![USGS science for a changing world]

Geological Impacts and Sedimentary Record of the February 27, 2010, Chile Tsunami—La Trinchera to Concepcion

Open-File Report 2010–1116

U.S. Department of the Interior
U.S. Geological Survey

Geological Impacts and Sedimentary Record of the February 27, 2010, Chile Tsunami—La Trinchera to Concepcion

By United States and Chile International Tsunami Survey Team (ITST):

Robert A. Morton, Mark L. Buckley, Guy Gelfenbaum, Bruce M. Richmond,

Adriano Cecioni, Osvaldo Artal, Constanza Hoffmann, and Felipe Perez

Open-File Report 2010–1116

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia 2010

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Morton, R.A., Buckley, M.L., Gelfenbaum, G., Richmond, B.M., Cecioni, A., Artal, O., Hoffman, C., and Perez, F., 2010, Geological impacts and sedimentary record of the February 27, 2010, Chile tsunami; La Trinchera to Concepcion: U.S. Geological Survey Open-File Report 2010-1116, 22 p. [http://pubs.usgs.gov/of/2010/1116/].

FRONT COVER: Photograph of trees with broken limbs showing the height of the tsunami at Constitucion, Chile

Contents

Figures

Table

Geological Impacts and Sedimentary Record of the February 27, 2010, Chile Tsunami—La Trinchera to Concepcion

By United States and Chile International Tsunami Survey Team (ITST):
Robert A. Morton[1], Mark Buckley[2], Guy Gelfenbaum[3], Bruce M. Richmond[2], Adriano Cecioni[4], Osvaldo Artal[4], Constanza Hoffmann[4], and Felipe Perez[4]

[1]U.S. Geological Survey, Austin, TX., U.S.A.
[2]U.S. Geological Survey, Santa Cruz, CA., U.S.A.
[3]U.S. Geological Survey, Menlo Park, CA., U.S.A.
[4]Universidad de Concepcion, Concepcion, Chile

Summary

The February 27, 2010, Chilean tsunami substantially altered the coastal landscape and left a permanent depositional record that may be preserved at many locales along the central coast of Chile. From April 24 to May 2, 2010, a team of U.S. Geological Survey (USGS) and Chilean scientists examined the geological impacts of the tsunami at five sites along a 200-km segment of coast centered on the earthquake epicenter. Significant observations include: (1) substantial tsunami-induced erosion and deposition (+/- 1 m) on the coastal plain; (2) erosion from return flow, inundation scour around the bases of trees, and widespread planation of the land surface; (3) tsunami sand deposits at all sites that extended to near the limit of inundation except at one site; (4) evidence of multiple strong onshore waves that arrived at different times and from different directions; (5) vegetation height and density controlled the thickness of tsunami deposits at one site, (6) the abundance of layers of plane-parallel stratification in some deposits and the presence of large bedforms at one site indicated at least some of the sediment was transported as bed load and not as suspended load; (7) shoreward transport of mud boulders and rock cobbles where they were available; and (8) the maximum tsunami inundation distance (2.35 km) was up an alluvial valley.

Most of the tsunami deposits were less than 25 cm thick, which is consistent with tsunami-deposit thicknesses found elsewhere (for example, Papua New Guinea, Peru, Sumatra, Sri Lanka). Exceptions were the thick tsunami deposits near the mouths of Rio Huenchullami (La Trinchera) and Rio Maule (Constitucion), where the sediment supply was abundant. The substantial vertical erosion of the coastal plain at Constitucion and La Trinchera also indicates that the flow was accelerating as it crossed the shore.

Introduction

On February 27, 2010, a magnitude 8.8 earthquake offshore of the central coast of Chile generated a series of tsunami waves that inundated more than 550 km of the shore. In response to requests for assistance from the Chilean government through UNESCO, the U.S. Geological Survey (USGS) sent a team of scientists to collaborate with Chilean scientists in investigating the geological impacts of the tsunami. The purpose of the 10-day trip (April 24–May 2) was to better understand the 2010 event and to provide information for improved modeling and prediction that can be used to mitigate loss of life and damage from future events. Principal in-country support was provided by Dr. Adriano Cecioni and students from the Universidad de Concepcion.

The central coast of Chile is a structurally controlled shore with variable alignments consisting of rocky headlands and adjacent arcuate segments or embayments with sand beaches that are intersected by river mouths with associated alluvial valleys. Most of the coastal towns and villages are constructed on coastal plains near the river mouths or along the coast on shore-adjacent uplifted terraces. Tsunami runup elevations and morphological impacts were highly variable over short alongshore distances as a result of alongshore variations in the tsunami wave heights, offshore bathymetry, shoreline orientations, and topography. The highest measured runup elevations typically were associated with steep slopes where beaches were narrow or absent, and lower runup elevations generally were reported where beaches and the adjacent coastal plains were broad and elevations were low.

The USGS team selected five sites for comprehensive investigation along a 200-km segment of coast that included diverse geological settings (delta plain, deeply embayed alluvial valley, coastal plain near river mouth) both north and south of the earthquake epicenter (fig. 1). All of the sites were selected because their geological settings made them efficient catchments for tsunami deposits and therefore excellent recorders of the 2010 tsunami and potential recorders for past extreme events. Long segments of the central coast of Chile are backed by rocky shores or uplifted terraces that have steep nearshore slopes. Detailed observations of tsunami impacts were not made at either of these settings because they would not be likely sites for preserving tsunami deposits. At four of the five sites studied, detailed measurements were made of topography, flow depths, flow directions and flow direction histories, inundation distances, vertical erosion, and sediment deposition (table 1). The measurements were made in a manner consistent with data collected by USGS scientists during previous post-tsunami surveys, such as those conducted in Papua New Guinea after the 1998 event (Gelfenbaum and Jaffe, 2003), in Peru after the 2001 event (Jaffe and others, 2003), in Sri Lanka and Sumatra after the 2004 event (Gelfenbaum and others, 2007; Jaffe and others, 2006; Moore and others, 2006), and in American and Western Samoa after the 2009 event (Jaffe and others, 2010).

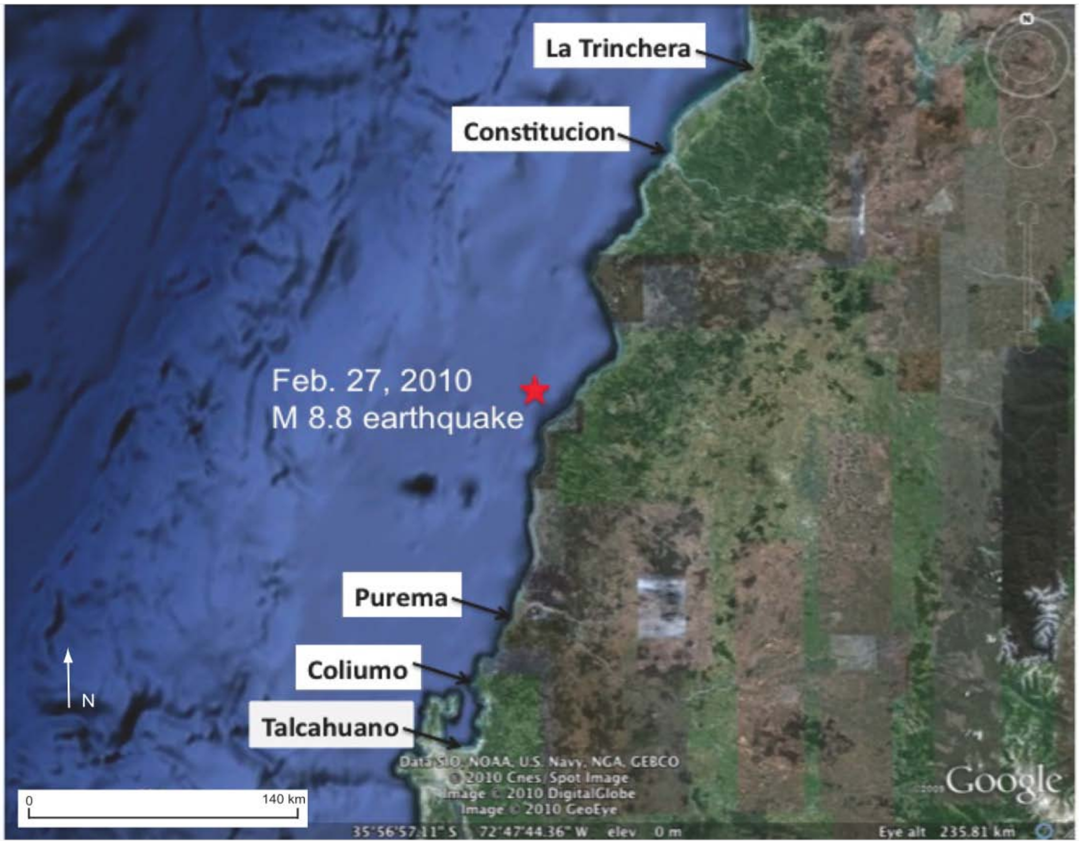

Figure 1. Google Earth image showing the general locations of the five study sites on the Chilean coast and the location of the earthquake epicenter.

Table 1. Summary of the number and magnitude of parameters measured at the five central Chile tsunami study sites.

Location	La Trinchera	Constitucion	Purema	Coliumo	Talcahuano
General latitude	35.1077S	35.3063S	36.4463S	36.5569S	36.7353S
General longitude	72.2013W	72.3987W	72.8834W	72.9563W	73.0526W
Area surveyed (km^2)	0.2	1.4	0.25	0.9	0.25
Flow depth measurements	13	42	17	41	7
Maximum flow depth (m)	5.5	8.8	5.6	7.0	3.8
Flow directions measured	26	183	1	3	3
Inundation distance (m)	1,020	1,050	1,100	2,350	550
Topographic profiles	8	13	0	9	6
Max. vertical erosion (cm)	120	110	80	150	160
Trenches measured	9	14	4	35	16
Trenches sampled	4	6	2	7	7
Deposit thickness range (cm)	1-40	3-93	5-15	1-20	2-25
Maximum boulder size (cm)*	14x9x7	107x62x29	60x35x30	75x65x15	70x70x30

*Dimensions are for mud boulders except for rock boulders at Coliumo.

Observations

The five sites studied are described in geographic order from north to south. The general geologic setting is summarized and features, including human modifications, that could influence the morphological impacts, magnitudes of erosion and deposition, or the flow, are noted. Also included are statements indicating the important scientific findings at each study site.

La Trinchera

Geologic Setting.—A coastal plain downdrift (north) of the Rio Huenchullami, a moderately large river that supplies abundant sand to the littoral system, as indicated by the large dune fields to the north and south. The gently curved shoreline is exposed to the Pacific Ocean to the west. Before the tsunami, there was a broad subaerial sand bar and narrow lagoon that were an alongshore extension of the river mouth and minor interior drainage. After the tsunami, the bar was severely eroded (fig. 2) and its sand was redistributed. A low ridge of sand covered by trees before the tsunami formed the highest elevations near the shore. Landward of the ridge was a relatively broad coastal plain with low elevations and slope.

Human Modifications.—The coastal plain surface was transected by an elevated paved road, and the foundations of a few destroyed houses were located seaward of the road.

Significant Observations.—The superposition of bent but still rooted trees, bushes, and grass, plus the distribution of trapped debris, indicated multiple strong onshore flows from waves approaching from different directions (fig. 3). An eyewitness interviewed by another team reported that the first wave came from the west, whereas a later wave came from the southwest (Patricio Winckler, oral commun., 2010). The flow-direction history derived from superposition of bent vegetation is consistent with the eyewitness account. An extremely large volume of sand was eroded from the subaerial sand bar, greatly reducing its width. After the tsunami, the shoreline was located near the former seaward edge of the lagoon. Trees along a low sand ridge were excavated around the roots and removed from the ridge, leaving an irregular erosional scarp on the landward side of the ridge (fig. 4). The limit of inundation was on a low slope near the landward margin of the coastal plain. The inland limit of sand deposition was substantially less than the limit of tsunami inundation.

Figure 2. Post-tsunami oblique photograph of the La Trinchera study site taken on April 5, 2010, by the UNESCO team.

Figure 3. Sequential flow directions (red arrows) at La Trinchera indicate multiple strong onshore flows from waves approaching from different directions. View toward the east

Figure 4. Landward side of a coastal dune ridge at La Trinchera, showing the erosional scarp left after the tsunami removed entire trees from the ground, leaving only a few roots as evidence. Maximum vertical erosion of the surface was 1.2 m.

Constitucion

Geologic Setting.—The mouth and delta plain of Rio Maule (fig. 5), where sediment supply was abundant. Prominent morphological features included a broad gravel and sand beach, a wide ramp that was covered with planted trees before the tsunami, and, farther inland, vegetated sand-dune ridges forming the highest elevations near the shore.

Human Modifications.—An oval mound 200 m across and 10 m high of waste products from lumber processing locally altered the tsunami inundation and return-flow directions. A landing strip and tree farm near the limit of inundation did not appear to significantly alter the flow.

Significant Observations.—Flow-direction indicators show that tsunami flow patterns were complex and included strong onshore flow from multiple waves (fig. 6). There were large changes in land elevation due to vertical erosion (110 cm maximum, fig. 7) and deposition (93 cm maximum, fig. 8). Mud boulders, as large as 70 cm in diameter, were excavated and deposited inland more than 350 m from the shore. A broad zone of sand deposition extended inland to the limit of tsunami inundation. Where it was unprotected by vegetation, eolian processes were modifying the surface of the tsunami sand deposit. Sedimentary structures in a small field of large (6 to 8 meter wavelength) low-amplitude bedforms were constructed on the northern margin of a low ridge, indicating that some deposition occurred during the return flow. The basal contact of the tsunami deposit was variable and at some trenches included delta-plain mud and at others a soil with in-place grass. The limit of inundation was influenced by steep slopes and dense vegetation, with the greatest inundation limit near the landing strip where there were no dunes. The tsunami destroyed planted areas of eucalyptus and pine trees that occupied much of the area seaward of the sand-dune ridges (figs. 6, 7, and 9).

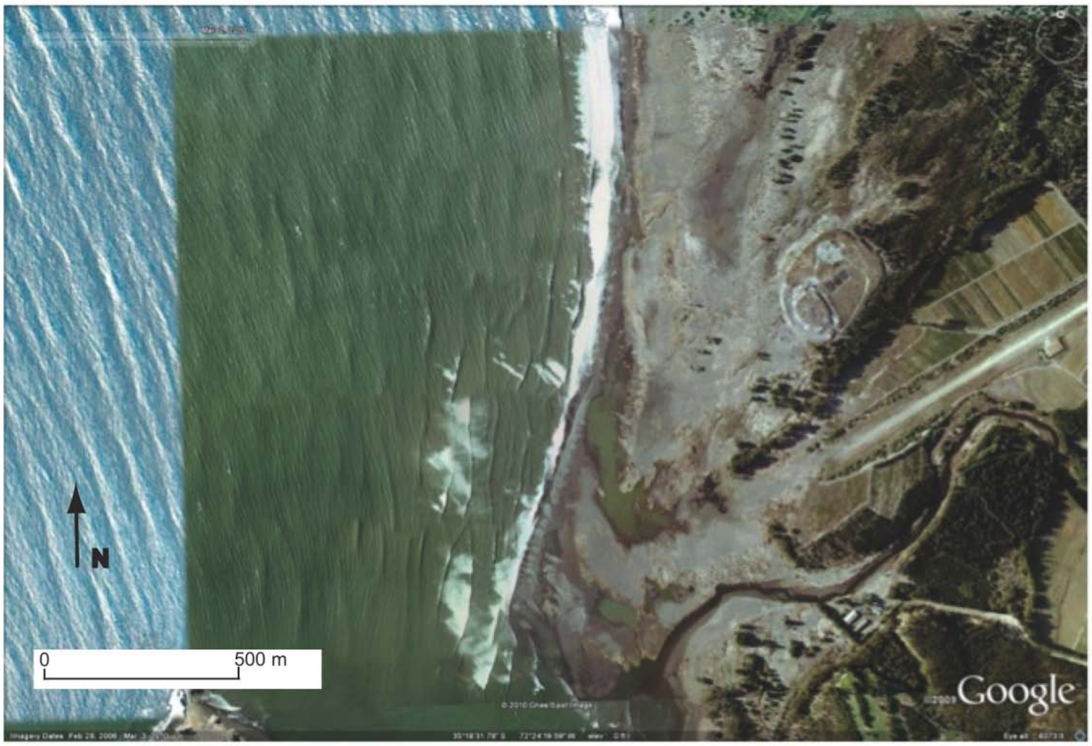

Figure 5. Google Earth image of the Constitucion study site near Rio Maule taken 3 days after the tsunami.

Figure 6. Field evidence at Constitucion indicates flow during multiple waves approaching from different directions. View is toward the northeast.

Figure 7. Exposed roots of this former pine tree show that the tsunami caused at least 110 cm of vertical erosion of the coastal plain at Constitucion.

Figure 8. Tsunami sand and cobble deposit 73 cm thick at Constitucion.

Figure 9. Splintered stumps of planted eucalyptus and pine trees destroyed by the tsunami at Constitucion. View is south toward the mouth of Rio Maule.

Purema

Geologic Setting.—A coastal embayment and pocket beach bounded by rocky headlands and fronting an alluvial valley that is partly filled by a small meandering stream (fig. 10).

Human Modifications.—An elevated road with a small bridge crossed the valley. Several buildings near the shore were destroyed. Post-tsunami plowing of a field inland from the road prevented establishing the inland limit of sand deposition.

Significant Observations.—There was a broad zone of beach and coastal plain erosion extending inland from the shore (fig. 10). Sand deposits near the inland limit of erosion were relatively thick (15 cm, fig. 11). The tsunami deposits contained multiple layers of laminated sand with both coarse and fine textures (fig. 11). The surface of the tsunami deposit was unprotected and undergoing modification by eolian processes driven by strong winds. The limit of tsunami inundation was on a low gradual slope.

Figure 10. Post-tsunami oblique photograph of the Purema study site taken on April 5, 2010, by the UNESCO team.

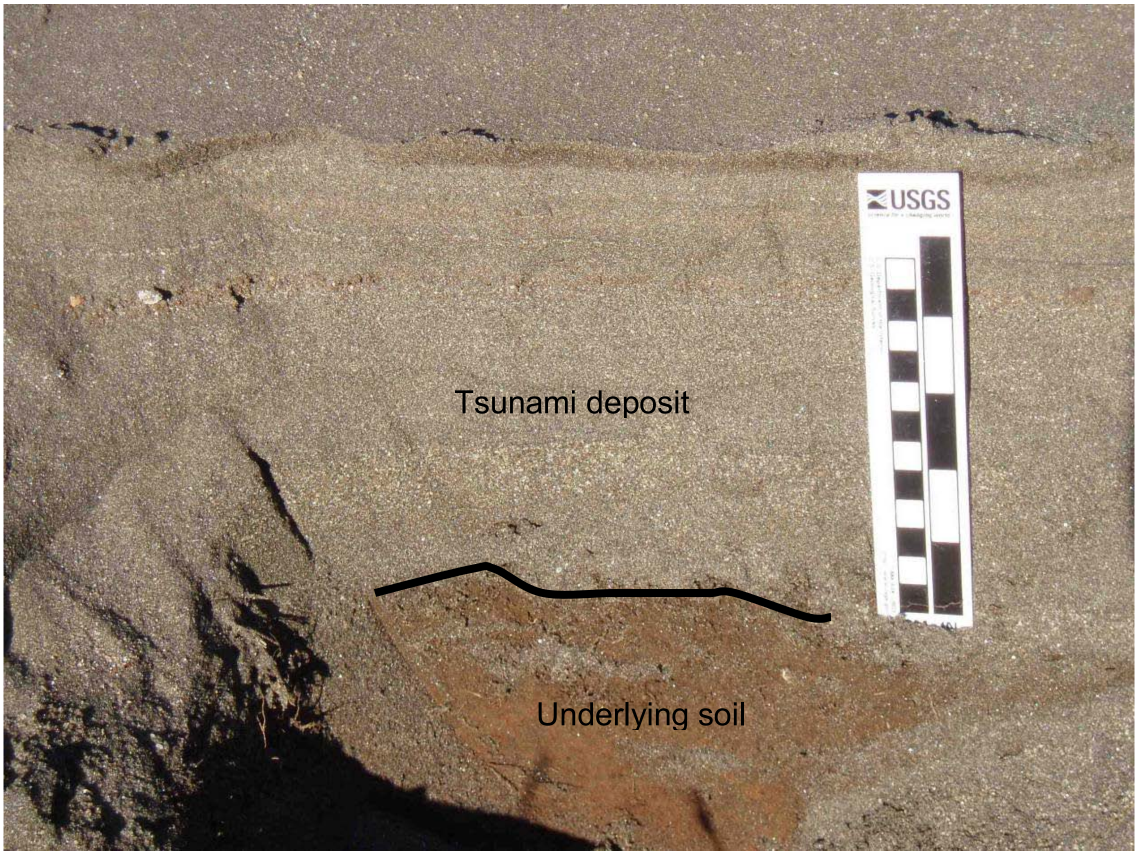

Figure 11. Laminated tsunami sand deposit 15 cm thick at Purema consisting of alternating coarser and finer layers.

Coliumo

Geologic Setting.—A moderately deep coastal embayment containing a pocket beach bounded by rocky headlands and fronting an alluvial valley that is partly filled by a small river (fig. 12).

Human Modifications.—A low road transected the valley, and a few houses constructed on the margin of the valley floor were destroyed. The area was used to graze cattle, and strips of the land had been cultivated.

Significant Observations.—Considering the flow depths and extent of inundation, an exceptionally large volume of water must have flooded into the valley, perhaps influenced by moderate water depths within the embayment. Flow directions were steered primarily by the valley topography, with the tsunami floodwaters returning seaward down the laterally confined valley. The limit of tsunami inundation along the margin of the valley was partly controlled by the increased slope. The furthest extent of tsunami inundation was 2.35 km from the shoreline. At least three large boats from the harbor were carried inland by the tsunami and grounded after the tsunami retreated. Horizontal erosion of the coastal plain near the shore was substantial and highly irregular, as indicated by the post-tsunami morphology and comparison with pre-tsunami images. Thicknesses of the tsunami sand deposits were partly controlled by vegetation density and flow depth. In general, sand was thinner where vegetation was low or sparse (fig. 13*A*) and thicker where vegetation was high and dense (fig. 13*B*). Also, sand thicknesses increased along the valley margin, where flow depths decreased and flow decelerated. Sand deposits extended inland to near the limit of inundation. Major bank failure along the small river increased the stream width (fig. 14) and, in conjunction with the tsunami removing failed banks, altered the channel morphology (width/depth ratio).

Figure 12. Pre-tsunami Google Earth image of the deeply embayed Coliumo study site. The open coast is approximately 3 km to the north-northeast of the top of the figure.

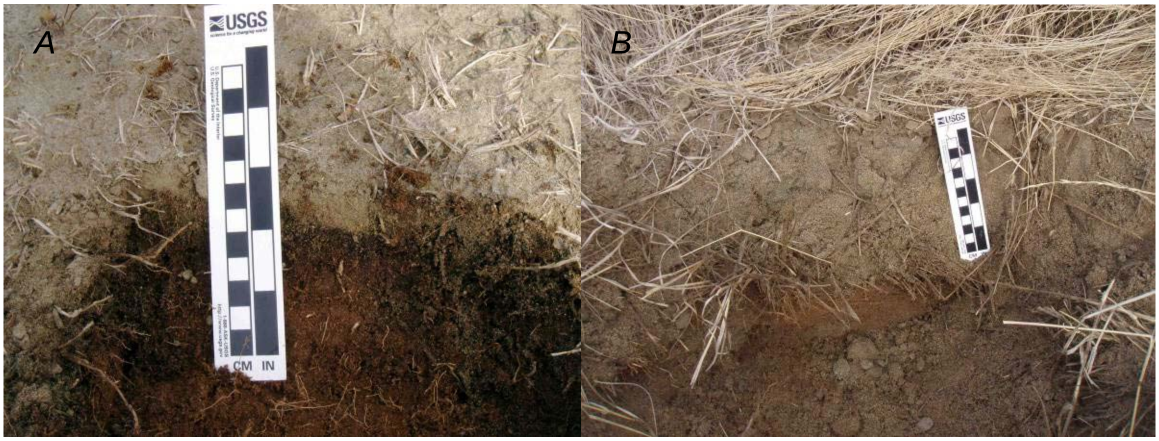

Figure 13. Comparison of thicknesses of tsunami sand deposited in (*A*) low, thin, sparse, vegetation and in (*B*) tall, thick clumps of dense vegetation at the Coliumo site.

Figure 14. Bank failure abruptly widened the small river at Coliumo.

Talcahuano

Geologic Setting.—A large, low-energy embayment (Bahia de Concepcion) and inactive delta plain of the Rio Bio-Bio.

Human Modifications.—An unpaved road and landfill where the dunes would naturally form at the shore artificially increased elevations, partly blocking the tsunami inundation and increasing the depth of channel incision by the return flow (figs. 15 and 16). An elevated roadway (fig. 15) caused a flow disturbance, possibly a hydraulic jump on the landward side, that scoured a road-parallel trench that was the source of mud boulders deposited in the adjacent marsh (fig. 17).

Significant Observations.—An erosional scarp formed along the dune/unpaved road berm, but retreat of the shoreline was not significant. The headward erosion of the return-flow channels (fig. 16) extended landward about 100 m from the shore. At the time of field observations, the small ebb deltas deposited at the mouths of the return-flow channels (fig. 15) were being reworked and eliminated by normal wave action in Bahia de Concepcion. Landward of the artificial berm was a broad zone of thin sand deposits that coincided with a prior overwash zone. The thickest tsunami sand deposits were landward of the elevated roadway, and sand deposits extended to near the limit of inundation. Some cobbles were transported far inland and deposited on the marsh vegetation of the pre-tsunami surface and at the base of the tsunami sand deposit (fig. 18).

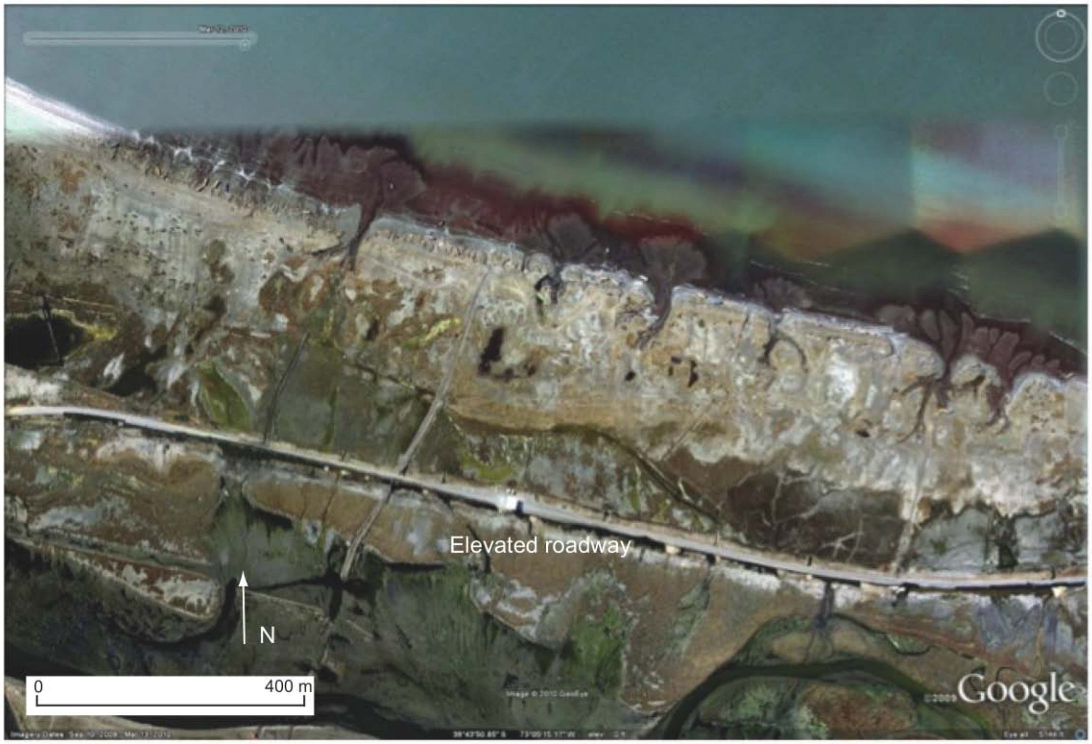

Figure 15. Google Earth image of the Talcahuano study site taken 13 days after the tsunami. Note large return-flow incised channels and ebb-flow deltas.

Figure 16. Inland limit of erosion of return-flow incised channel at Talcahuano.

Figure 17. Field of small mud boulders at Talcahuano excavated from a scour trough on the landward side of the elevated highway (out of view to the rear). The trough was eroded by accelerated flow over the roadway during tsunami inundation. View looking inland.

Figure 18. Tsunami deposit at Talcahuano 24 cm thick, consisting of sand with cobbles at the base, overlying the grass and soil of the pre-tsunami surface (trowel).

Acknowledgements

We thank Bruce Jaffe and Alex Apostos, who reviewed the draft manuscript and provided helpful suggestions that improved the clarity of the report. Betsy Boynton and Steve Watt assisted by formatting the report for publication.

References Cited

Gelfenbaum, G., and Jaffe, B., 2003, Erosion and sedimentation from the 17 July 1998 Papua New Guinea tsunami: Pure and Applied Geophysics, v. 60, no. 10-11, p. 1969-1999.

Gelfenbaum, G., Vatvani, D., Jaffe, B., and Dekker, F., 2007. Tsunami inundation and sediment transport in vicinity of coastal mangrove forest: Proceedings of Coastal Sediments 07, May 2007, New Orleans, La., p. 1117-1128.

Jaffe, B., Gelfenbaum, G., Rubin, D., Peters, R., Anima, R., Swensson, M., Olcese, D. Bernales L., Gomez, J., and Riega, P., 2003, Tsunami deposits; identification and interpretation of tsunami deposits from the June 23, 2001 Peru tsunami, *in* Proceedings of the International Conference on Coastal Sediments 2003: CD-ROM published by World Scientific Publishing Corp and East Meets West Productions, Corpus Christi, Texas, U.S.A. ISBN 981-238-422-7, 13 p.

Jaffe, B.E., Borrero, J.C., Prasetya, G.S., Dengler, L., Gelfenbaum, G., Hidayat, R., Higman, B., Kingsley, E., Lukiyanto, McAdoo, B., Moore, A., Morton, R., Peters, R., Ruggiero, P., Titov, V., Kongko, W., and Yulianto, E., 2006, The December 26, 2004 Indian Ocean tsunami in northwest Sumatra and offshore islands: Earthquake Spectra, v. 22, no. S3, p. S105-S136.

Jaffe, B.E., Gelfenbaum, G., Buckley, M.L., Watt, S., Apotsos, A., Stevens, A.W., and Richmond, B.M., 2010, The limit of inundation of the September 29, 2009, tsunami on Tutuila, American Samoa: U.S. Geological Survey Open-File Report 2010-1018, 27 p.

Moore, A., Nishimura, Y., Gelfenbaum, G., Kamataki, T., and Triyono, R., 2006, Sedimentary deposits of the 26 December 2004 tsunami on the northwest coast of Aceh, Indonesia: Earth, Planets, and Space, v. 58, p. 253-258.