159.

7

Tsunami

The 23 June 2001 earthquake generated a destructive tsunami that struck the coast of southern Peru within 30 minutes of the earthquake and was observed at tide gauges throughout the Pacific. International media reported significant tsunami impact soon after the earthquake, with waves extending as much as 1 km inland. Both Peruvian and international tsunami field investigation teams were organized to study the nature and extent of the tsunami in the impacted area.

ITST FIELD SURVEYS

In the past decade, the international scientific community has responded to all major tsunami disasters[1] by dispatching groups of scientists that have come to be known as the International Tsunami Survey Team (ITST). The team, invited by organizations within the affected country, follows guidelines established in 1993 during the 14th Session of the Intergovernmental Oceanographic Commission (IOC), which operates within UNESCO. The purpose of ITST is to observe and document the effects of tsunamis, collect perishable data as soon as possible after an event, increase understanding of the nature and impact of tsunamis, and make recommendations to both the affected country and the international community on future research, planning, and preparedness (Tsuji et al. 1995).

A number of national and international field survey teams visited the southern Peruvian coast in the months following the earthquake. A team from the Peruvian Navy's Dirección de Hidrografía y Navegación conducted a reconnaissance survey of tsunami impacts in the first week after the earthquake, and noted evidence of inundation from Atico to Ilo, and major damage in the vicinity of Camaná.

When significant tsunami impact was confirmed, a team was organized to document the extent and impact of the tsunami. The first ITST team visited Peru from 06-15 July 2001, measuring tsunami inundation and collecting eyewitness accounts along a 400 km stretch of coastline from Yauca to Ilo. Photographs from this field survey are posted at http://www.usc.edu/dept/tsunamis/peru01/ and descriptions of the field stops are reported by Borrero (2002). A second International Tsunami Survey Team visited Peru in September and focused on tsunami deposits. A preliminary report on the sediment characteristics is posted at: http://walrus.wr.usgs.gov/peru2/. An earthquake reconnaissance team from New Zealand spent time in the Camaná area in late July. Ongoing fieldwork in the tsunami-affected area is being conducted by researchers from the Instituto Geofísico del Perú.

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[1] Nicaragua 1992; Flores, Indonesia 1992; Okushiri, Japan 1993; East Java, Indonesia 1994; Mindoro, Philippines 1994; Kuril/Shikotan Islands, Russia 1994, Manzanillo, Mexico 1995, Irian Jaya, Indonesia 1996; Chimbote, Peru 1996; Papua New Guinea 1998; Izmit Bay, Turkey 1999; Vanuatu 1999; Papua New Guinea 2002.

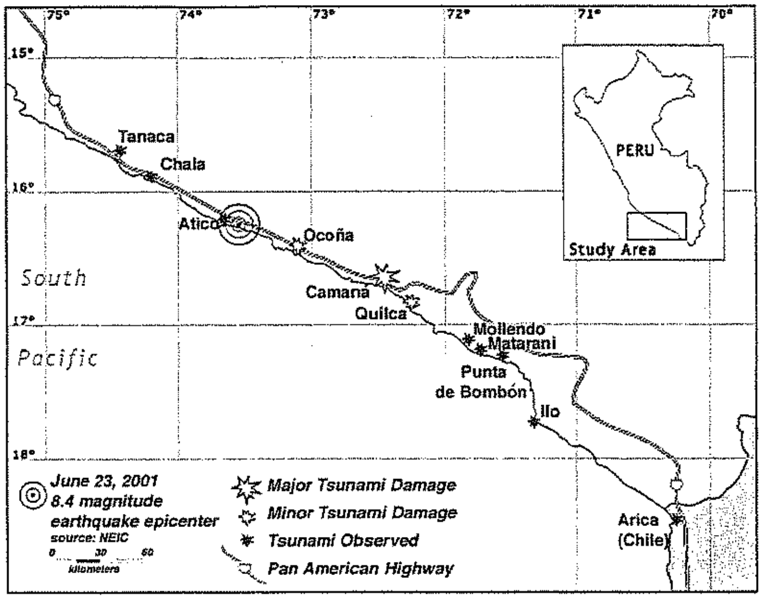

Figure 7-1. Coastal areas affected by the 23 June 2001 Southern Peru tsunami.

HISTORICAL BACKGROUND

Since the Spanish conquest, 42 credible tsunamis originating from earthquakes along the Peruvian and northernmost Chilean coast had been documented prior to the 23 June 2001 event (Table 7-1). Of these, 14 caused damage and 10 caused loss of life.

The 23 June 2001 Southern Peru earthquake and tsunami affected a 700 km stretch of the Peruvian coastline, extending from the Nazca Ridge to the Arica Bight (Figure 7-1). The region was the site of mega-thrust events in 1604 and 1868 that destroyed almost all structures over a 650 km long area, with local tsunami runup reaching at least 15 m, and significant far-field tsunami damage in Japan, Hawaii, New Zealand, and other locations in the Pacific Basin. The 1604 and 1868 events are usually considered as repeat earthquakes (Dorbath et al. 1990; Swenson and Beck 1996). These two mega-thrust events define an interseismic window during which significant (but not gigantic) earthquakes took place in 1687 and 1784 along the same part of the subduction zone. According to the reports compiled by Dorbath et al., both of these shocks featured higher accelerations along the coast than were documented in 2001. There was a tsunami associated with the 1784 earthquake, but the 1784 tsunami was apparently smaller than the 2001 event. There is no report of a tsunami for the earthquake of 21 October 1687. The 23 June 2001 earthquake appears to have no directly comparable predecessor in terms of both shaking and tsunami effects in the documented historical database. This illustrates the high variability in the patterns of segmentation along this portion of the plate boundary.

Prior to the 23 June 2001 event, there had been only two tsunamis documented in the past 25 years, both in 1996. The February 1996 tsunami had significant impact in northern Peru, where it killed 12 and injured 57 in the Chimbote area (Bourgeois et al. 1999). It is considered a tsunami earthquake where the amplitude of the tsunami waves was larger than expected for the earthquake magnitude (Tanioka et al. 1996). The Chimbote tsunami accelerated the tsunami hazards mapping efforts of the Dirección de Hidrografía y Navegación of the Peruvian Navy, and evacuation maps are now complete for 20 coastal areas (http://www.dhn.mil.pe/english/tsunami.html).

The mapping effort prior to the 23 June 2001 earthquake had focused on northern and central Peru. None of the areas impacted by the 2001 tsunami had been mapped prior to the event. The November 1996 Nazca earthquake (M = 7.7) generated a small tsunami that was only detected on tide gauges and caused no damage.

Table 7-1. Historic tsunamis in the Peru region, 3.5°-18.6°S.

Date	Epicenter Lat°S	Epicenter Lon°W	Magnitude M_w	Magnitude M_s	Magnitude M_t	Peak Runup (meters)	Comments	Source
22 Jan 1582	17.0	72.0	7.5		7.7-8.0	1-2 (?) at Islay	No damage reported	1
09 July 1586	12.2	77.7	8.1	8.5	8.5	up to 24 at Callao	Damage to Callao, 20 deaths	1,2,3
24 Nov 1604	17.0	72.0	8.7	8.4	8.8-9.0	up to 16 at Arica	Damage to Arica, Camaná, Pisco, 74 deaths	1,2,3
16 Sep 1615	18.2	71.0		7.9		4 at Arica	No damage reported	2,3
07 May 1647	14.2	75.7		8.5		2.8 at Callao	Damage at Arica, at least 14 deaths	2,3
16 Jun 1678	10.5	78.0	7.7-8.0	8.2	8.5	5 (?) at Pisco	No damage reported	1,3
10 Mar 1681	18.5	70.3		7.5		observed at Arica	No damage reported	3
20 Oct 1687	13.5	76.5	8.4	8.5	8.5-8.8	5 – 10 m at Callao	Damage Puerto Caballas to Callao; 500 deaths	1,2,3
22 Aug 1715	18.5	70.3		7.5		observed at Arica	No damage reported	2,3
27 Mar 1725	16.6	72.7				2.0 at Camaná	No damage reported	2,3
28 Oct 1746	12.0	77.0	8.6	8.0	9.0-9.2	24 at Callao	Major damage at Callao, ~3800 deaths	1,2
13 May 1784	16.8	72.0	8.4		8.0 - 8.4	2 - 4 Camaná to Ilo	No damage reported	1
01 Dec 1806	12.1	77.1		7.5		1	No damage reported	2,3
23 May 1847	12.1	77.1				2	No damage reported	2,3
23 Apr 1860	12.0	77.1				0.7 at Callao	No damage reported	2,3
08 Jan 1865	12.0	77.1				2.0 at Callao	5 deaths and damage at Callao	2,3
13 Aug 1868	18.6	71.0	8.8	8.8	8.9	15 - 18 Arica to Chala	Great Pacific-wide tsunami, 1,000s of deaths	1,2,3
02 Oct 1868	17.0	72.5				1.0 at Talcahuano	No damage reported	2,3
19 Aug 1869	16.0	73.5		6.5		observed	No damage reported	2
24 Aug 1869	18.6	70.0		7.4		2 at Arica	Damage in Arica, Iquique	2,3

Table 7-1. *Continued.* Historic tsunamis in the Peru region, 3.5°- 8.6°S.

Date	Epicenter		Magnitude			Peak Runup (meters)	Comments	Source
	Lat°S	Lon°W	M_w	M_s	M_t			
21 Aug 1871	13.0	77.0		7.0		2	No damage reported	2,3
12 Dec 1908	14.0	78.0		8.2		2	No damage reported	2,3
28 Jul 1913	17.0	74.0		7.0		0.7 at Mollendo	No damage reported	2,3
06 Aug 1913	17.0	74.0	7.7	7.9		observed	No damage reported	2,3
12 Jan 1914	12.0	76.6				1.0 at Callao	Damage at Callao	2,3
26 Feb 1914	17.9	67.0		7.2		observed	No damage reported	2,3
06 Jan 1922	16.5	73.0	7.0	7.2		observed	No damage reported	2,3
27 Apr 1928	13.0	69.5		6.7		observed	No damage reported	2,3
18 Jul 1928	5.5	79.0		7.0		observed	No damage reported	2,3
24 May 1940	10.5	77.0	8.1	8.4	8.2	3 at Callao	No damage reported	1,2,3
24 Aug 1942	15.0	76.0	8.2	8.6	8.2	2 at Lomas	Settlement flooded in Lomas	1,2,3
10 Dec 1950	14.6	76.3		7.0		0.7 at Pisco	No damage reported	2,3
15 Feb 1953	12.0	77.5		5.5		0.7 at Chancay	No damage reported	2,3
12 Dec 1953	3.5	81.0	7.4	7.8		0.5 at Talara	No damage reported	2,3
13 Jan 1960	15.8	72.8		7.8		0.25	Damage at Ancon	2,3
20 Nov 1960	6.8	80.7	7.7	6.9	7.7	9 at Pimental	Lobos de Afuera Islands devastated, 3 deaths	2,3
17 Oct 1966	10.7	78.8	7.7		8.2	3 at Casma	$2 million (U.S.) damage, 3 deaths	1,2,3,5
03 Sep 1967	10.6	79.8		7.0	-	2	No damage reported	2,3
31 May 1970	9.2	78.8	7.9	6.6	-	1.8	No damage reported	2,3
03 Oct 1974	12.3	77.8	7.9	8.1	8.1	1.8 at Callao	No damage reported	2,3
21 Feb 1996	9.6	79.6	7.5	6.6	7.8	5.1 at Chimbote	12 killed, 57 injured in Chimbote	3,4
12 Nov 1996	15.0	75.7	7.7	7.3	7.9	0.35 at Arica	No damage reported	3,6
23 Jun 2001	16.3	73.6	8.4	8.2	8.1-8.3	7.25 at Camaná	86 dead/missing in Camaná	this report

M_t after Abe (1979)

Sources:
1.) Dorbath et al. 1990
2.) Lockridge 1985
3.) HTDB/PAC 2001
4.) Bourgeois et al. 1999
5.) Lomnitz and Cabre 1968
6.) NEIC 1996

RECORDED TSUNAMI WAVE HEIGHTS

A network of real-time tide gauges covers the Pacific. The network recorded a maximum wave height (peak to trough) of 2.57 meters in Arica, Chile, and waves were detected throughout the Pacific (Table 7-2). The Arica tide gauge (Figure 7-2) is located about 400 km from the earthquake epicenter, but only about 100 kilometers from the southern edge of the rupture zone and shows a similar tidal range (1.3 meters) as the southern Peru coast. The first waves arrived about 35 minutes after the earthquake and coincided with low tide. For all of the records in the Pacific network where it was possible to discern the initial sense of motion, a rise was identified. (A complete tabulation of recorded tsunami wave heights and marigrams is posted at http://wcatwc.gov/06-23-01.htm.)

The closest tide gauges to the fault rupture zone were located at the Port of Matarani, 125 km away from the epicenter and directly above the rupture zone. The United States Coast and Geodetic Survey analog flotation-type paper recorder marks the first visible motion at 15:34 local time (20:34 UTC) (Figure 7-3). The motion was likely produced by oscillations of the counterweight of the gauge due to surface seismic waves. The onset of the first tsunami arrival is about 6 minutes after the origin time of the earthquake; the first peak (0.75 m) at 11 minutes. The second peak (1.86 m), at 38 minutes after the earthquake, is the largest amplitude at Matarani.

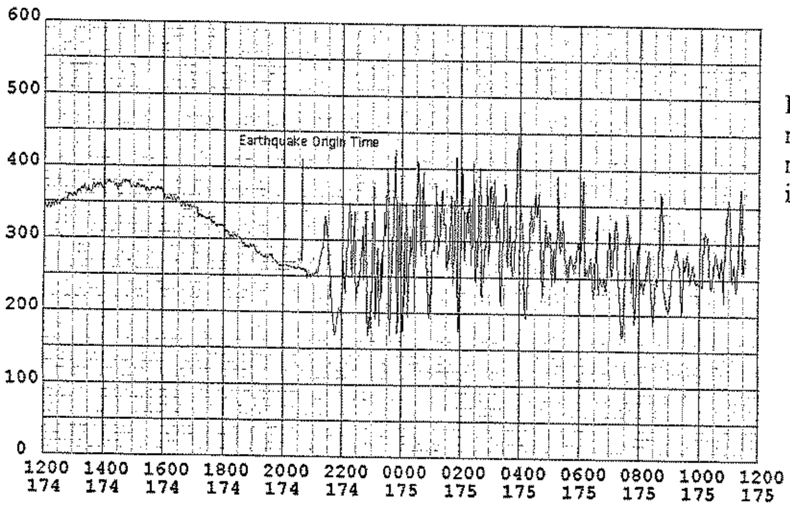

Figure 7-2. Arica, northern Chile, tide gauge recording; vertical scale is in centimeters.

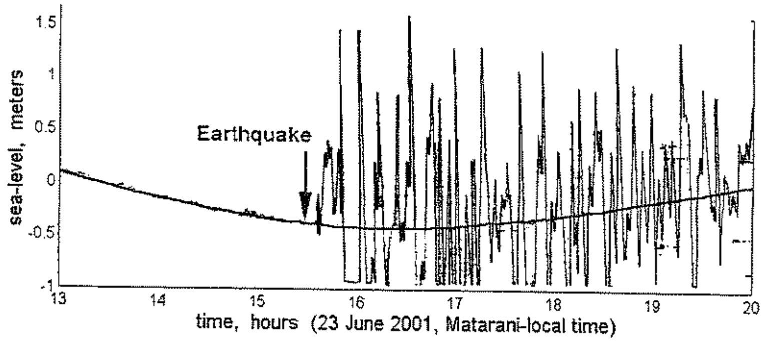

Figure 7-3. Analog recording from Matarani, Peru, 125 km from the epicenter and directly above the rupture zone. Solid line is the predicted tidal variation. The first peak (0.75 m) arrives about 11 minutes after the earthquake origin time; the second peak is the highest (1.86 m), arriving 38 minutes after the earthquake.

Table 7-2. Recorded tide gauge heights.

Gauge Location	Distance (km)	Wave Height cm (peak - trough)	Initial Motion	Travel Time hr:min	*
Arica, Chile	415	257	rise	0:35	1
Callao, Peru	609	80	rise	1:34	1
Antofagasta, Chile	856	90	rise	1:02	1
Valparaiso, Chile	1,886	60	rise	2:27	1
Talcahuano, Chile	2,283	250	rise	3:41	1
Santa Cruz, Galapagos Is.	2,523	90	rise	3:59	1
Easter Is., Chile	3,905	35	?	5:41	2
Cabo San Lucas, Mexico	5,960	25	?	8:56	2
La Jolla, CA	7,170	10	?	11:19	2
Los Angeles, CA	7,304	10	?	11:36	2
San Francisco, CA	7,887	7	?	12:51	2
Crescent City, CA	8,280	40	?	13:13	2
Hilo, HI	9,770	70	rise	13:27	1
Chatham Is., NZ	9,781	55	?	14:05	2
Sitka, AK	9,929	5	?	16:02	2
Apia, Western Samoa	10,450	25	?	14:49	1
Kodiak, AK	10,890	8	?	16:59	2
Sand Point, AK	11,298	24	?	17:08	2
Nukualofa, Tonga	11,489	20	?	15:07	1
Midway Is., USA	12,188	15	?	16:27	2
Adak, AK	12,317	20	?	17:27	2
Kwajalein, Marshall Is.	13,347	10	?	18:00	2
Wake Is.	13,679	10	?	18:11	2
Omaezaki, Honshu, Japan	16,259	25	?	21:39	2
Naha, Okinawa, Japan	17,565	10	?	23:05	2

* 1.) travel time measured from recorded arrivals
2.) travel time estimated from algorithm; source:http://wcatwc.gov/06-23-01.htm

The 23 June 2001 tsunami was not detected on any of the deep ocean pressure sensors deployed as part of the DART (Deep Ocean Assessment and Recording of Tsunamis) program. Five sensors were in operation at the time of the earthquake, three offshore of Alaska and the Aleutian Islands, and two offshore of the Pacific Northwest. A sixth sensor, located offshore of South America near the equator, was unfortunately not deployed until two months after the earthquake.

Abe (1979) developed an algorithm for estimating magnitude based on maximum wave heights and distance away from the epicentral area. Tsunami magnitudes for the 23 June 2001 Peru event based on the far-field amplitudes from tide gauge records in California, Alaska, Hawaii, and Japan ranged between 8.1 and 8.3 (Abe 2001). This suggests that the Peru tsunami was the size in the far field expected for an earthquake in the low magnitude 8 range, and was not a tsunami earthquake. Preliminary modeling using a dislocation source appears to adequately explain both far- and near-field tide gauge records of the tsunami (Koshimura and Titov 2001).

The largest aftershock (07 July 09:38:43.5 UTC, M = 7.6) also produced a tsunami that was recorded on the Matarani and Arica tide gauges. The earthquake was centered about 45 km offshore of Matarani and produced a series of waves that began arriving about 6 minutes after the earthquake. The first peak (0.82 m) arrived about 12 minutes after the earthquake and was quickly followed by a 0.99 m negative wave. A second peak of about the same amplitude as the first arrived about 15 minutes after the first peak. There were no reports of damage from the 07 July event and no eyewitness observations, not surprising as the event occurred at 4:38 am.

TSUNAMI WARNING SYSTEM AND THE PERU TSUNAMI

The Pacific Tsunami Warning Center (PTWC) in Ewa Beach, Hawaii is responsible for issuing tsunami bulletins to all areas of the Pacific, except the West Coast of the U.S. and Canada. PTWC issued the first bulletin for the Peru earthquake 41 minutes after the earthquake. The initial Warning area included Peru, Ecuador, northern Chile, and southern Colombia. Within Peru, tsunami bulletins are disseminated by the Dirección de Hidrografía y Navegación of the Peruvian Navy to local coastal naval facilities. PTWC bulletins are intended primarily to warn for distant tsunami events, and the initial bulletin was too late to be of use in evacuating the coastline in the epicentral region. Officials in Mollendo and Matarani, Peru organized evacuations of low-lying areas after the water drawdown was observed. The port authorities evacuated the Matarani Port area and local police directed the Mollendo evacuation of the beach and waterfront.

Tide gauge recordings from Arica, Chile confirmed the tsunami 35 minutes after the earthquake. Hourly bulletins expanded the Warning and Watch zones to include all of the west coast of South and Central America, Mexico, and French Polynesia. The Warning and Watch bulletins were cancelled eight and a half hours after the earthquake, when water level data made it clear that a damaging Pacific-wide tsunami had not been generated.

The West Coast Alaska Tsunami Warning Center (WCATWC) is responsible for issuing bulletins to the U.S. West Coast, Canada, and Alaska. The initial WCATWC bulletin was an Advisory message issued 42 minutes after the earthquake. However, WCATWC Bulletin 2, issued 1 hour 43 minutes after the earthquake, declared a Tsunami Watch for the California and Oregon coasts. The alert was the result of a calculation error in the estimated wave arrival time at a California location. The error was corrected and the Tsunami Watch changed back to a Tsunami Advisory 48 minutes later. When the estimated arrival times for the California coast were less than 6 hours, the Watch was reinstated for the California coasts as far north as Cape Mendocino, and was eventually extended as far north as Cascade Head, Oregon. It was cancelled at 10:03 PM PDT, 8 hours after the earthquake, when the tide gauge data made it clear that the wave amplitudes were not large enough to be damaging. The change in Watch/Advisory status, difficulties in dissemination of the tsunami bulletins to a number of California counties, and problems at the dispatcher level caused confusion in a number of coastal California areas.

SETTING

The coast of southern Peru is extremely arid and devoid of vegetation except in alluvial valleys fed by perennial streams, or in irrigated areas. Much of the coastline is steep and terminated by cliffs that drop abruptly to the water, and many of the hills are unconsolidated sand and loose rock and highly unstable. In the winter months (May-August), the coast is affected by storm swells. The largest swells may generate surges that reach a few meters above normal high tide several times a year. The storm berm, when identified by ITST transects, was about 2-3 meters above sea level. Ocean conditions at the time of the 23 June tsunami were relatively calm. However, a large swell was observed by the first ITST about two weeks after the earthquake. The normal tidal range is about 1.5 m. The 23 June 2001 earthquake coincided with one of the lowest tides of the year, -0.35 meters below mean sea level.

Most of the southern Peru coast is undeveloped. The most populated areas on the coast are in the port cities of Matarani, Mollendo, and Ilo and several summer resort towns near Camaná—collectively referred to as La Punta. During the winter months, La Punta is inhabited only by a few hundred housesitters employed by owners to watch their summer homes. La Punta hotels, restaurants, and other tourist concessions are closed in the winter. There is significant cultivation, primarily onions and maize, and a developed irrigation system of canals and pumping stations in the alluvial valleys and river deltas associated with the Rio Ocoña, Rio Camaná, and the Rio Tambo near Punta de Bombón. The smaller towns and villages of Tacna, Chala, Atico, and Quilca are located near natural coves and harbors and have economies strongly dependent on fishing.

FIELD METHODS

The purpose of post-tsunami field investigations is to document the extent of inundation, height and nature of the waves, thickness and character of sediment deposits, and to collect information on impacts. Teams use a combination of methods:

1. Observing and recording water height and inundation indicators such as debris and strand lines, watermarks on soil and buildings, elevation of damage such as broken windows and stripped roofs, debris and sands deposited on stairs, upper floors and roofs (Figure 7-4). Care must be used in interpreting watermarks as they relate to episodes when the water was still enough to leave a mark, and almost always are less than the peak water height.
2. Interviewing eyewitnesses. It is easy to misinterpret debris and strand lines, which may be caused by high tides and storm waves, unless corroborated as a tsunami deposit by eyewitnesses. Human perception during catastrophic events can be skewed, however. There were instances where an eyewitness reported wave heights that were incompatible with field evidence or other eyewitnesses. Several media and NGO (nongovernmental organization) reports claimed water heights of 30 meters; the ITST teams found no credible watermarks over 9 meters. Whenever possible, the ITST team spoke with several different groups of people to ensure a consistent story, and some interviews were recorded on videotape for a permanent archive.
3. Surveying profiles. Lines were surveyed with optical or laser survey equipment along the beach profile from the breaking waves to the maximum inland extent of inundation. Elevations were calibrated relative to the ambient tidal level at the time of the tsunami.

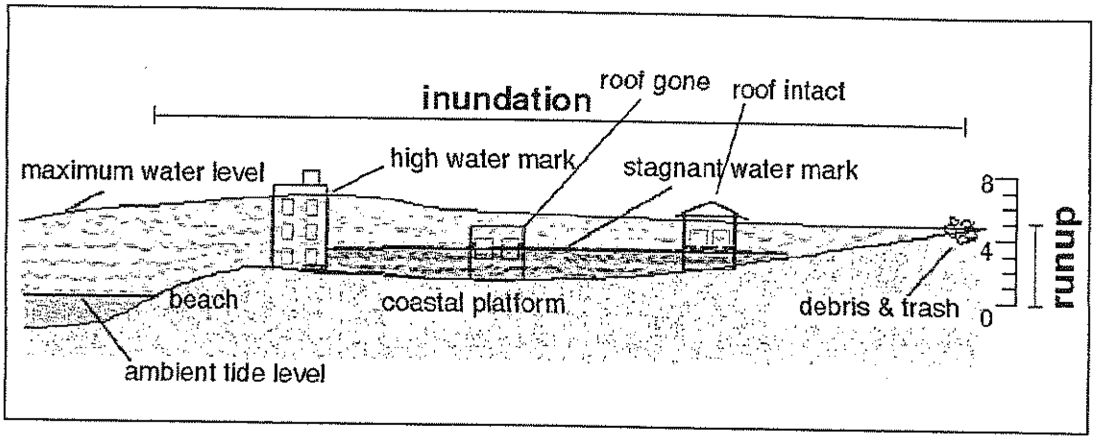

Figure 7-4. Typical tsunami field data observed by the ITST. Inundation is the horizontal extent of water penetration and runup is the vertical elevation of the highest point on land flooded. High watermarks can sometimes be measured when sand and debris are deposited on the upper floors of buildings or in trees or power lines. In some cases, water elevation can be estimated by height of damage, such as blown out windows or roofs. Buildings, walls, or trees may have one or more watermarks left by stagnant water.

4. Interviewing government officials and aid workers and collecting reports, maps, photographs, and other materials pertinent to the tsunami.
5. Sediment studies. Additional transects were selected by the second ITST to measure sediment thickness and topographic profiles along with runup and inundation information. More than 120 samples were collected for laboratory analyses for grain size distribution, microfossils, mineralogy, and chemistry. Sedimentary characteristics of the tsunami deposits and underlying material were logged and photo-documented. Box cores and sediment peels were taken at several sites to preserve the stratigraphy of the sediments. Erosion, flow direction indicators, watermarks on buildings, and damage to structures were also documented.

FIELD OBSERVATIONS

Tsunami survey data were restricted to the relatively few areas of coastal access, typically fishing villages near coves or natural harbors, developed alluvial valleys, and beaches.

Runup and inundation data was collected during both ITST visits (Table 7-3). Letters designate the local setting; most sites were fishing villages situated near coves and harbors, maize and onion fields with extensive irrigation systems built on flat, low elevation coastal platforms near rivers, or resort communities developed along flat, wide beaches. Table 7-3 also notes the nature of where the water stopped; whether the waves ran up against an abrupt change in elevation such as a cliff or roadbed, dissipated on the relatively flat coastal platform, or never made it over the high tide berm.

The tsunami was observed by eyewitnesses along 400 km of coastline from Tanaca to Arica but produced wave heights well above high tide only from Atico to Quilca, and damaging waves along the 50 kilometers of coast straddling the Rio Camaná. The highest runup measured (8.8 m) was on the narrow beach at Playa Chira, where the coastal platform narrows to less than 500 meters (Figure 7-5). Eyewitnesses described splashing of the waves against the cliffs in this area, and the measured watermark may overestimate the true peak wave height. At several locations, other

Table 7-3. Tsunami runup and inundation data.

Name	ITST	Site Location		Distance (km)	Setting	marks (m)	Water Runup (m)	Inundation (m)	Water stopped by
		Lat (°S)	Lon (°W)						
Tanaca	1	15.71	74.5	-215.5	undeveloped coastal platform		bb		wave slope
Chala	1	15.86	74.25	-183.5	cove or harbor		bb		wave slope
Punta Blanca	1	16.23	73.7	-112.6	cove or harbor		bb		wave slope
Atico 1	1	16.23	73.61	-104.7	rocky beach		2.38	51.2	wave slope
Atico 2	1	16.23	73.61	-104	undeveloped coastal platform		3.03	54	wave slope
Pescadores 1	2	16.44	73.24	-58.7	agricultural field		4.75	83.5	
Pescadores 2	2	16.44	73.24	-58.7	lagoon			679.6	
Ocoña	1	16.45	73.1	-44.8	undeveloped coastal platform		2.94	41.5	flat coastal platform
Playa Chira 1	2	16.52	72.92	-24.23	undeveloped coastal platform		8.22*	228.9	cliff or hill
Playa Chira 2	2	16.52	72.92	-23.76	undeveloped coastal platform		6.44*	321.2	cliff or hill
Playa Chira 3	1	16.53	72.9	-22.3	undeveloped coastal platform		7.71*	254	cliff or hill
Playa Chira 4	1	16.53	72.9	-21.7	undeveloped coastal platform		8.77*	390	cliff or hill
Hawai Bajo	1	16.53	72.88	-20.2	undeveloped coastal platform	3.59	3.59	504	flat coastal platform
Jahuay 1	2	16.55	72.87	-18.4	agricultural field		2.4	357.1	flat coastal platform
Jahuay 2	1	16.56	72.85	-15.8	agricultural field		4.46	725	flat coastal platform
Santa Monica	1	16.57	72.82	-12.4	agricultural field		5.14	1000	flat coastal platform
Pucchún	1	16.62	72.78	-6.1	agricultural field		5.2	1358.5	flat coastal platform
San José	1	16.64	72.74	-1.3	agricultural field	3.95	2.78	1042.7	flat coastal platform

Table 7-3. *Continued.* Tsunami runup and inundation data.

Name	ITST	Site Location Lat (°S)	Lon (°W)	Distance (km)	Setting	marks (m)	Water Runup (m)	Inundation (m)	Water stopped by
La Quinta 1	1	16.65	72.72	1.3	agricultural field	4.3-5.1	3.3	750	flat coastal platform
La Quinta 2	2	16.65	72.72	1.16	agricultural field		5.81	760	flat coastal platform
El Chorro 1	1	16.65	72.7	3.2	agricultural field	5.29	2.81	536.6	flat coastal platform
El Chorro 2	1	16.65	72.69	4.2	agricultural field		4.89	785	flat coastal platform
La Punta	1	16.65	72.69	5.1	developed coastal platform	7.25			
Cerrillos	1	16.65	72.67	6.3	developed coastal platform		3.79	483	elevated roadbed
Amecosupe	2	16.66	72.66	7.57	developed coastal platform		5.72	492.2	elevated roadbed
Las Brisas	1	16.66	72.65	8.8	developed coastal platform		5.43	345	elevated roadbed
Cerrillos II	1	16.66	72.65	9.2	developed coastal platform	4.67	4.67	282	cliff or hill
Blue Church	1	16.66	72.63	11	developed coastal platform		4.78	240	cliff or hill
Las Cuevas	1	16.66	72.61	13	developed coastal platform		4.39	130	cliff or hill
La Bajada 1	1	16.68	72.56	19	undeveloped coastal platform		4.67	160	flat coastal platform
La Bajada 2	2	16.68	72.56	19.02	undeveloped coastal platform		6.58	175.3	flat coastal platform
Pampa Grande 1	1	16.69	72.5	25.3	undeveloped coastal platform		3.56	202	flat coastal platform
Pampa Grande 2	2	16.69	72.50	25.52	undeveloped coastal platform		3.01	147.8	flat coastal platform
Quilca 1	1	16.7	72.47	28.2	undeveloped coastal platform		3.25	110	flat coastal platform
Quilca 2	1	16.7	72.46	30	undeveloped coastal platform		3.4	41.2	flat coastal platform
Quilca 3	1	16.71	72.44	32.6	cove or harbor		3.18		

Table 7-3. *Continued.* Tsunami runup and inundation data.

Name	ITST	Site Location Lat (°S)	Lon (°W)	Distance (km)	Setting	marks (m)	Water Runup (m)	Inundation (m)	Water stopped by
Quilca 4	1	16.71	72.43	32.7	cove or harbor	2.62			
Quilca 5	1	16.71	72.43	32.8	cove or harbor	3.88	3.72	30	
Quilca 6	1	16.72	72.42	33.9	cove or harbor		2.29	19.8	
Puerto Matarani	-	17	72.11	77.3	cove or harbor	1.8^t			
Matarani Beach	1	17.03	72.01	87.9	developed coastal platform	-	bb		wave slope
Mollendo North	1	17.05	71.99	91.2	developed coastal platform	-	bb		wave slope
Mollendo South	1	17.05	71.97	92.7	undeveloped coastal platform	2.45		72.5	wave slope
Mejía	1	17.09	71.91	100.9	lagoon		bb		wave slope
Ilo	1	17.63	71.34	183.6	developed coastal platform		2.68	40	wave slope
Playa Bolivia Mar	1	17.74	71.26	198.5	undeveloped coastal platform		2.33	72	wave slope
Arica, Chile	-	18.47	70.33	326.4	cove or harbor	1.3^t			

* watermark on cliff may represent splash

t = tide gauge reading

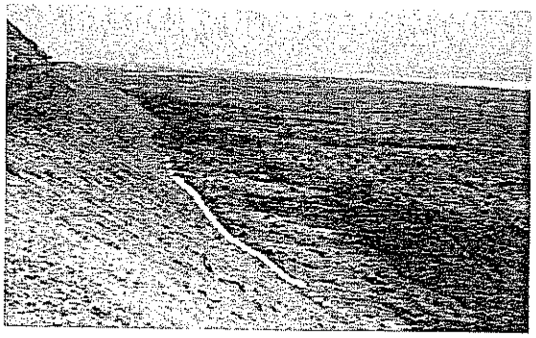

Figure 7-5. The highest measured runup was at Playa Chira. Tsunami inundation, marked by the difference in coloration (white demarcation line added), reaches to the cliffs at the back of the beach. The Pan-American Highway is on the left.

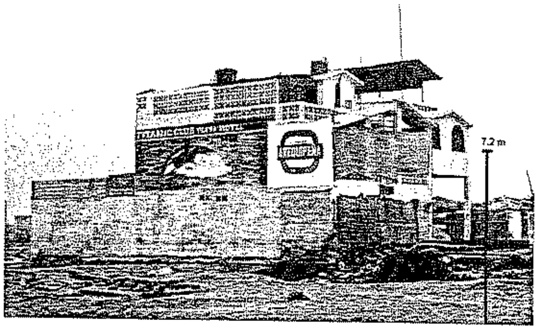

Figure 7-6. Titanic Club Playa Hotel, La Punta. Sands and a watermark were observed on the third floor stairs at an elevation of 7.2 m above the sea level at the time of the tsunami. The windows were broken and the foundation was partially undermined, but this reinforced concrete building only 20 meters from the beach sustained little other structural damage.

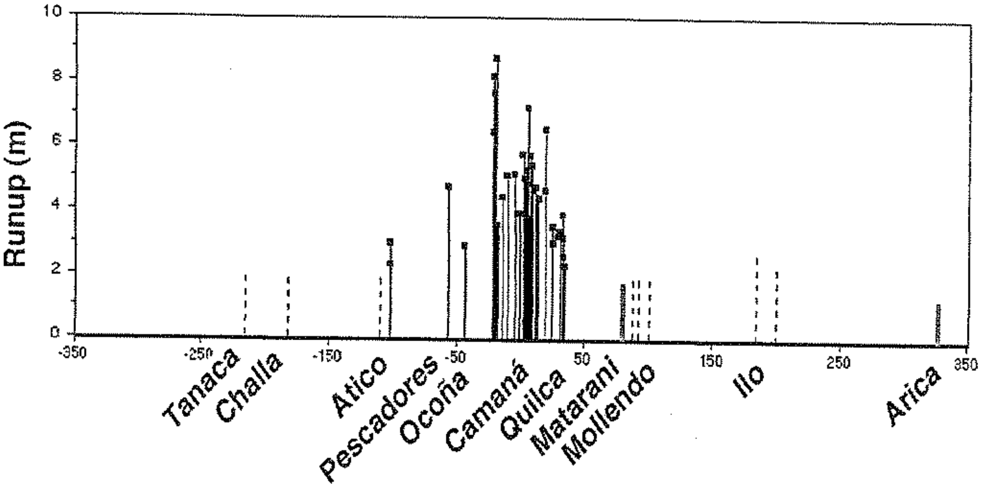

Figure 7-7. Measured runup and high watermarks from the 23 June 2001 Southern Peru tsunami. Distance is measured in kilometers along the coast relative to Camaná. Solid black lines topped by squares are water heights from Table 7-3. Dashed lines are measurements where tsunami did not breach the high tide berm. The two gray bars at Matarani and Arica are from tide gauge recordings.

indicators of high water were measured; the highest was the 7.2 m sand deposit and watermark on the third-floor stairs of the Titanic Club Playa Hotel (Figure 7-6). The high water values for the Ports of Matarani and Arica are from tide gauges.

Peak water heights (Figure 7-7) are measured as a function of distance from the Rio Camaná delta (16.64°S and 72.73°W), roughly the center of the inundation zone. Figure 7-7 presents the distribution of runup heights as a function of distance along the coastline. The maximum value of water height is 7.25 m (excluding the higher values that may have resulted from water splashing against the cliff at Playa Chira). This amplitude is approximately 1.5 times the maximum fault slip inferred from Kikuchi and Yamanaka's (2001) source tomography, a value considered within the general range of dislocation derived tsunamis (Hoffman et al. 2002). The shape of the tsunami heights versus distance shown in Figure 7-7 is relatively broad. Okal et al. (2002) compare tsunami wave heights versus distance for several recent tsunamigenic earthquakes and conclude that the 23 June 2001 Southern Peru tsunami is compatible with the seismologically derived dislocation source and does not require generation by an underwater landslide or slump.

TSUNAMI CHARACTERISTICS NORTH AND SOUTH OF CAMANÁ

Outside of the Province of Camaná, the tsunami had little direct impact. All eyewitnesses from Tanaca to Ilo felt the earthquake strongly. Most described a drawdown of the sea beginning about 10 to 25 minutes after the earthquake. The water retreated to a distance 50 to 100 meters offshore, corresponding to an elevation of roughly 4 to 5 meters below the ambient water level. The water remained low for "a long time," variously described as 15, 20, or more minutes. In the fishing villages, residents were familiar with tsunami hazards and many expected a significant positive wave to follow, but the wave did not breach the high tide berm, at an elevation of about 2 meters above the sea at the time of the earthquake. Three or four more oscillations of the water were observed, but none of the waves reached any higher. Several observers in the Tanaca and Chala area reported that the sea stayed lower than normal for many days.

The eyewitness accounts of an initial water retreat contradict the tide gauge data. The Peruvian and northern Chile tide gauges (Figures 7-2 and 7-3; Table 7-2) all show an initial positive wave, not a drawdown. Only one observer, a woman working in a souvenir shop 20 meters from the Matarani tide gauge house, noticed an initial rise. She observed the boats in the harbor rise about one meter, and then watched the water drain so that the boats rested on the sea floor. A videographer for a Matarani television station caught this sequence on video taken from the port overlook about 5 to 10 minutes after the earthquake (Figure 7-8). The film showed what was probably the initial rise and the first drawdown. Port authorities then ordered a complete evacuation of the harbor area, and the videographer was unable to film the larger waves.

The first tsunami wave everywhere else along the southern Peru coast may also have been positive, but because of its relatively small amplitude and the extreme low tide at the time of the earthquake, eyewitnesses may not have noticed the tsunami until the larger negative pulse. It is also possible that the first wave in these areas was not positive; coseismic deformation and the slip distribution may have caused complexities in the wave characteristics not reflected in the sparsely distributed tide gauge data.

Although there was no structural damage caused by the tsunami in these areas, there was an indirect impact. Fishermen had heard about the Arica seismic gap and were concerned that a second earthquake might occur and produce a larger tsunami. Some had memories of the 1942 tsunami that caused major damage in the Chala area. Few were willing to take their boats out, and some people had moved into the hills where temperatures were very cold, disrupting the economy and causing some health problems.

The coastal communities outside of Camaná, although little affected by tsunami, were impacted by the earthquake (detailed elsewhere in this volume). Liquefaction in alluvial valleys and on coastal planes caused localized subsidence and damaged bridges, roads, and some structures. The coastal roads, including the Pan-American Highway, suffered severe damage from failures on steep grades and dune slopes. Two workmen died in Matarani when the slope behind the port failed. The slope failure complicated local evacuation efforts. More detailed descriptions of the tsunami north and south of Camaná are given in Borrero (2002).

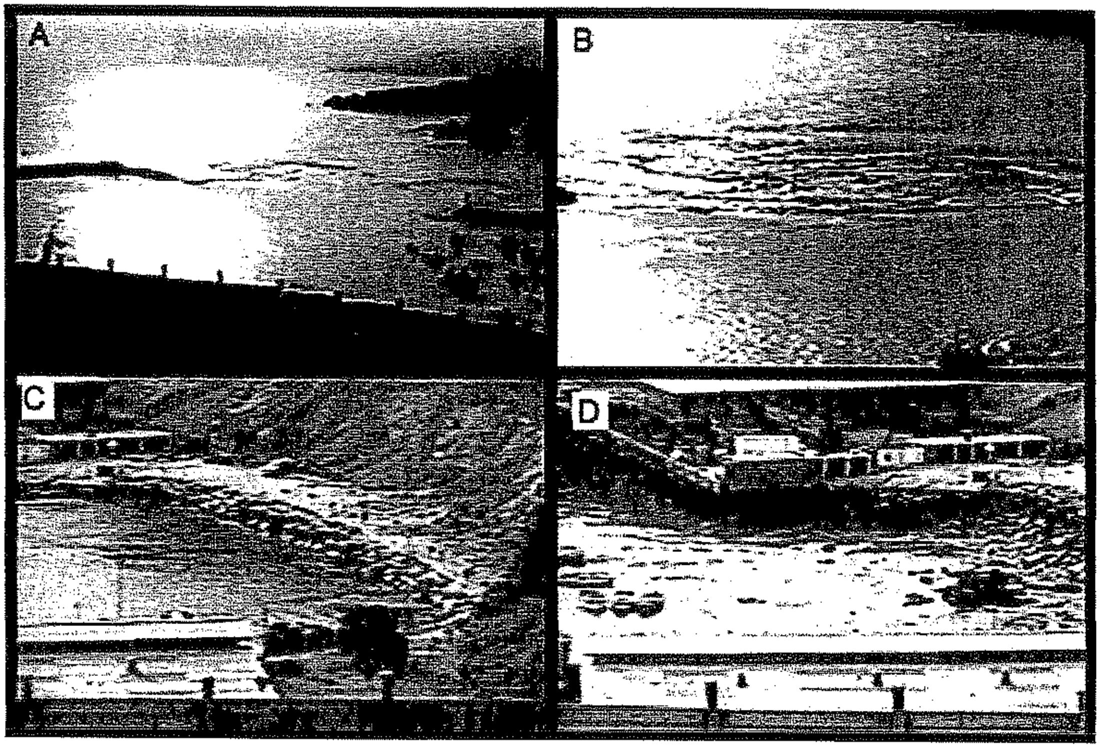

Figure 7-8. Frame grabs from the video recorded at Matarani. Panel A: the withdrawal of the water can be seen flowing through the gap in the breakwater. A vortex is generated off of the tip of each breakwater segment. Panel B: a fishing boat contemplating a run for deeper water with the vortex in the background. Panel C: about 10 minutes after the earthquake when water is near the peak of the initial rise. Panel D: the water level at maximum withdrawal. The boats on the left are grounded.

TSUNAMI IMPACTS IN CAMANÁ

The province of Camaná (population 53,000) has eight districts that include coastal resort towns, farming regions, and fishing villages. It includes the small fishing harbors at Quilca and Ocoña, the undeveloped beaches of Playa Chira and east of Las Cuevas, cultivated fields along the Rio Ocoña, Rio Camaná, and Playas Pucchún, Jahuay, Santa Monica, and El Chorro. The most developed area is La Punta, which prior to the tsunami was a thriving summer resort catering to the well-to-do from Arequipa and Lima. La Punta had about 3000 structures, including summer homes, hotels, restaurants, and discotheques. During the summer months, more than 5000 people are in residence, and hundreds of tourists fill the beach concessions (Figure 7-9).

Based on survey lines, photographs, and eyewitness accounts, the inundation in the Camaná area reached at least 500 meters inland in all areas, where the waves dissipated on the low elevation coastal platform (Figure 7-10). The deepest penetration was over the flat agricultural fields near Playa Pucchún where the water reached nearly 1.4 km from the coast. The tsunami also flooded the boundaries of the lagoon and extended at least 1 km up the Rio Camaná. To the north and south of the river delta, the coastal platform narrows. Waves were stopped by the abrupt cliffs behind Playa Chira (Figure 7-5) to the west and the Pan-American Highway and cliffs behind Las Cuevas and the uninhabited beach further east.

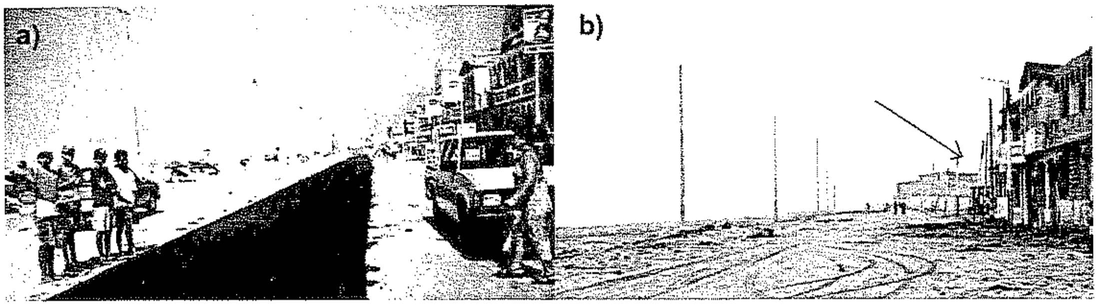

Figure 7-9. The waterfront area of La Punta before (a) and after (b) the 23 June 2001 tsunami. The frontage road is about 30 meters from the water and at an elevation of 2 meters above high tide. The buildings in this view were hotels and restaurants. Note the missing buildings where the arrow is pointing in (b). The road has been covered with sand deposited by the tsunami.

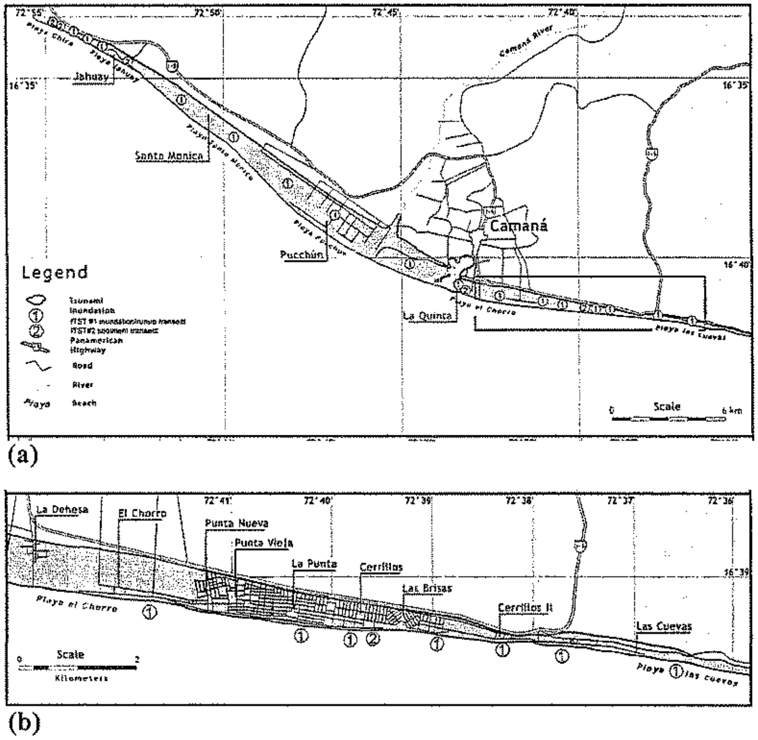

Figure 7-10. Inundation map of the Province of Camaná. (a) Coastline from Playa Chira to Las Cuevas. Numbers in circles refer to the survey profiles of the ITST teams. In the developed beach resort area, about 3000 structures were within the inundation zone (b).

Eyewitnesses in Camaná described an initial drawdown that lasted 15 minutes or more. These reports are similar to accounts from communities outside the damage zone described previously. Most agreed that the initial positive wave was small and did not overtop the beachfront road, situated about 20–50 m from high tide. The second and third waves were the most destructive and of much greater impact, flooding nearly the entire inundation zone. Eyewitnesses described fast, turbulent surges of debris-laden water as the waves entered and withdrew. There is no evidence that any of the waves were bores (steep-fronted breaking waves) and, in contrast to recent tsunamis in Papua New Guinea and Indonesia, no mention was made of an abnormally large roar accompanying them. Much of the area remained flooded for days after the tsunami (Figure 7-11), restricting access and search and rescue operations.

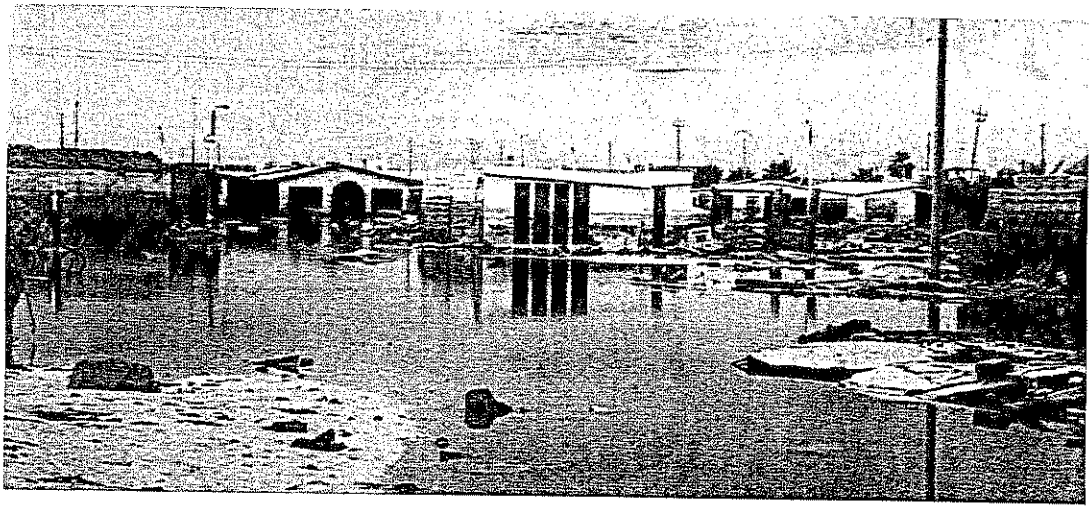

Figure 7-11. Standing water in central La Punta, seven days after the tsunami. Higher watermarks can be seen on buildings. This area is about 150 m from the coast.

Many survivors self-evacuated after observing the initial withdrawal of the sea or at the urging of others. No one moved inland after feeling the ground shaking, even though all felt the earthquake strongly. There were several reports of people going out to look at the exposed sea platform when the water withdrew.

The situation was different for farm workers. Many of the fields were too far from the coast and/or behind a berm or irrigation dike to observe the initial withdrawal. The workday ended at 4:00 pm on Saturdays, and even when told by others to evacuate, some were reluctant to leave before their shift was over.

Table 7-4 summarizes tsunami damages by district. The district of Camaná includes the city center (out of the inundation zone), the mixed resort/farming area of El Chorro, and the farming communities of La Dehesa and La Quinta, both mainly in the inundation zone. Mariscal Cáceres district extends along the coast west of the lagoon and includes the farm communities of Jahuay, Pucchún, and Santa Monica within the inundation zone, and the inland areas west of the Camaná city center outside of the flooding. The majority of the destroyed and damaged structures, the 7 deaths, 2 missing, and most of the injuries in these two districts are attributed to the tsunami. About 2,500 hectares of farmland was flooded, destroying all of the onion and maize crops, and the irrigation control and canal system (Figure 7-12). The districts of Nicolás de Piérola, Mariano Nicolás Valcárcel, and José Maria Quimper are located to the north and northwest of Camaná city center and are entirely outside of the tsunami zone. Damage in these areas was entirely caused by the earthquake. Ocoña, a farming and fishing town about 50 km northwest of Camaná, and the city closest to the earthquake epicenter, suffered some damage to the harbor from the tsunami, but the only death and most of the structural damages are attributed to the earthquake. The impacts in Quilca, the small fishing village 30 km east of Camaná, were minor and caused by the earthquake.

The district of Samuel Pastor was hardest hit by the tsunami. It includes the resort communities of Punta Nueva, Punta Vieja, La Punta, Cerrillos, Las Brisas, Cerrillos II, Las Cuevas, and the farmlands just west of Punta Nueva. The developed part of the district lies almost entirely within the tsunami inundation zone. The 77 dead and missing in Samuel Pastor, and all of the injuries and destroyed structures are attributed to the tsunami. Officials estimated that only about 15 of the approximately 2000 structures within the inundation zone in this district survived the tsunami with

Table 7-4. Damages and casualties in Camaná district.

District	Dead	Missing	Injured	Structures Damaged	Population Destroyed	Affected	Comments
Camaná	4	0	16	300	300	2,700	Deaths, injuries all due to tsunami
José Maria Quimper	0	0	0	0	200	1,200	Out of inundation zone
Mariano Nicolás Valcárcel	0	0	0	0	254	1,524	Out of inundation zones
Mariscal Cáceres	3	2	0	30	115	780	Deaths, missing all due to tsunami
Nicolás de Piérola	0	0	0	11	28	201	Out of inundation zone
Ocoña	1	0	0	484	330	3,432	Mainly earthquake impacts
Quilca	0	0	0	1	3	21	Mainly earthquake impacts
Samuel Pastor	17	60	25	430	2,500	3,000	Deaths, injuries all due to tsunami
Total	**25**	**62**	**41**	**1,256**	**3,730**	**12,858**	

Source: INDEC 2001

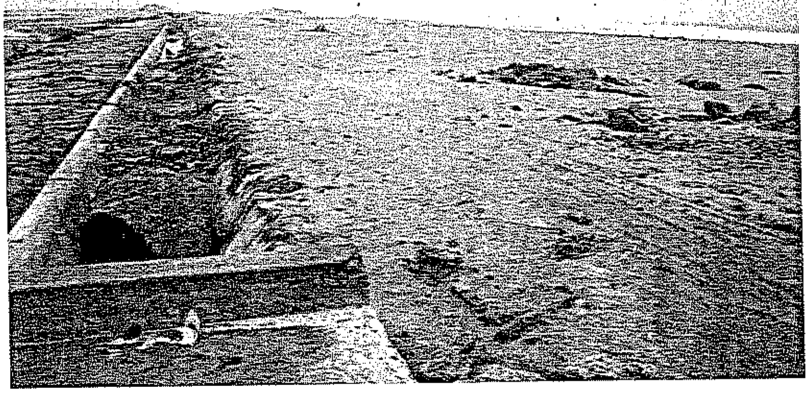

Figure 7-12. Damaged irrigation canal at Playa Jahuay. Onion fields to the left of the canal are covered with tsunami deposits. The 1.5 m diameter boulder was originally with the group of rocks on the right and was transported approximately 8 m up the beach slope and into the canal.

no structural damage. Fortunately, these resort towns were almost uninhabited at the time of the earthquake, most of the hotels, restaurants and discotheques were closed and only a few summer home caretaker families were in residence.

The Instituto Nacional de Defensa Civil (INDEC 2001) provided demographic information by district. Of the 24 documented tsunami casualties they list in Camaná, 8 were children and 16 adults; demographics for the 62 missing were not provided. Fifty-five percent of the tsunami victims in Camaná were male. In contrast, the victims killed by ground shaking effects were 65 percent female. Of the adults killed by the tsunami, half were aged between 30 and 50 and none were over 70. Of the shaking-related deaths in Moquegua, Arequipa, and the other inland areas, 40 percent were over 70 and fewer than 30 percent adults in their prime. A possible explanation of the difference is that most of the tsunami victims were adult field workers and housesitters; in the inland areas the elderly and the very young were more likely to be indoors on a Saturday afternoon and were crushed when houses collapsed. Only about 40 people were injured by the tsunami, less than half the number killed and missing. This is typical of tsunamis, where people caught in the water are more likely to be killed than injured. In the 1998 Papua New Guinea tsunami, over 2,100 people were killed and fewer than 1,000 injured (Dengler and Preuss, in press). Ground shaking is much more likely to injure than kill. In the areas outside the inundation zone, 51 people died and over 2,700 were reported injured as a result of the shaking effects of this earthquake (INDEC 2001).

Damage to structures in the inundation zone was nearly total. Buildings in the coastal area are of three general types. In the farming areas and fishing villages, weak adobe structures and shacks of bamboo and other lightweight materials predominate. In the resort area, the majority of structures are less than ten years old and substantial. Most were built on concrete slab foundations about 25 to 30 cm thick with reinforced columns at the corners. Preformed brick blocks were filled in between the columns to make the walls. A number of hotels, some restaurants, and a few homes were built of reinforced concrete walls and columns with thicker foundations. There were no wood structures in the inundation zone. Eyewitnesses reported that the earthquake caused damage to some of the shacks and adobe structures and caused a few to collapse, but none of the stronger buildings were damaged by the ground shaking. While liquefaction was observed in soil pits, there was no indication that it contributed to the structural damage in the La Punta area. Eyewitnesses said the buildings were undamaged before the tsunami hit, and the concrete foundation slabs examined by ITST members were generally intact, unless undermined by scour.

The weak adobe structures and bamboo shacks were obliterated by the tsunami and no sign of them remained afterwards. Infilled wall structures also performed poorly; walls perpendicular to the incoming wave direction were typically blown out (Figure 7-13). Scour was common at the corners of structures, undermining thinner slab foundations (Figure 7-14). Scour also was concentrated along the edges of roads (Figure 7-15) and near earthen berms separating fields. In contrast, there was little evidence of scour on the smooth, undeveloped coastal platform along Playa Chira (Figure 7-5). Reinforced concrete structures with thicker foundations were most likely to survive, even when located close to the beach (Figure 7-6). However, some substantial structures built on filled river deposits failed when the tsunami completely undermined their foundations (Figure 7-16).

The degree of structural damage caused by the tsunami did not correlate with distance from the coast—buildings near the limit of inundation were as likely to be destroyed as those closest to the beach. The beachfront structures were mainly restaurants, hotels, and discotheques and appeared to be better constructed than the summer homes farther back from the coast, which may have contributed to their survival. Structures farther back from the beach may have been more vulnerable to the battering of debris picked up by the waves as they damaged structures closer to shore.

Figure 7-13. Damaged summer home, La Punta. Typical construction consists of reinforced columns on a 20-30 cm thick concrete slab foundation with unreinforced brick infilled walls. Walls perpendicular to the direction of the tsunami (arrow) failed. Dashed line on remaining center wall shows a stagnant watermark.

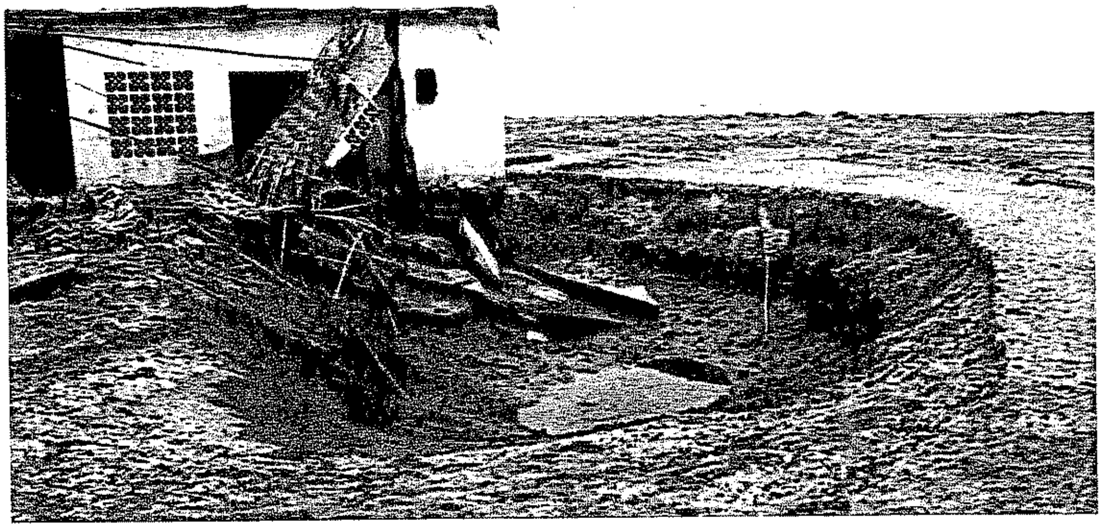

Figure 7-14. Scour around the southwest corner of a La Punta house, 30 m from the coast. Scour was observed at the corners of almost every structure in the inundation zone.

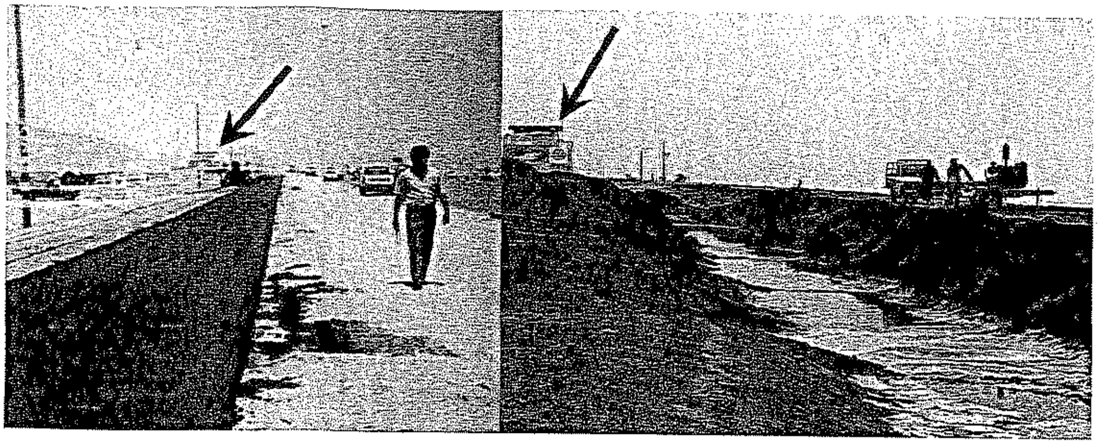

Figure 7-15. La Punta beachfront road looking east before and after the tsunami. Arrow points to Titanic Club Playa Hotel (see also Figure 7-6). The tsunami scoured the landward side of the road to depths of 3 meters.

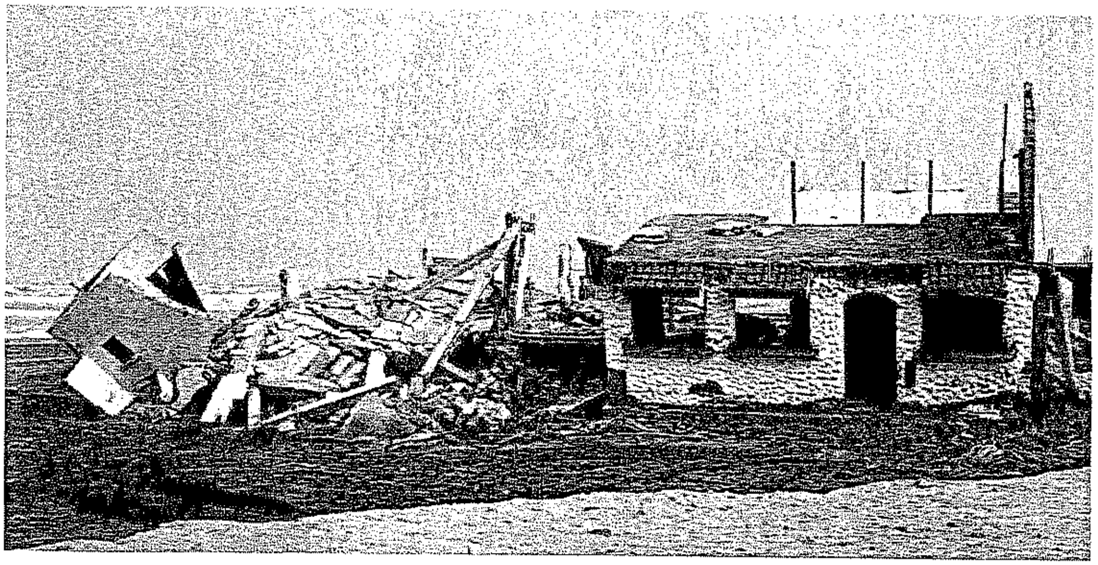

Figure 7-16. El Chorro discotheque built on filled river channel. Tsunami flow has undermined foundations of structure on the left.

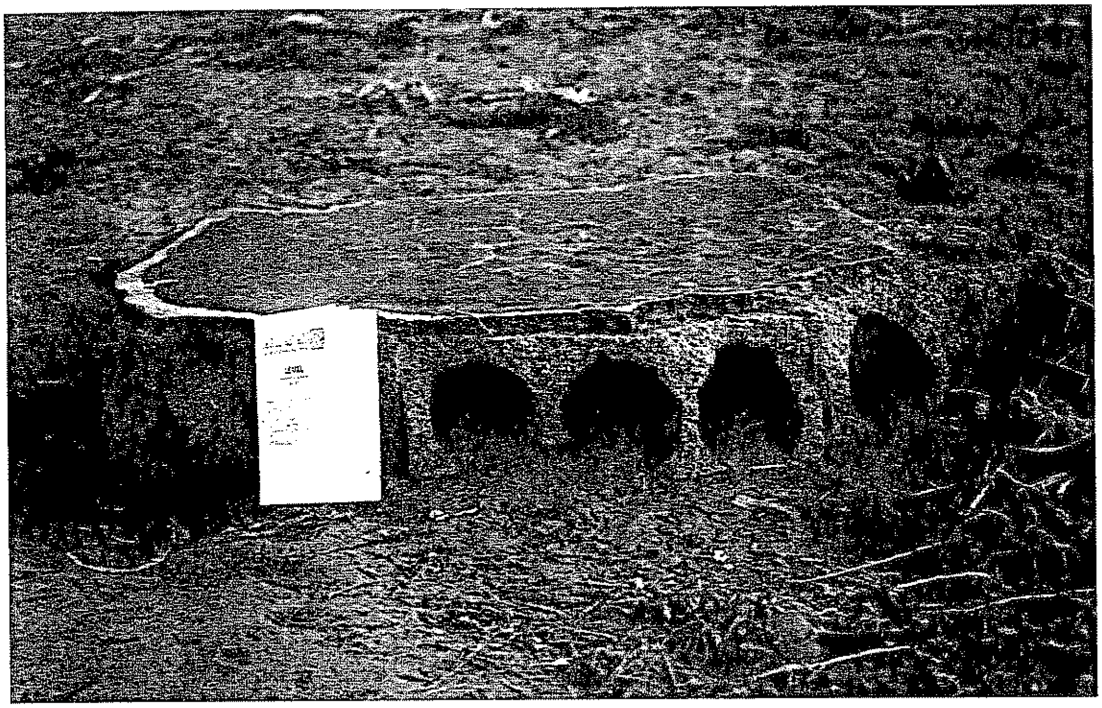

Figure 7-17. Brick in onion field displaced 200 meters by tsunami flow. Thickness of deposit is 25 cm beneath brick; an additional 2 cm deposited on top. This brick is typical of those used in infill wall construction. Composite brick slabs have hollow cores that are plugged about every 40 cm. Bricks broke at the solid-hollow interface and were preferentially oriented with the open cores pointing in the direction of tsunami flow. Note salt deposits on the top left of the brick.

SEDIMENT DEPOSITS

The tsunami transported sand, rocks, and debris substantial distances in Camaná Province. The largest object observed displaced was a 1.5 m diameter boulder on Playa Jahuay that was transported at least 8 meters up the wave slope and deposited in an irrigation canal (Figure 7-12).

Sections of brick walls were displaced as much as 200 meters (Figure 7-17) and oriented relative to the flow direction. Sands deposited by the tsunami were ubiquitous in the inundation zone. The thickness, stratification, and character of the sediment deposits record important information about the wave that deposited them. By examining the thickness and grain size distribution of tsunami deposits, the wave height and flow velocity may be estimated.

Where the deposits were overlying a known preexisting surface that was texturally distinct, such as farm soils (La Quinta, Playa Jahuay) or the compacted coastal platform in the developed areas of La Punta, identification of the interface was fairly simple. Where the underlying material was beach sand that was similar both texturally and visually, identification was more difficult. Several criteria were used to distinguish the tsunami deposits, including differences in texture, grain size, and color. In tsunami deposits, grain size generally fines upwards and rip-up clasts (pieces of material from the underlying sediment entrained by the tsunami) may be present. The base of the deposit erodes underlying structures, and a heavy mineral layer may be present at the base. When examined, underlying sands were often trampled, while tsunami sands were relatively

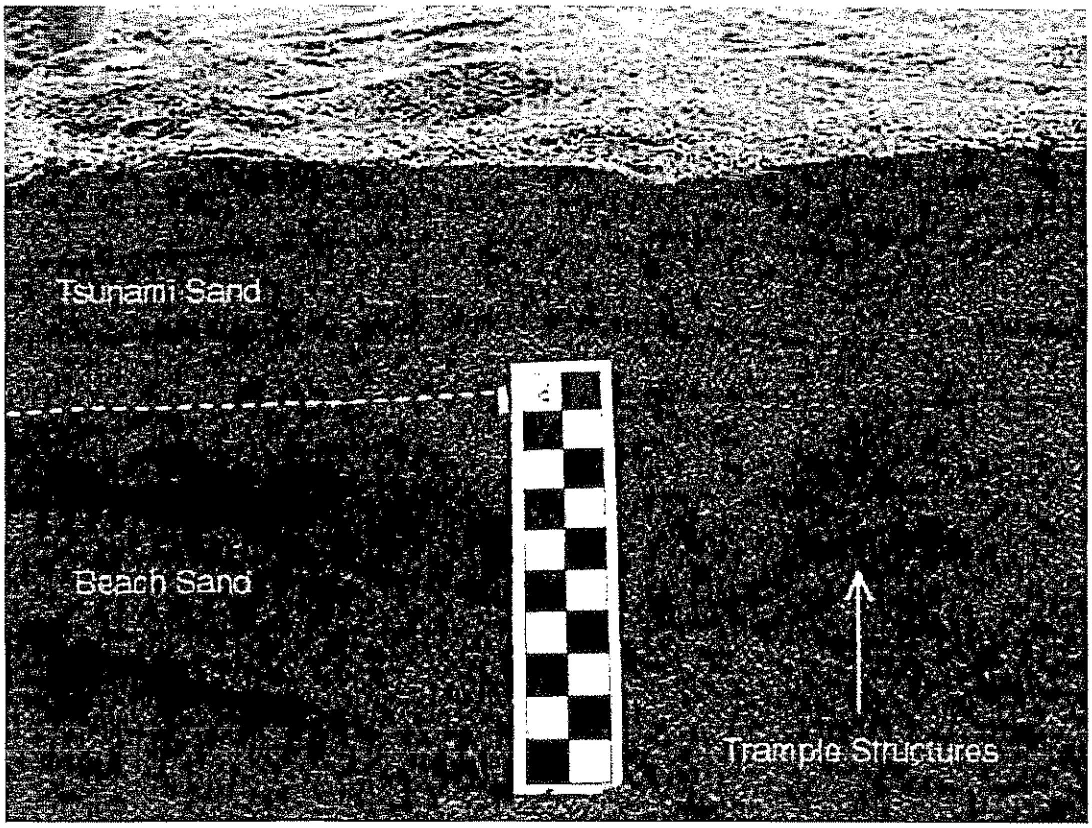

Figure 7-18. Layered tsunami deposit overlaying trampled structures at Amecosupe near Los Cerrillos. The preexisting beach sands show rounded, irregular trample structures caused by walking on the sand. The tsunami deposits are more laminar. At least four layers are seen at this location, suggesting four different waves.

undisturbed (Figure 7-18). Many of the tsunami deposits had multiple layers. Many of the elements found in tsunami deposits from Papua New Guinea, such as rip-up clasts, multiple layers, and fining upwards sequences, were also found in Peru (Gelfenbaum et al. 2001).

Seven transects of the coastal platform between Playa Chira and Pampa Grande (Figure 7-10) were sampled by the second ITST in order to characterize tsunami deposits. Deposits were found at all sites and exhibited a wide variety of forms throughout the study area. Thickness varied both with distance inland and with site. The thickest deposits measured were at Amecosupe, the transect close to Los Cerrillos (Figure 7-19). The tsunami penetrated about half a kilometer at this site; the thickest deposits (nearly 30 cm) are closest to the coast. Sediment deposit thickness is not a simple function of distance inland, however, but is affected by distance from the shoreline, local topography, and change in slope. Flow indicators such as bent vegetation, transported objects, and ripple marks suggest significant onshore flow and weaker, but significant, offshore flow as the waves withdrew. While sedimentary structures were usually absent within the tsunami deposits, many deposits contained two to four internal layers (Figure 7-18). Each layer is believed to

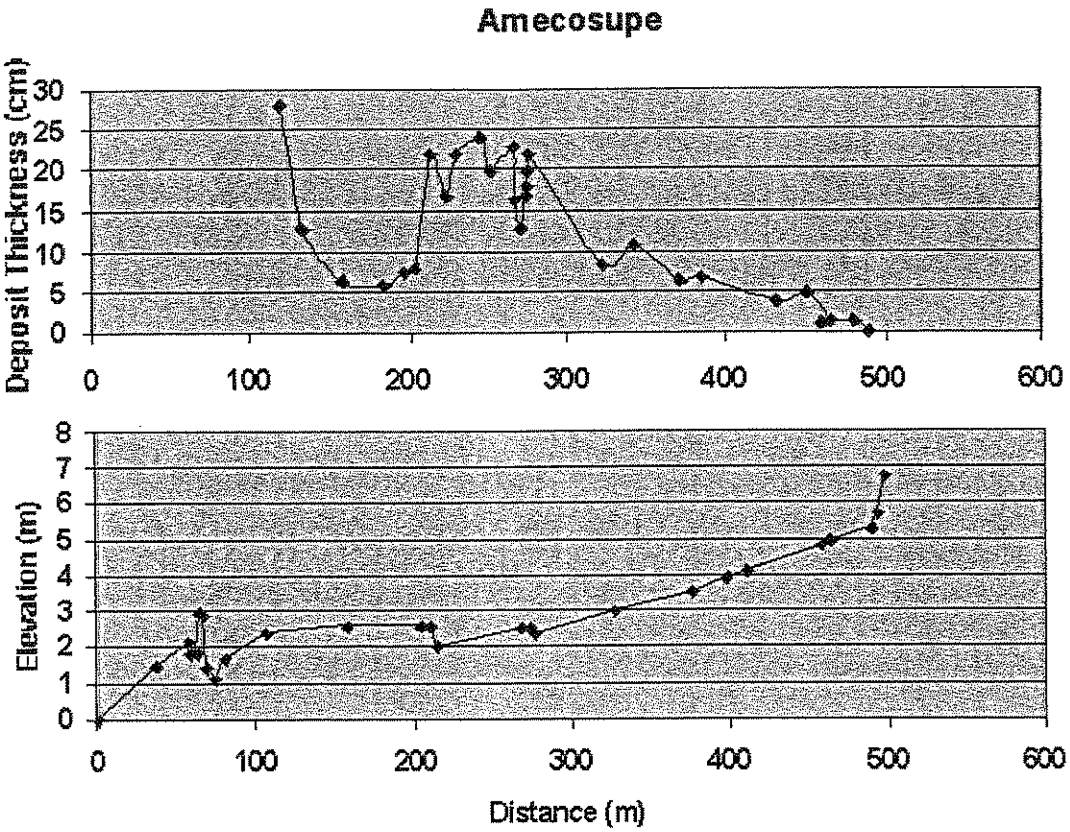

Figure 7-19. Tsunami deposit thickness and transect elevation at Amecosupe.

Figure 7-20. Bulldozed tsunami sand deposits, La Punta.

represent deposition from a single wave within the tsunami wave train. This is consistent with eyewitness reports that the tsunami consisted of three to four waves, with the second and third waves being the largest.

The sand deposits caused both immediate and long-term impacts. The deposits covered fields, smothering crops with salt-laden sands. Structures within the inundation zone had up to 50 cm of sand deposited within them and larger amounts outside. A major part of the initial emergency response was devoted to sand removal (Figure 7-20). Farmers had to remove sand deposits and flush their fields with fresh water to remove salt in order to prepare their fields for replanting.

DISCUSSION

The 23 June 2001 earthquake generated a tsunami that produced waves large enough to cause significant damage along 50 km of coast and to be observed by eyewitnesses for over 400 km. The tsunami was the most widely recorded in the Pacific since the 1994 ($M_w = 8.2$) Kuril Islands earthquake. The size of the 23 June 2001 tsunami appears to be consistent with a seismogenic source—the largest waves averaged 5 meters, with some approaching 7 to 8 meters, which is similar in scale to the maximum slip on the fault. The distribution of tsunami wave heights along the coast, near- and far-field modeling of the tsunami, and the tsunami magnitude are all consistent with a dislocation and not a landslide source.

While the amplitude of the tsunami scaled consistently with the size of its source, it was somewhat surprising that, outside of the city of Camaná, the size of the positive waves may have been less than the drawdown. Eyewitness accounts both north and south of Camaná consistently described a withdrawal of the water with amplitude on the order of 4 to 5 meters. Many expected the positive wave to be equally large, evacuated to high ground and were surprised that the waves did not overtop the high tide line. The tide gauge recordings at Matarani and Arica, Chile, the two closest stations, do not exhibit any profound asymmetry (Figures 7-2 and 7-3), but both are located in harbors and the waves are affected by local resonances. The asymmetry, if real, might result from a combination of the complex distribution of slip on the fault and permanent uplift of the coast. Kikuchi and Yamanaka's (2001) slip model implies a large uplift near the coast about 65 km ESE of Camaná that could explain an initial drawdown as the water flowed away from the uplifted area towards offshore. The same slip model suggests 0.5 to 1 m of coseismic uplift of the coast between Quilca and Chala, possibly making the positive wave appear smaller in much of the area. It is also possible that the eyewitness accounts are unreliable and, perhaps, biased by the extreme low tide.

The only direct evidence of coseismic deformation is from the Matarani tide gauge recordings (Figure 7-21). A comparison of pre- and postearthquake tide recordings shows that the site is about 15 cm lower after the earthquake. There are two possible explanations of this subsidence: regional coseismic deformation related to elastic deformation triggered by the fault rupture, or localized subsidence caused by site conditions. A local network of five benchmarks had been established in the Matarani Port area. Comparing benchmark data three weeks after the earthquake to pre-earthquake levels show about 15 cm of localized subsidence of the house where the tide instruments were located, suggesting no regional elastic uplift or subsidence at the Matarani site. The Matarani data does not preclude land level changes elsewhere. Preliminary modeling of the deformation implied by Kikuchi puts Matarani near the zero isobase line for uplift/subsidence.

The tsunami caused major damage to Camaná, and its impacts were much more significant than the impacts of ground shaking in this area. Unfortunately, the largest waves produced by the 23 June 2001 earthquake hit one of the most developed beach areas along the southern Peruvian coast, which, in general, is sparsely populated. Tsunami waves penetrated over 1 km inland and damaged or destroyed nearly all of the 3,000 structures in this zone. Damaged structures were built on ground below 5 meters in elevation above sea level, reaffirming the hazards of development

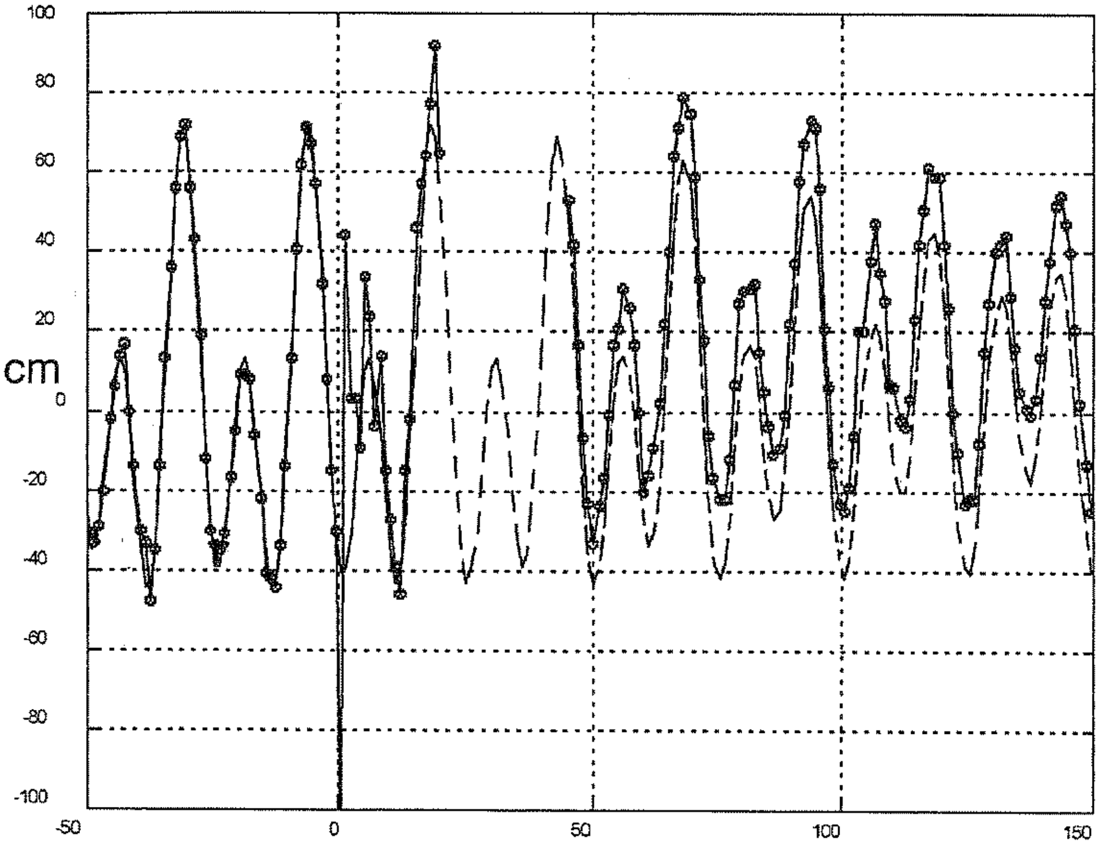

Figure 7-21. One hour averaged tide levels (dots) recorded on the Matarani digital tide gauge. Solid line is the interpolated tide through the actual data points. Dashed line is the calculated tidal variation assuming no land level deformation. The line at 0 marks the origin time of the earthquake. Prior to the earthquake, the calculated and actual data match each other. After the earthquake, the actual tide averaged about 15 cm above calculated values.

along exposed coastal platforms at low elevation. Poorly built adobe buildings were obliterated and almost all brick infilled wall structures destroyed. The few structures that survived had more reinforcing and thicker foundations.

While the extent of inundation and the number of structures damaged or destroyed was significant, the number of lives lost was much less than caused by other recent large tsunamis. It was also lower than what might have been expected from the scale of structural damage within the inundation zone. There are a number of reasons for the relatively light loss of life:

1. *Time of year.* First and foremost, the earthquake and tsunami occurred in winter. The summer resident population of the Camaná beach towns increases by 5,000 people plus an additional influx of tourists. Had the same earthquake occurred in the summer, when the beach discotheques, hotels and cafes were full, casualties would undoubtedly have been much higher.
2. *Time of day.* The earthquake and tsunami occurred during daylight hours. Seeing the water retreat was the key to self-evacuation. Had the earthquake occurred at nighttime, fewer people may have responded. However, fewer farm workers would have been in the exposed zone.

3. *Ambient sea level.* The tsunami coincided with a minus 35 cm tide, one of the lowest tides of the year. A high tide would have added over 1 meter to the final runup. The seas were relatively quiet the day of the earthquake. Large winter storm swells would have further exacerbated the impact.
4. *Initial drawdown of water and period of wave.* It is not clear whether the large drawdown was preceded by a positive wave, in which case the latter was of benign amplitude. For the purpose of this discussion, a key aspect of the tsunami strongly mitigating its impact was that the first *noticeable* motion of water was a *large retreat.* This, and the significantly long period of the phenomenon (at least 15 minutes) allowed even people unfamiliar with tsunamis to react to the very unusual state of the sea and to reach higher ground.
5. *A tsunami-aware coastal population.* Many of the people interviewed knew what tsunamis were, recognized the water drawdown as a sign of danger, and self-evacuated. This was true primarily among the traditional coastal communities of fishermen, who "know the sea," are educated about tsunami hazards, and many of whom had experienced similar events in the past. By contrast, the victims were mainly farm workers and housesitters hired for the winter, many of whom came from inland and were unaware of tsunami hazards.
6. *Relatively low exposure.* The 300 km long coastline adjacent to the rupture is mostly steep and arid. Only along the river deltas does it constitute habitable land at low elevation. Consequently, both the area available for flooding, and more important, the population at risk were minimized.

It should be noted that the survivors used the drawdown of the water, rather than the earlier ground shaking during the earthquake, as the trigger to self-evacuation. This behavior among a well-informed community at first surprised field team members, since in principle the ground shaking would have given them an additional 10-15 minutes head start. However it must be borne in mind that the real-time human evaluation of tsunami hazard based on shaking is next to impossible: even a seasoned observer would do no better than estimate intensity, which is a notoriously poor proxy for static moment. Strongly felt earthquakes are common along the southern Peru coast, but very few produce damaging tsunamis. Perhaps for this reason the ancestral wisdom passed down from one generation to the other is that "when the water goes down, the sea comes back big." The fishing communities have adopted the retreat of the sea as a traditional, and arguably rational, warning that results in fewer false alarms. Had all of the people within the inundation zone responded to strong ground shaking and immediately moved inland, no one would have died from the tsunami in the Camaná area. The next major tsunami to hit the Peruvian coast might not begin with a substantial drawdown, or it may happen during the night when the sea cannot be readily observed. Tsunami hazard education programs need to encourage people to respond to shaking, even if it results in unnecessary evacuations.

The 23 June 2001 tsunami does not represent the largest tsunami hazard to the inhabitants of the southern Peruvian coast. The 1604 and 1868 events certainly produced waves that were twice as high and impacted a much larger area of the coast. Even the relatively distant 1877 Chilean earthquake produced tsunami waves of larger amplitude at many locations along the southern coast of Peru than did the 2001 event (Solov'ev and Go 1984). While the 2001 earthquake may have relieved part of the accumulated strain along the interface boundary, a recurrence of a larger event is still possible and poses a significant risk. Education about the local tsunami hazard is both the most economical and most effective way to reduce losses from future events.

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