13.0 TSUNAMI EFFECTS

One of the major consequences of the February 27, 2010 earthquake was the tsunami generated by sea floor deformation. While detailed ground reconnaissance of the height and distance of run-up resulting from the tsunami along the coast was beyond the scope of activities being conducted by the GEER team, there was nevertheless the opportunity to make measurements in selected locations along the coast to better understand the pattern of uplift and subsidence as detailed in Section 4 of this report. In addition, a few members of the GEER team conducted a more focused study of tsunami inundation extent and associated consequences for the city of Dichato and these are presented in this chapter. Careful measurements of inundation height and distance were made by the NSF funded Tsunami Ocean Sciences Group under the leadership of Costas Synolakis of the University of Southern California and Hermann Fritz of Georgia Tech along the Chile coast from as far North as San Antonio to as far South as Tirua. Results from these extensive tsunami reconnaissance studies will be published elsewhere.

GEER team observations focused on patterns of tsunami-related damage documented during aerial reconnaissance and cataloguing simple tsunami characteristics including minimum flow depth measurements and delineating the landward limit of inundation where possible. We also asked local residents to describe the tsunami waves including: (1) the time of wave arrival; (2) whether the first tsunami wave involved sea level rise or sea level fall; (3) the number of tsunami waves; (4) the largest tsunami wave; (5) the direction of wave arrival and other descriptive characteristics of the event. The following summary descriptions of tsunami impacts documented along the coast is organized by area from south to north, including Laraquete, Talcahuano, Dichato, Curanipe to Constitución, Iloca to Bucalemu, and Pichilemu.

13.1 Laraquete

In Laraquete, sand blanketing the road along the beach and accounts from local residents indicate the tsunami reached the first row of houses. Considerable flooding of the beach and along the river channel is evident by deep scouring that damaged the outfall of a storm sewer near the river bank (Figure 13.1). At one beach front house a car was pushed tens of meters landward and water marks on the foundation indicate a minimum flow depth of 0.55 m (Figure 13.2).

13.2 Talcahuano

Several flow depth measurements and interviews of witnesses provide information about tsunami impacts at Talcahuano. Visual surveys of damage and estimates of tsunami inundation by the Chilean government (http://www.ine.cl/canales/sala_prensa/noticias/2010/marzo/not190310.php) show the greatest impacts affected nearshore areas along the Bahia Concepcion and the Rio Andalien. Gas station attendants in Talcahuano recall three waves arriving around 4 am. Second hand accounts report a 15-m-high wave at a beach along the Tumbes Peninsula. In a different account, a worker at a storage warehouse on the waterfront who witnessed the wave said the tsunami arrived about 1.5 hours after the earthquake and commenced as a slow rise in sea level.

Figure 13.1. Tsunami scoured out the foundation of this storm sewer outfall at Laraquete (S37.165352° W73.188051, 1907 hrs on 03/16/2010).

Figure 13.2. Beach-front homes in Laraquete were inundated by the tsunami. At this woman's home, tsunami flow depths reached at least 0.55 m, which transported the white car from the street to the backyard. The tape measure left of the woman indicates the flow depth measured from a water stain on the building (S37.165650° W73.188136, 1915 hrs on 03/16/2010).

Minimum tsunami flow depths were measured at four sites in Talcahuano. At the storage warehouse, water lines left by flooding indicate 0.65 m flow depths along Perez Gacitua Street near Rio Andalien (Figure 13.3). West of the warehouse, high water marks showed sustained flow depths of about 0.63 m (Figure 13.4). To the north, sites closer to the bay experienced greater flow depths. At one building along Avenue Manuel Rodriquez the tsunami left marks 1.6 m high above ground (Figure 13.5). Port facilities along the shore of Bahia San Vicente experienced heavy damage caused by ground failure due to liquefaction and tsunami inundation. Near a fish processing plant at the port in west Talcahuano, lateral spreading dropped the waterfront down making it more susceptible to moderate tsunami flooding. Here the tsunami left a 1-m-high, indelible dark tarry stain along waterfront buildings that had slid toward the bay (Figure 13.6). At adjacent areas unaffected by lateral spreading and settlement, including a vast fuel tank farm, little or no flooding occurred. In light of the relatively modest tsunami inundation in western Talcahuano compared to more extensive inundation and damage observed in the eastern part of the city, we propose that Punta Pardo and the massive Tumbes Peninsula may have offered some protection to the northeastern shoreline of Bahia San Vicente, especially if tsunami waves propagated from north to south.

Figure 13.3. Tsunami flow depths reached a minimum of 0.65 m at this waterfront warehouse in Talcahuano along Perez Gacitua Street (S36.728263° W73.109199°, 1136 hrs on 03/16/2010).

Figure 13.4. Tsunami flow depths reached a minimum of 0.63 m at this green house on El Morro Street in Talcahuano (S36.727354° W73.109530°, 1206 hrs on 03/16/2010).

Figure 13.5. Along Avenue Manuel Rodriquez in Talcahuano, the tsunami reached minimum flow depths of 1.6 m (S36.725249° W73.106313°, 1215 hrs on 03/16/2010).

Figure 13.6. One-meter high dark stains on buildings at Talcahuano port facilities along Bahia San Vicente mark the elevation of the tsunami. Major damage of port facilities, including a fish processing plant were caused by a combination of factors, including modest tsunami inundation in areas that dropped vertically due to liquefaction-induced lateral spreading (S36.727076° W73.128058°, 1258 hrs on 03/16/2010).

13.3 Tsunami Observations in Dichato

13.3.1 Population distribution

The largest town in Coliumo Bay is Dichato, located at the South end of the bay that measures approximately 2 km West to East and 2.5 km South to North. Many of the homes in Dichato are built on the floodplain of a small river called the Rio Dichato. Pingueral is a gated residential community, about 2 kilometers north of Dichato, on the east side of the bay. Pingueral has a wide swimming beach that faces northwest towards the Pacific Ocean. There are three small fishing communities built on the steep hillsides of the west side of the bay. From south to north, they are Las Vegas de Coliumo, Caleta de Medio and Los Morros de Coliumo. On the northwest corner of the bay is Nocochea Beach, where there are about 25 vacation homes built along a beach facing north towards the Pacific Ocean. The location of the various population centers are shown in Figure 13.7.

13.3.2 General observations

The maximum inland incursion of the tsunami in the Dichato area was about 2.2 kilometers. Based on ground measurements, it is estimated that the maximum depth of the water in the town of Dichato was about 6 m, and about 6.5 m in the agricultural valley that extends to the South of Coliumo Bay west of Dichato as shown in Figure 13.8. A photograph of a large portion of the town of Dichato taken during an aerial reconnaissance flight is shown in Figure 13.9. An expanded view of the inundation extent and depth based on ground observations at the location of the black open dots is shown in Figure 13.10. Structure locations are overlaid in Figure 13.11. Most residents of the Dichato area agree that the first wave arrived within an hour after the earthquake. A second set of waves entered Coliumo Bay between 6:30 and 7:00 am. A third surge of water entered the bay at about 10:00 a.m. Depending on location, the largest and most destructive waves were either the second or third set of waves. Eyewitness accounts stated that the waves did not generally advance as cresting breakers, but moved into the bay and onto the land as surges, first causing flooding and then creating an outwash that carried structures and debris back into the ocean.

Coliumo Bay remained agitated and large surges continued to inundate the low-lying south end of the bay until mid-to-late afternoon on February 27th.

The variations in how the tsunami affected different areas around Coliumo Bay are dramatic. The homes facing directly onto the Pacific in Necochea experienced the smallest waves and the least tsunami damage; whereas, many of those structures built inside Coliumo Bay were washed away, especially those built less than 5 meters above sea level.

13.3.3 Water flow observations

Walls and structures on the east and west sides of Dichato were moved away from the bay, while walls and structures in the center of town were carried north towards the bay. This is consistent with a report from one witness who reported that the tsunami seemed to advance south along both sides of the bay into the east and west sides of town, and then to combine together in the center of Dichato before flooding back towards the bay through the center of town.

Evidence suggests that the tsunamis created a clockwise water flow within Coliumo Bay. The greatest flooding and deepest water in Dichato was on the eastern side of town. Residents of Pingueral witnessed a slow-moving vortex at the mouth of Coliumo Bay which circulated houses, boats and debris in a clockwise direction from about 7:00 a.m. until 2:00 p.m. The center of this vortex is marked on the map in Figure 13.8 with a red dot. After the tsunami, the beaches of the east shore of the bay were relatively clean, while the south and west sides of the bay were choked with debris.

Although the motion of the water was primarily north-south, fishermen on the west side of the bay observed east-west surges during the morning of the 27th February. Large waves that struck the west side of the bay seemed to have been reflected off the eastern shore. Pre and post event image pairs showing tsunami damage are given in Figures 13.12 and 13.13.

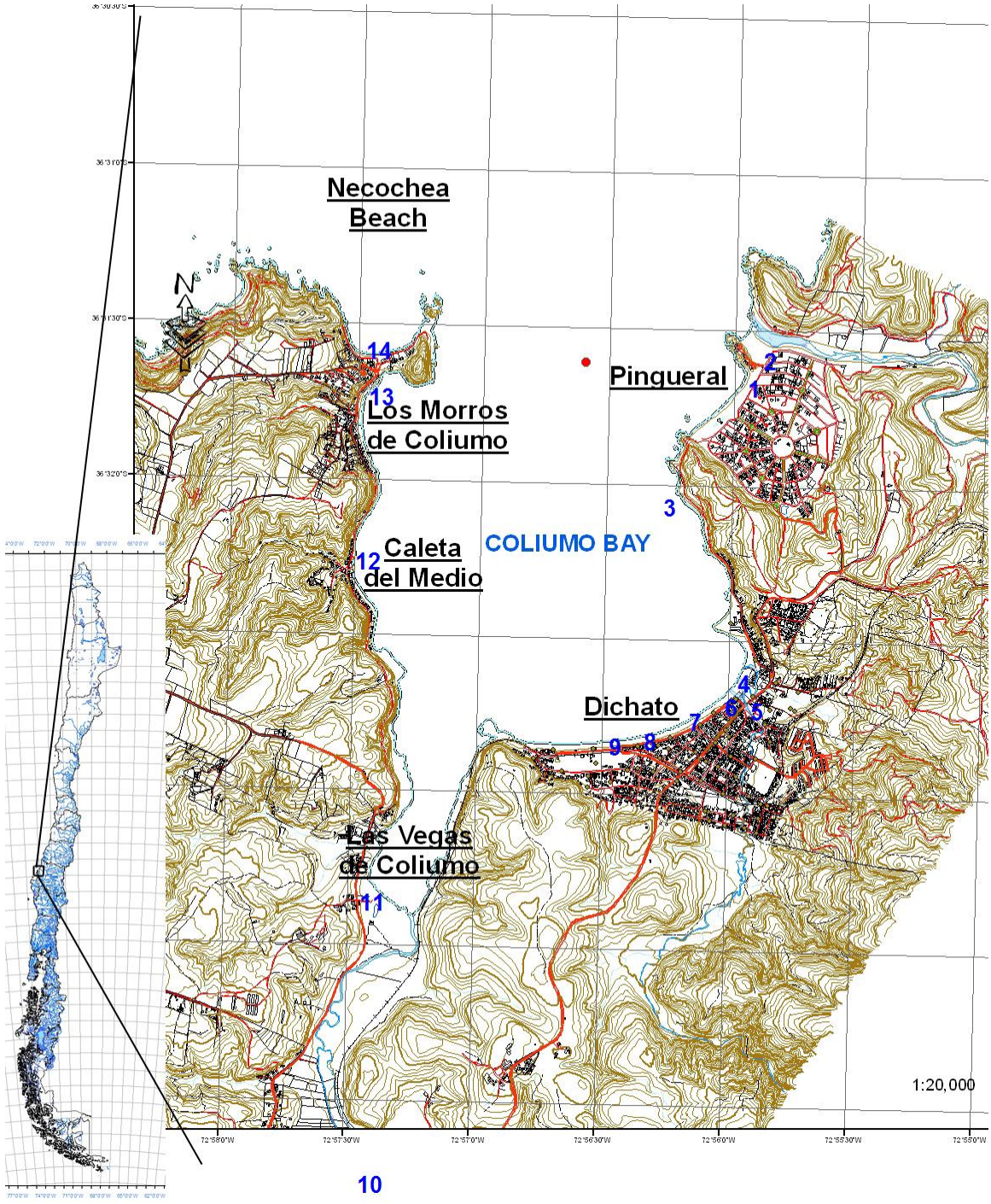

Figure 13.7 Location of population centers around Coliumo Bay (after Zoa et al.).

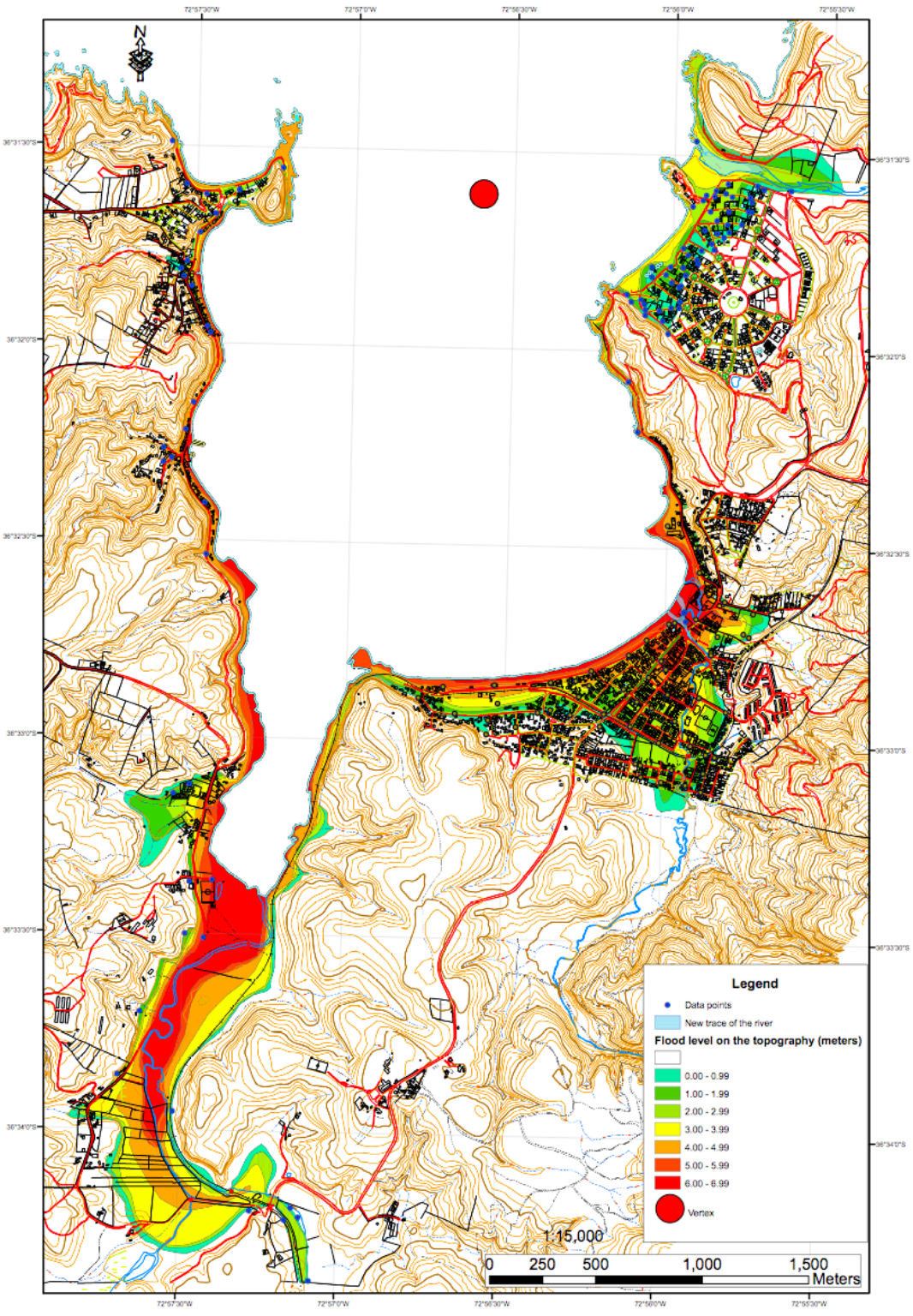

Figure 13.8 Inundation extent and depth for Dichato region based on ground observations by Zoa et al.

Figure 13.9 Aerial reconnaissance photograph of portion of Dichato and Coliumo Bay (S 36.5488° W72.9314°)

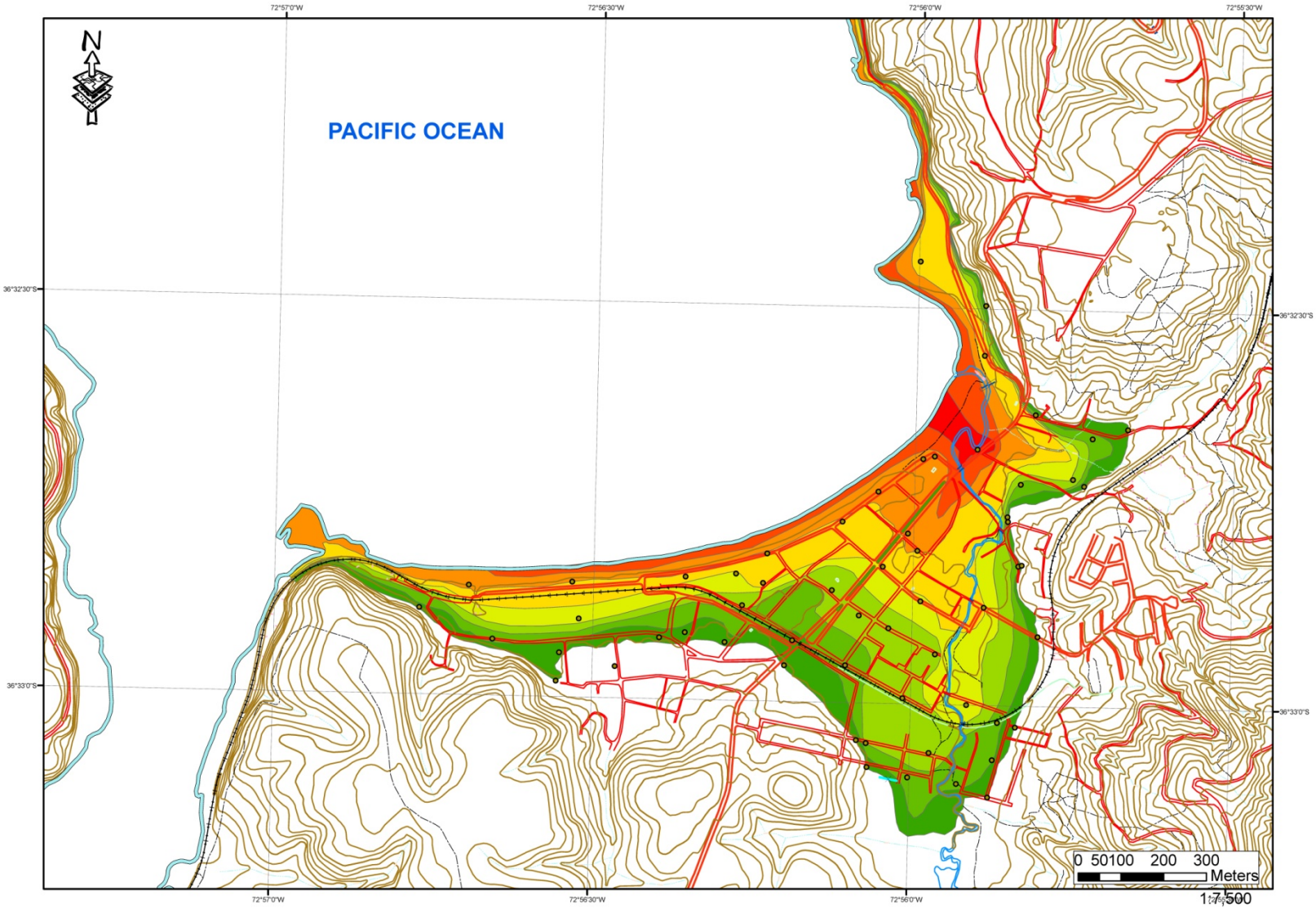

Figure 13.10 Inundation extent and contours of inundation depth in Dichato by Zoa et al.

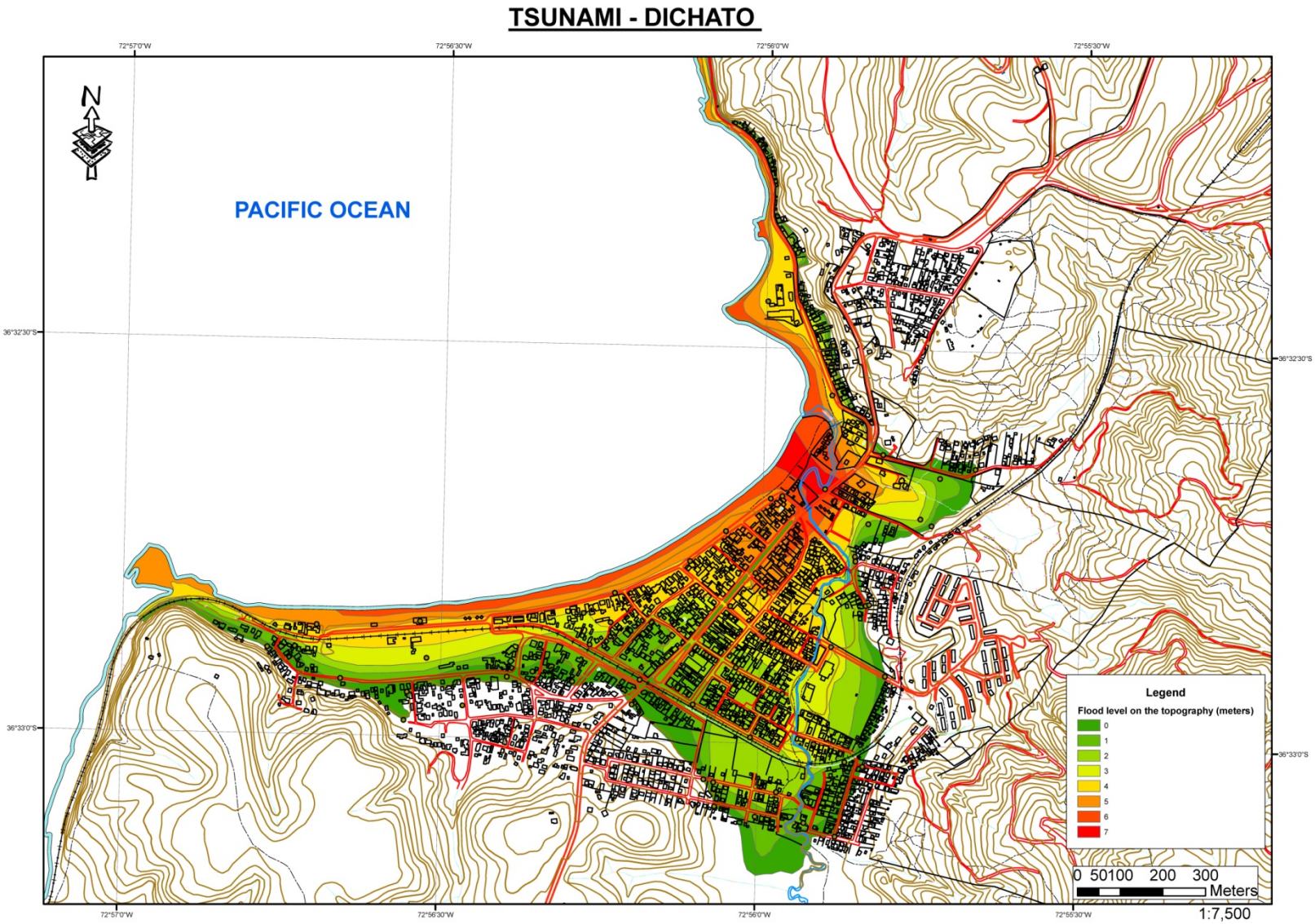

Figure 13.11 Inundation extent and contours of inundation depth showing structures in Dichato by Zoa et al.

13.3.4 Additional observations and reports

Immediately after the earthquake, residents of Pingueral moved to a ridge east of town at an elevation of about 60 meters. From this viewpoint, they noted that the ocean was as smooth as a lake. There was no wind, swells or ripples. As the full moon was setting to the northwest, its reflection was visible as a circle on the surface of the ocean. From 4:05 until 4:20 a.m., the moon´s reflection on the ocean stretched slowly from a circle into an oval, elongating towards the shore. This change in the shape of the moon´s reflection indicates that a change in the curvature of the ocean was taking place. At 4:20 a.m., three dark lines appeared on the northwest horizon, advancing towards the coast. All that remains of the Pingueral marina is a section of a floating pier which is anchored offshore. All structures and boats are missing. Almost no debris is present on the eastern shore near where the marina used to be.

Near Rio Dichato, there is a stand of mature pine trees. Seaweed was observed hanging from the branches of these trees approximately 6 m above ground level. There were freshly broken branches 7 m above the ground. The seaweed in the trees seems to be a reliable indicator that the water depth was at least 6 m in this area. The tree branches may have been broken by one of the fishing boats washed inland.

On the west side of Dichato there are two 10 story apartment buildings. These buildings incurred no obvious structural damage as shown in the pre and post images in Figure 13.14 and the aerial reconnaissance photo in Figure 13.15. They withstood the earthquake and at least one 3 m wave. Although the first floor apartments and the basement show significant flooding damage, the upper floor apartments were intact and were available to be reoccupied after the residents cleaned up broken items inside them. Behind the 10-story apartment buildings are about a dozen homes and shops which are constructed of lightweight materials, such as wood and corrugated metal. Little damage occurred to these structures suggesting that they may have been sheltered from a direct impact from the tsunami by the 10-story apartment buildings located between them and the bay. A pre and post image pair for the area further to the East of the apartment buildings shows significant damage to smaller structures much further inland (Figure 13.16). Severe damage to homes in central Dichato illustrate the effects of the tsunami with a wave depth of about 5 meters (Figures 13.17 and 13.18).

Sea water surged 2.2 km into the agricultural valley southwest of Dichato as previously shown in Figure 13.19. Several large fishing boats and other vessels remain beached in these fields and farmlands, which are now brown and dead due to salt poisoning.

Residents of Nicochea Beach described the earthquake strong motion as being sufficient to throw objects into the air and break every breakable object in their houses. Across the bay in Pingueral, a survivor of the 1960 earthquake in Valdivia reported that there was no violent motion in the February 27th earthquake, only long, rolling motion. Objects on his kitchen counters remained in place and nothing in his house was broken during the earthquake.

Figure 13.12 Pre/Post Imagery of Dichato (S36.546°, W72.933°)

Figure 13.13 Pre/Post Imagery of Dichato (S36.548°, W72.935°)

Figure 13.14 Pre/Post Imagery of Dichato (S36.548°, W72.942°)

Figure 13.15. Aerial reconnaissance photograph of high-rise apartment buildings (S36.548°, W72.942°)

Figure 13.16 Pre/Post Imagery of Dichato (S36.551° , W72.933°)

Figure 13.17 The home in this picture was lifted by the 3rd wave and dropped onto a tree (S36.547˚, W72.939˚, 2010 hrs, 3/13/10).

Figure 13.18 The tsunami wave removed the lightweight wooden second story of this house from its more substantial masonry and concrete block first floor (S36.546˚, W72.935˚, 2010 hrs, 3/13/10).

13.3.5 Changes in stream channels

The course of the Rio Dichato has been altered as shown in Figure 13.17. Prior to the earthquake, the river meandered through a neighborhood with gardens abutting the river, before exiting to the bay at the east end of town. The tsunami´s greatest water depth -- and presumably the most destructive erosional power -- was in the area of this meander. The tsunami removed the soft sediments that formed a barrier between the river and the bay and the meander has been eliminated. Now, the mouth of the river is about 100 meters southwest of its former location. A delta is forming where a neighborhood used to be. The area of the former river bed is now a low-lying mudflat, which floods at high tide.

There is a lagoon and stream at the north end of Pengueral. The lagoon is separated from the lagoon by a sandbar. During the flooding which occurred from 10:00 to 10:30 a.m., water flowed in and out over the sandbar 3 or 4 times. After the last flood retreated, residents noted that the sandbar had changed shape, with more sand at the southern end. Also in Pengueral, there are five wooden houses which were lifted, with their foundations somewhat intact, and moved several meters towards the east and southeast, parallel to the flooding which surged up the stream valley north of Pingueral.

DICHATO PRE IMAGE (04-25-2006)

DICHATO POST IMAGE (03-05-2010)

Figure 13.17 Pre/Post Imagery of Dichato (S36.541°, W72.933°)

13.4 Curanipe to Constitución

Communities we visited along the coast between Curanipe and Constitución were particularly hard hit by tsunami inundation. At Curanipe two local women we interviewed reported that the tsunami came from the north and noted that much of the sand had been removed from the beach, possibly due to erosion by the tsunami. Emilia Sagado Alveal, a Curinape resident, said she witnessed the first wave arrive about 10 minutes after the earthquake. She remembers three waves in all and the water nearly covered the Roca San Pedro leaving only the cross on top above water (Figure 13.20). Alveal also indicated that geographers from the Universidad de Catolica had surveyed the area and estimated average tsunami wave heights of 6.5 m. Water stains on the wall of a restaurant near the beach indicate that minimum flow depths at this site were about 1 m (Figure 13.21).

At El Torreon, a small beach community south of Pelluhue, the tsunami destroyed a number of houses and caused at least 5 fatalities (Figure 13.22). Witnesses interviewed included Chilean Army Lieutenant Alfredo Diaz and local residents of the community. One resident reported that the earthquake seemed to last for 5 minutes and the first tsunami wave arrived about 30 minutes later at 4:05 am. Some witnesses noted that the ocean did not recede after the earthquake and they assumed no tsunami was coming until the first wave arrived. A total of 7 to 13 waves continued to arrive over the next 4 hours, according to different accounts. The flow depths remained high until 8 am when the water level started to retreat. At one house that partially survived the tsunami, water marks indicate minimum flow depths between 1.6 and 2.2 m (Figure 13.23). The brother of the owner of the house said debris carried by the tsunami broke the windows on the first floor not the wave and also noted that water did not enter the second floor.

In communities between Pelluhue and Constitución , buildings in low-lying areas within a few hundred meters of the coast sustained heavy damage. For example, beach front houses in the small fishing village of Los Pellines were severely impacted as was a derelict wood pulp processing plant in Las Cañas. However, in other areas coastal dunes appeared to present barriers to tsunami inundation preventing more extensive damage. In Reserva Nacional Frederico Albert near Chanco, 3- to 4-m-high dunes on the beach apparently prevented the tsunami from penetrating further inland (Figure 13.24).

We did not conduct detailed surveys of tsunami impacts in Constitución . A rapid tour of the tsunami impacted area by car confirmed reports of extensive damage to the city along the south bank of Rio Maule. We noted high water marks on several buildings in Constitución that suggest minimum tsunami flow depths were near 2 m at sites close to the river (Figure 13.25). Further information on the tsunami impacts at Constitución and tsunami runup estimates, including high resolution inundation maps have been compiled by Armijo et al. (2010).

Figure 13.20. Roca San Pedro, a prominent landmark in Curanipe, was almost entirely submerged by the tsunami says one local resident. Only the cross remained above the water (S35.8436°, W72.6390°, 03/17/2010).

Figure 13.21. Watermarks on a restaurant in Curanipe indicate minimum tsunami flow depths of 1 m at this location (S35.8436°, W72.6365°, 03/17/2010).

Figure 13.22. The blue and white two-story house in the beach community of El Torreon was heavily damaged by the tsunami and all but the walls of the adjacent vacation house was destroyed. The tsunami arrived at 4:05 am, about 30 minutes after the earthquake, and the water remained high for four hours when it started to retreat around 8 am (S35.8215°, W72.5990°, 03/17/2010).

Figure 13.23. On this post inside the first floor of a beach front house in El Torreon, a small community south of Pelluhue, visible lines mark the water height 1.6 m above the ground providing a minimum estimate of the tsunami flow depth at this location (S35.8214°, W72.8215°, ~1556 hrs on 03/17/2010).

Figure 13.24. The tsunami carried wood and debris about halfway up these dunes near Chanco but left the walkway along the dune crest undamaged (S35.739239° W72.571586°, 1829 hrs on 03/17/2010).

Figure 13.25. Watermarks on damaged buildings in Constitución indicate tsunami flow depths reached at least 2 m along the waterfront on Calle Blanco (S35.336 W72.403, 1757 hrs on 03/15/2010).

13.5 Iloca to Bucalemu

Communities between Iloca and Bucalemu may have been more severely impacted by the tsunami because this region of the coast may have dropped vertically during the earthquake (see evidence in Section 4). Evidence of high flow depths comes from debris caught in the railings of a bridge damaged by the tsunami at Pichibudi. A temporary road had been constructed over the river to detour around the bridge. Grass debris in the bridge indicates minimum flow depths of 5.2 m above the river (Figure 13.26). Local residents encountered at the bridge attest the wave topped 6.6 m and report of a bus that was carried 80 m inland.

At Bucalemu we interviewed two men outside of a small market along the front street at the west end of town. The older man said the tsunami consisted of 3 or 4 waves, the first was the largest arriving at 4 am and the water moved back and forth, oscillating in the low valley north of town. The younger man, Carlos, and the woman in the market say the largest wave arrived around 7 am. The older man says the wave came from the north. A slightly different account of events comes from two police officers interviewed in Bucalemu. Both men recount 3 tsunami waves and the largest wave arrived at 4 am, but instead of coming from the north, the wave came from the southwest and flowed into the lagoon and up the river valley. They attest that the largest wave overtopped the rocks where the bridge is located on the beach at Bucalemu.

Bucalemu was clearly harder hit by the tsunami than Pichilemu. Residents say the wave was ~2 m deep in the valley at the river mouth. Flow depth measurements show the highest water levels in the west end of town decreasing toward the east. Damaged siding at a restaurant on the waterfront suggests wave heights of 3.5 m or more near the beach (Figure 13.27). At La Estrella, in a small sandwich shop near the lagoon, water marks on the building and in the interior of the store indicate flow depths of 1.35 to 1.5 m (Figure 13.28). At the east end of Bucalemu, water marks on buildings indicate flow depth of 0.1 m or less near the limit of inundation (Figure 13.29).

At Puente Cahuil, a bridge over Rio Est Nilahue, we investigated tsunami impacts at a campground with small wooden kiosks and a fence that appear to have been moved around by high water. Near the first intact fence and kiosk evidence of high water offers measurements of tsunami flow depth near the probable upper limit of inundation (Figure 13.30). Dead and dried vegetation strewn in wooden lattice fencing along with what appears to be a water mark on the adjacent kiosk indicate water depths of 0.3 to 0.4 m. Between this location and the river, small cabanas or kiosks appear to have been transported ~30 m landward. A yellow metal fence has been pushed over in the direction of a wave flowing inland.

Figure 13.26. Debris clinging to the railing of this damaged bridge in Pichibudi suggests minimum tsunami flow depths reached 5.15 m. Local residents reported flow depths of 6.65 m above the creek. Anecdotal accounts suggest the tsunami moved a bus 80 m up the creek valley. Tsunami damage along coast becomes heavier toward the south of this site in Iloca (S34.880055° W72.155819°, 1515 hrs on 03/15/2010).

Figure 13.27. Damaged siding on this building suggests tsunami flow depths reached at least 3.5 m at the west end of Bucalemu (S34.640097° W72.044194°, 1130 hrs on 03/15/2010).

Figure 13.28. Tsunami flow depths reached a minimum of 1.5 m along the waterfront in Bucalemu (S34.641882° W72.043158°, 1051 hrs on 03/15/2010).

Figure 13.29. Tsunami flow depths at the east end of Bucalemu reached 0.1 m or less near the landward limit of tsunami inundation (S34.642586° W72.037371°, 1228 hrs on 03/15/2010).

Figure 13.30. At Puente Cahuil tsunami flow depths reached a minimum of 0.3 to 0.4 m and pushed kiosks at a campground several tens of meters landward (S34.479276° W72.017610°, 1922 hrs on 03/14/2010).

13.6 Pichilemu

The impact of the tsunami in Pichilemu was considerably less relative to the severe damage observed at locations to the south. Residents report that at least 3 waves arrived beginning about 10 minutes after the earthquake. The first two waves were slow rises of water level, the third wave was the largest. Other witnesses noted that there was no receding wave at Playa Hermosa and Playa Infernio. The tsunami did fill a small lagoon north of Pichilemu, evident as you enter the town, then the water flowed out. Debris dangling from limbs of trees east of the lagoon indicate minimum flow depths of 2.5 to 3 m (Figure 13.31). Tracing the wrack line of debris inland showed that tsunami inundation in the lagoon extended several hundred meters east of the beach (Figure 13.32).

North of town, we encountered a surfer and two friends walking along a street near the western margin of a lagoon. Inundation by the tsunami at this site was evident as a wrack line, or line of debris chiefly composed of dried reeds from the marsh in the nearby lagoon to the west. The surfers recalled the first wave arrived at about 4 am and approached from north to south. They remember several waves arriving between 4 am and 7 am.

The daughter in law of the owner of Cabanas Gusman-Lyon testified that the height of the first wave reached about 1.5 m high on a chain-link fence near the beach and about the same height in a small shed a few meters away (Figure 13.33). She said the first wave arrived between 3:30 and 4 am in the morning.

Our interviews with people in Pichilemu and elsewhere converged on a common theme: the wave came from the north and traveled to the south. After talking with multiple (3 to 4) witnesses with consistent accounts, it appears that along this part of the coastline the tsunami had a directionality and approached the shore from the north. One man said the wave struck the large rocks at the tip of Punta del Lobos. Other witnesses interviewed at Punta del Lobos attest that the tsunami overtopped the sea stacks, which from the overlook at the point appear to be about 15 m above sea level.

Figure 13.31. Debris suspended in trees along a lagoon north of Pichilemu indicate tsunami flow depths exceed 3 m at this site (S34.385195° W71.999901°, 1619 hrs on 03/14/2010).

Figure 13.32. Tsunami inundation north of Pichilemu was restricted to a small coastal lagoon, leaving stems of reeds, trash and other debris near the landward limit of inundation. The “wrack line” of debris indicates the tsunami reached the fence in the distance but probably did not overtop the higher ground in the right of the photo (S34.384558° W71.996936°, 1631 hrs on 03/14/2010).

Figure 13.33. Below Cabanas Gusman-Lyon, a local lodging along the water front in Pichimelu, tsunami flow depths reached about 1.5 m, destroyed a wooden fence (in this photo the fence has been replaced by a new one) and washed away cars in the parking area (S34.384288° W72.003774°, 1711 hrs on 03/14/2010).