degraz, 1838). Terrible earthquakes were experienced causing great damage. (Repetti, 1939) **Validity 2.**

1837, October. Extraordinary movement was experienced at sea. A type of tempest disturbed it and caused flooding, landslides and damage. Four islands in the Caroline Islands were over-washed and only parts of two remained above the water level. Survivors migrated to Guam and settled on Saipan. Degraz (1838). Terrible earthquakes were experienced causing great damage. (Repetti, 1939) **Validity 2.**

1849, January 25, 5:10, UT. At 2:49 P.M. local time as reported by the Governor to his superiors (Driver, 1993), a great earthquake occurred which lasted one and a half minutes and caused great damage. Aftershocks continued every four to eight minutes until 11 o'clock that night. They began again at 2:30 A.M. local time and continued for weeks. About 150 felt earthquakes were noted by March 11. The population was fearful that they were on a volcano and the island might explode or sink. Sand boils discharging sea water opened up cavities which had measured depths of one to six yards. Twelve to seventeen of the cavities were in a line parallel to the river by Santa Cruz just south of Agana. The only reported loss of life was to Josefa Lujan, a woman caught by one of the three reported tsunami waves, near the Talofofo River. She was from Agana and going to Inarajan. She is the only reported fatality due to a tsunami in Guam's history. Her two year old niece received bruises on her face and was carried 40 yards and deposited among some rocks (Driver, 1993). The Governor's report placed the woman at her ranch near the beach.

Tsunami observations for the 1849 event:

At Agana and the north coast the sea was seen to recede but did not rise or return quickly. This may suggest uplift of the island. At old Agat which was situated about 1 1/4 miles north of the present Agat centered north and south of the Pelagi Islets along the Ayuga River. The sea swept through the streets which were 1,000 varas (917 yards as a vara is about 33 inches) (839 meters) inland from the high tide mark at an elevation of about 20 feet.

At Umatac three waves came into the bay. The Captains of two whaling frigates reported that they were anchored in 96 feet of water that receded and left them high and dry for 5 minutes. They lost their anchor chain on the third wave. The ships probably had a draft of 15 feet. The water came up the Laelae River for about a league (3 miles, or colloquially, just a long way) nearly to the location of the settlement with buildings at a minimum of 12 feet above sea level and destroyed many plantings. The 1819 chart shows the La Paz anchorage point in 42 feet of water. The rivers did not empty into the bay but into coastal ponds. The chart shows them to be only 2.08 miles long and with a slope of 10%. The 20-foot contour is about 2,500 feet upstream. These numbers for the reported depths, and inundation are probably exaggerated.

On the following day casks and barrels that the frigates were using to collect water were found at a great distance in the jungle. Two bridges were destroyed. Pendleton (1865) reported "I had a boat on shore at the time, and the inflood of the water was so great that it took her into the tops of the trees near the ocean, and swept water casts and such things a fourth of a mile or more into the country. When the water receded, it left them with hundreds of fishes high and dry and the land at the watering place sank about 12 feet. When the water receded it took my ship back with such force that it parted my chain, and I lost an anchor. Several ships in Apra Harbor lost anchors by being covered up on the bottom of the harbor, and they had to cut their chains. I think six were lost. The motion of the water was east to west." Submarine landslides in the harbor may have caused this.

At Inarajan the ocean entered along the Laolao River and swept three homes away depositing them 400 varas (366 yards) distant. It flooded the town (elevation of only five feet). About 15 plots of rice and seven of sweet potatoes were lost and the soil washed away. It washed away three bridges, two adjacent to the town and one over the Acfallan River. It also washed away the raft used to cross the Talofofo River. (Driver, 1993)

At Pago the sea rose as far as the church patio and flooded the entire village (located about 2,000 varas (1833 yards) from the beach on a sloping rise). The water receded leaving the streets covered with fish (Driver, 1993). The river level is only 10 feet at a distance of 3,000 feet upstream.

On April 14, a sea-going canoe with eight Carolinians from the Island of Satawal arrived at Agana. They claimed to have survived great earthquake and the ensuing flood by climbing trees. They had remained on the island as they lacked boats to leave. Many perished on the Island of Satawal and some were left behind. The survivors reported that the earthquake had occurred two and one-half moons ago and at about 3 P.M., about the same time as the Guam earthquake. Satawal is 450 nautical miles S.S.E. of Guam. The next day two more canoes arrived from a neighboring Caroline Island, Lamotrek Island, with 41 men and women survivors. They were also granted asylum (Stafford, 1933, p. 115). Both Satawal and Lamotrek Islands are very low with heights of about 8 feet. **Validity 4.**

1892, May 16, 11:31 UT. At 9:10 P.M. local time when clocks stopped, a strong earthquake that lasted a minute caused tiles to fall from roofs. The sea receded to the reefs in Agana Harbor but due to its slow return it did not pass its ordinary line except in the San Antonio quarter where it invaded the area. A larger wave would have destroyed the village of San Antonio. This wave was probably due to a submarine landslide in the bay given the local effect at San Antonio. (Repetti, 1939) **Validity 4**.

1903, February 10, 2:28 UT. There was a series of earthquakes and the (level of the sea?) rose 0.15 meters. Montessus de ballore, 1903 cited by Soloviev et al. 1984. Probably a 15 cm tsunami would not have been observed or reported so the change would have been due to a rise or drop of the land. **Validity 1.**

1990, April 5, 21:12 UT. A MW 7.5 earthquake in the Marianas Trench near Saipan produced an observable tsunami at the Tinian dock but no damage. The Civil Defense survey did not find evidence of a tsunami at Saipan, and considered news reports of three to four meter waves at Saipan and Tinian to be greatly exaggerated (*ITIC Tsunami Newsletter*, Vol. 23, No. 1, p. 35-37). However, crewmen of the *Jungle Boat* on the Talofofo River, Ted, Andy and Lauren Fairfield told Paul Hattori that they were at the loading area at about 8:00 A.M. when they saw a rush of foamy sea water coming under the bridge to the loading raft going up the river. The raft rose 5 to 6 feet. The water receded to the bay after 15 minutes or longer and took the form of a strong rip current. As in 1993, debris was carried up the river for a distance of two miles. Talofofo bay is shaped to focus the water to the river mouth at the head of the bay giving a higher water level there. However, there must have been observable waves elsewhere on the northern and western coasts but this area is lightly developed and no known surveys were taken. The tsunami was not reported as having been recorded in Guam and the marigrams have not yet been located. It was recorded in Japan with heights of 26 cm at Hachi, 24 cm at Murotomisaki, 23 cm at Chichijima, 22 cm at Tosashimizu, 19 cm at Yaene, 16 cm at Mera, 15 cm at Kushimoto, 10 cm at Aburatsu, 7 cm at Owase, 6 cm at Choshi, and 4 cm at Uchiura and Naha, in Hawaii with a height of 24 cm at Kailua-Kona, at Midway Island with a height of 6 cm, at Wake Island with a height of 4cm, and at Truk Island with a height of 3 cm. (*ITIC Tsunami Newsletter*). **Validity 4.**

1993, August 8, 08:34 UT. A magnitude 8.1 (Mw) earthquake in the Marianas Trench caused over $200 million dollars in damage and generated a minor tsunami. Low tide was recorded at 1 foot at 06:10 UT. The tsunami was recorded with amplitudes of 15cm at Apra Harbor, and 10 cm at Agana Harbor. 15 cm was reported at Kwajalein Atoll. At Hawaii: Honokohau, 5 cm, Nawilili, 6 cm; Haleiwa, 10-14 cm; Kahului, 12 cm; Lanai, 15 cm; Port Allen, 15-19 cm. (*ITIC Tsunami Newsletter,* December 1993, and other sources). At Japan: Muroto-misaki. Shikoku, 98 cm; Chichi-shima, Bonin Islands, 68 cm; Tosashimazu, Shikoku, 58 cm; Abratsu, Kyushu, 56 cm; Mera and Owase, Honsu, 34 cm; Ayukawahama, Honshu, 44 cm; Omae-zaki, Honshu, 42 cm; Hanasaki and Kushimoto, Honshu, 34 cm; Hirara, Ryukyu Islands, 34 cm; Ofunato, Honshu, 28 cm; Hachinoe, Honshu, 12 cm.

A personal account in the *Pacific Sunday News* by a fisherman, Tony Guerrero, fishing in Pago Bay reported that after the earthquake he started walking toward his truck parked 125 yards away and 15 yards beyond the water line. It took him about 10 minutes to reach his truck and the water was calm. As he reached the truck a wave came up to his legs. As he drove along the shore, a second wave swept him and his truck, which was parked on the beach, into the bay about 30 feet from shore. Water rose over the windshield. He could not open the door due to the water pressure but, as the waters receded, he escaped by rolling down a window and climbing into the truck bed. He waded ashore in chest deep water (*Pacific Sunday News*, Sept 5, 1993). The truck was destroyed. He was lucky to survive since he would have been in grave danger if the bay had been deeper, or if a third wave had come in while he was wading ashore.

Several graduate students told their instructor that they were snorkeling or boogie boarding behind the University of Guam Marine Laboratory on Pago Bay. They reported that the sea receded, and they left the water. The water withdrew and left the reef dry. The sea returned but the students didn't give an estimate of the run-up height. A family was at a week-end picnic at Tarague Beach on the north shore when the water was seen bubbling and the sand swirling. As the family began to drive away after the earthquake, they saw water come over the reef. It was three feet high as it passed their truck. The tide was at low stage.

Although the mayor of Inarajan did not see any unusual activity of the sea, afterwards he had to clear debris from the roads which was brought in by the sea waves about two feet above the high water level. At the Jungle River Tour Boat dock on the Talofofo River about half a mile above the bridge the river was estimated to have risen about 7 feet nearly topping the bridge at 8 feet above the river. Tree debris was evident 1/4 mile further up the river from a river bore.

Mr. Joaquin Anderson was in his yard overlooking the Pago river just above the bridge and reported seeing the river first recede and then rise flooding family land and carrying off chunks of soil. Later he saw many fish lying on the ground well beyond the river. About 150 fresh water fish were found floating dead in the Pago River, possibly the result of a surge of salt water into the river (Petrovsky, 1993). The fish may have been killed by the earthquake by the shock waves or from silting. This has also been observed in Alaska many times.

Another man reported having his truck inundated in the parking lot below the bridge at Ylig Bay. The water overflowed the bridge that was about six feet above the river level (Hattori, report of August 22, 1993 citing information from Prof. B. Lorenz.)

Maria Rosario and Fabiana San Nicholas were stopped at the Talofofo bridge which had a gap between it and the road due to the earthquake As they were turning around at the lowest point the area was suddenly flooded.. There was little current but the water rose to the windows of the car, a level of over three feet and was chest deep. the water returned to normal level shortly. The water level at Inarajan bay subsided immediately after the earthquake and the bottom of the bay was visible for some distance. (*Man, Land and Sea, News of Guam and Her Ocean Environment*, Vol. VII, Bureau of Planning/Guam Coastal Management Program, No. 3, p. 2).

The International Coordinating Group for the Tsunami Warning System in the Pacific was completing its meeting when the earthquake struck. The great damage by the earthquake and the smaller tsunami effects on the less populated eastern coast caused the tsunami effects to not be widely published. The EERI Special Earthquake Report, October 1993, mentions only that "The Guam quake caused no significant tsunami although wave heights of 98 cm at Japan and 19 cm at Hawaii were recorded" and that was almost the only mention of the tsunami internationally even though the earthquake was examined by teams of seismologists (*ITIC Tsunami Newsletter*, vol. 25, No. 1, p. 1-2).

Teletsunamis Observed at Guam

Date	Source Area	Height (m)	Period (min)	Validity
1952, Mar. 4 01:23 UT	Hokkaido, Japan	0.1	21	4
1952, Mar 19 10:57 UT	Mindanao, Philippine Islands	<0.1		
	Recorded at Apra Harbor and Tarague (Murphy and Cloud, 1954, p 50)			
1952, Nov. 5 16:58 UT	Kamchatka	<0.1		
	An 8.25 (Mw) magnitude quake in east Kamchatka caused considerable damage and some loss of life locally. At Ylig Bay, it was observed to have an amplitude (height?) of 5 feet (1.5 m) and a period of 8 minutes, the natural period of the bay and hence may have been a seiche (Tracey et al.1960) *The Guam Daily* News (Nov. 6, 1952, p. 1) reported three waves were recorded at Ylig with the first arriving at 9:45 A.M. as two or three foot swells and the second arriving a little later and about the same height. The third wave was five and a half feet and arrived at 10:45 a.m.			
1957, Mar. 09 14:22 UT	Andreanoff Islands	3.5	54	
	Caused some damage and local waves of 15 meters at Scotch Cap, Unimak, Islands, Alaska. Travel time 6.7 hours.			
1960, May 22 19:11 UT	Chile	0.2		
	The great Chilean earthquake and tsunami caused more than 2,000 fatalities and $550 million in damage in Chile, 61 fatalities and $75 million in damage in Hawaii, 138 deaths and $50 million in damage in Japan, 32 fatalities and missing people in the Philippines and two fatalities and $500 thousand in damage to the U.S. West Coast. Travel time: 21. 5 hours.			
1963, Oct. 13 05:17 UT	Kuril Islands, Russia	<0.1		
	Travel time about 5.8 hours			
1964, Mar. 28 03:36 UT	Alaska	<0.1		
	Caused 106 fatalities and $84 million damage in Alaska, 16 fatalities and $20 million in damage on the U.S. West Coast. Travel time 8.2 hours.			
1966, Oct. 17 21:42 UT	Peru	<0.1		
1968, May 16 00:49 UT	Honshu, Japan	<0.1		
1968, Aug. 1 21:19 UT	Luzon, Philippines	<0.1		
1971, Dec. 15 08:30 UT	Kamchatka	<0.1		
1971, Dec. 2 00:20 UT	Mindanao, Philippines	<0.1		

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