

## Geology

### Five centuries of tsunamis and land-level changes in the overlapping rupture area of the 1960 and 2010 Chilean earthquakes

Lisa L. Ely, Marco Cisternas, Robert L. Wesson and Tina Dura

*Geology* published online 26 September 2014;  
doi: 10.1130/G35830.1

---

#### Email alerting services

click [www.gsapubs.org/cgi/alerts](http://www.gsapubs.org/cgi/alerts) to receive free e-mail alerts when new articles cite this article

#### Subscribe

click [www.gsapubs.org/subscriptions/](http://www.gsapubs.org/subscriptions/) to subscribe to *Geology*

#### Permission request

click <http://www.geosociety.org/pubs/copyrt.htm#gsa> to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

---

#### Notes

---

Advance online articles have been peer reviewed and accepted for publication but have not yet appeared in the paper journal (edited, typeset versions may be posted when available prior to final publication). Advance online articles are citable and establish publication priority; they are indexed by GeoRef from initial publication. Citations to Advance online articles must include the digital object identifier (DOIs) and date of initial publication.

---



# Five centuries of tsunamis and land-level changes in the overlapping rupture area of the 1960 and 2010 Chilean earthquakes

Lisa L. Ely<sup>1</sup>, Marco Cisternas<sup>2</sup>, Robert L. Wesson<sup>3</sup>, and Tina Dura<sup>4\*</sup>

<sup>1</sup>Department of Geological Sciences, Central Washington University, Ellensburg, Washington 98926-7418, USA

<sup>2</sup>Escuela de Ciencias del Mar, Pontificia Universidad Católica de Valparaíso, 1020 Valparaíso, Chile

<sup>3</sup>U.S. Geological Survey, Denver, Colorado 80225-0046, USA

<sup>4</sup>Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

## ABSTRACT

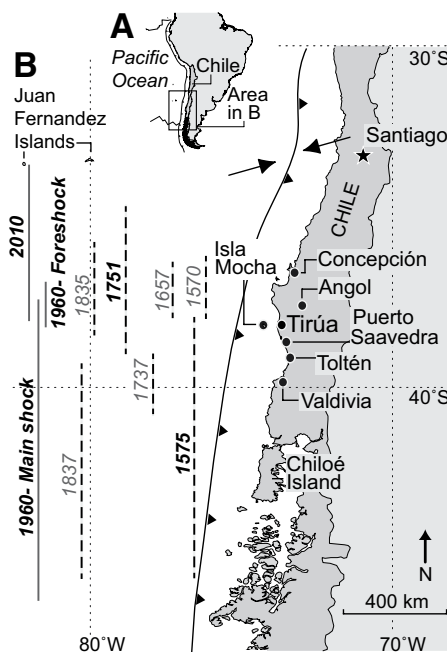
A combination of geological and historical records from south-central Chile provides a means to address general questions about the stability of megathrust rupture patches and the range of variation expected among earthquakes and tsunamis along a particular stretch of a subduction zone. The Tirúa River estuary (38.3°S) records four large tsunamis and coseismic land-level changes over the past 450 years within the overlapping rupture zones of the great subduction-zone earthquakes of A.D. 1960 ( $M_w$  9.5) and 2010 ( $M_w$  8.8). Sand layers 2 km up the Tirúa River represent the 2010 and 1960 tsunamis and two historical tsunamis, most likely in A.D. 1751 and 1575. Differing land-level changes during these earthquakes likely denote differences in the spatial distribution of slip on the megathrust in both the strike and dip directions within the overlapping rupture zone, with the uplift at Tirúa in 1751 and 2010 probably caused by slip extending farther landward and to greater depth than in 1575 and 1960, which showed subsidence or little change.

## INTRODUCTION

One of the most difficult issues in earthquake science is understanding the millennial-scale stability of megathrust rupture patches and the range of variation expected among earthquakes occurring along a particular stretch of a subduction zone. Although geologic data and historical observations of earthquakes are often sparse and irregular in their distribution, they provide critical constraints and essential clues to address the accuracy and completeness of historical accounts as well as variations in the timing, location, and distribution of slip among successive great earthquakes in both the strike and dip directions. Understanding these variations provides a basis for establishing more realistic error bounds in estimating the hazards from great earthquakes and tsunamis.

Tirúa, in south-central Chile (38.3°S), lies at the boundary of multiple subduction-zone earthquakes and tsunamis (Fig. 1). The  $M_w$  8.8 Maule earthquake on 27 February 2010 was the most recent great earthquake to strike south-central Chile (Vigny et al., 2011; Moreno et al., 2012), triggering a tsunami that inundated almost 1000 km of coastline with run-up heights exceeding 20 m in places (Fritz et al., 2011; Vargas et al., 2011). The 2010 rupture overlapped with the northern portion of the rupture zone of the giant ( $M_w$  9.5) Chilean earthquake of A.D. 1960 (Cifuentes, 1989). Few subduction zones worldwide offer both written and geological evidence for repeated overlap of the fault-rupture areas of great thrust earthquakes; the record at Tirúa

\*Current address: Sea Level Research, Rutgers University, 71 Dudley Road, New Brunswick, New Jersey 08901, USA



**Figure 1. Location map of Chilean sites mentioned in text and extent of historic subduction-zone ruptures. Solid lines show A.D. 1960 and 2010 ruptures; dashed lines show estimated rupture lengths based on historical accounts.**

allowed us to investigate long-term patterns in subduction-zone slip distribution, vertical displacement, and tsunami deposits.

The geological evidence of tsunami inundation and seismic land-level changes at Tirúa provides a means to differentiate the relative impacts of the historical earthquakes in the region. Pre-1960 documents from the region tell of several

large subduction-zone earthquakes and tsunamis since A.D. 1570 (Fig. 1; Lomnitz, 2004), but variations in the quality and distribution of the accounts introduce uncertainty into estimates of their relative magnitude and extent. In addition to preserving valuable information about the tsunamis, the tsunami deposits mark the stratigraphic horizons that coincide with great subduction-zone ruptures. The 2010 and 1960 earthquakes, as well as earlier events, show stratigraphic evidence of different directions of coseismic land-level changes at the study site, likely owing to differences in the spatial distribution of slip on the megathrust in the rupture zone beneath Tirúa.

## METHODS

We combined geological and historical records to compare the effects of the well-documented earthquakes and tsunamis in 1960 and 2010 with events of the past 450 years. Field work was conducted up to one month before the 2010 earthquake and tsunami and resumed two weeks afterward. The stratigraphy was documented at 27 sections along the river bank, five inland pits, and ten coring transects (Fig. 2; Fig. DR1 in the GSA Data Repository<sup>1</sup>). Methods for grain-size distribution, diatom analyses and radiocarbon and optically stimulated luminescence (OSL) dating are described in the Data Repository. Calculations of coseismic uplift during the 2010 earthquake were based on surveys of relative tidal levels in the Tirúa River estuary prior to the earthquake, in January 2010, and afterward in 2012 and 2013 (see the Data Repository).

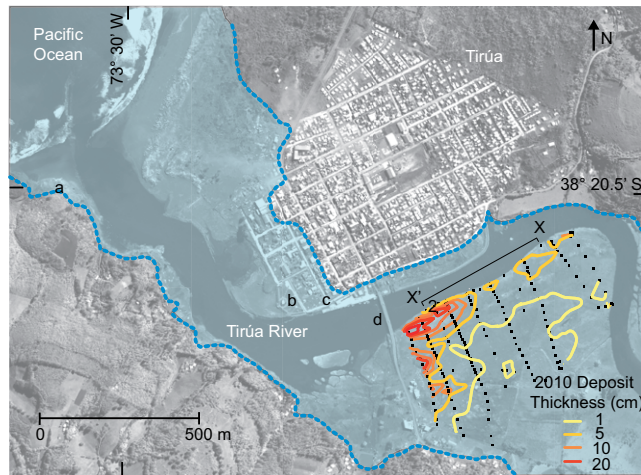
## TSUNAMI DEPOSITS AT TIRÚA

### 2010 Tsunami Deposits

Local residents described dark, sediment-laden water surging at least 3 km up the Tirúa River during the 2010 tsunami. Two weeks later, we surveyed flattened discolored vegetation up to 30 m above mean sea level (amsl) on the steep coastal headland and kelp hanging from electri-

<sup>1</sup>GSA Data Repository item 2014349, methods for determining ages, changes in relative MSL and slip distributions, supplementary photographs, stratigraphic descriptions, diatom identifications, and translations of historical documents, is available online at [www.geosociety.org/pubs/ft2014.htm](http://www.geosociety.org/pubs/ft2014.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

**Figure 2.** Tirúa, Chile, study site and isopach map of the A.D. 2010 tsunami sand layer. Dashed blue line shows upper limit of evidence for tsunami inundation. Evidence of 2010 tsunami mentioned in text: a—high-water marks 20–30 m above mean sea level (amsl) on headland; b—kelp 9 m amsl in town square (flow depth ~7 m); c—Astorga house that survived the A.D. 1960 tsunami, but was destroyed in 2010; d—bridge 1.3 km inland. X-X'—stratigraphic transect along the river bank in Figure 4; 2—stratigraphic section 2 where samples were collected for diatoms and grain size (Fig. 3; Figs. DR5 and DR7 [see footnote 1]). Black dots show core measurement sites for isopach map. Satellite image acquired 2 April 2010, copyright 2010 Digital Globe, NextView.

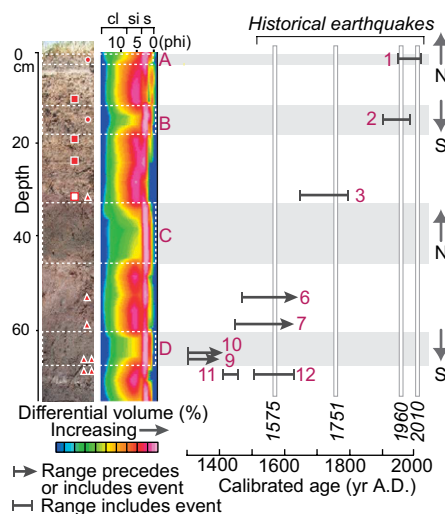


cal poles in the Tirúa town square 1 km inland at an elevation of 9 m amsl (Fig. 2). The latter translates to a minimum flow depth of ~7 m at our study site. Marine shells, barnacle-covered boulders, large stumps and logs, and >50-cm-diameter rocks from a bridge abutment 1.3 km upstream of the river mouth were strewn across the floodplain upstream of the bridge (Fig. DR2).

The incoming tsunami flowed across the floodplain, and the backflow mainly drained down the river channel. Vegetation on the floodplain south of the river was flattened in an up-valley direction (Fig. DR3). Local resident Don René Manríquez saw and heard the water flowing from the floodplain into the channel “like a cascade” as the tsunami receded. The tsunami blanketed the floodplain with fine- to medium-grained gray sand up to 2 km inland. The thickness of the deposit, while variable, generally decreases both upstream and away from the river channel, from an observed maximum of 32 cm near the south end of the bridge (Fig. 2). The 2010 sand layer is mainly massive, with occasional weak, 1-cm-scale horizontal bedding. The sand layer gradually thins until it becomes indistinguishable from the preexisting soil 130–300 m south of the river bank.

### Older Sand Layers

Three additional prominent sand layers are interbedded with silty floodplain sediment stratigraphically below the 2010 tsunami deposit along the south bank of the Tirúa River (Figs. 3 and 4; Figs. DR4 and DR5). We ascribe sands B, C, and D to tsunamis based on the notable similarities they share with the 2010 tsunami deposit (sand A) and with tsunami deposits described elsewhere (Bourgeois, 2009). All four layers are composed of gray, well-sorted, rounded, medium-grained sand that contrasts sharply with the intervening tan silt laminae



**Figure 3.** Stratigraphic column, grain-size distribution, and  $^{137}\text{Cs}$ , optically stimulated luminescence (OSL), and radiocarbon samples constraining age ranges of sand layers A–D on the Tirúa River bank (Chile): A = A.D. 2010; B = A.D. 1960; C = A.D. 1640–1800; D = A.D. 1500–1630. Triangles are  $^{14}\text{C}$  samples, circles are OSL samples, and filled/open red squares represent detection/non-detection of  $^{137}\text{Cs}$ . Numbered samples correspond to Figure 4 and Table DR1 (see footnote 1). Arrows represent minimum age constraint; bars represent age coincident with deposition.  $\uparrow\text{N}$  and  $\downarrow\text{S}$  = vertical displacement and rupture to north (N) or south (S) of Tirúa for each earthquake. Differential volume is the percentage of total volume in each grain-size class; cl—clay, si—silt, s—sand.

(1–2 mm) and organic-rich layers. The sand layers were traced for 700 m along the river bank, where they are generally tabular and range in thickness from 1 to 10 cm. Like the 2010 tsunami deposit, they pinch out 2 km upstream of the river mouth (Fig. 2). The thickest patches of

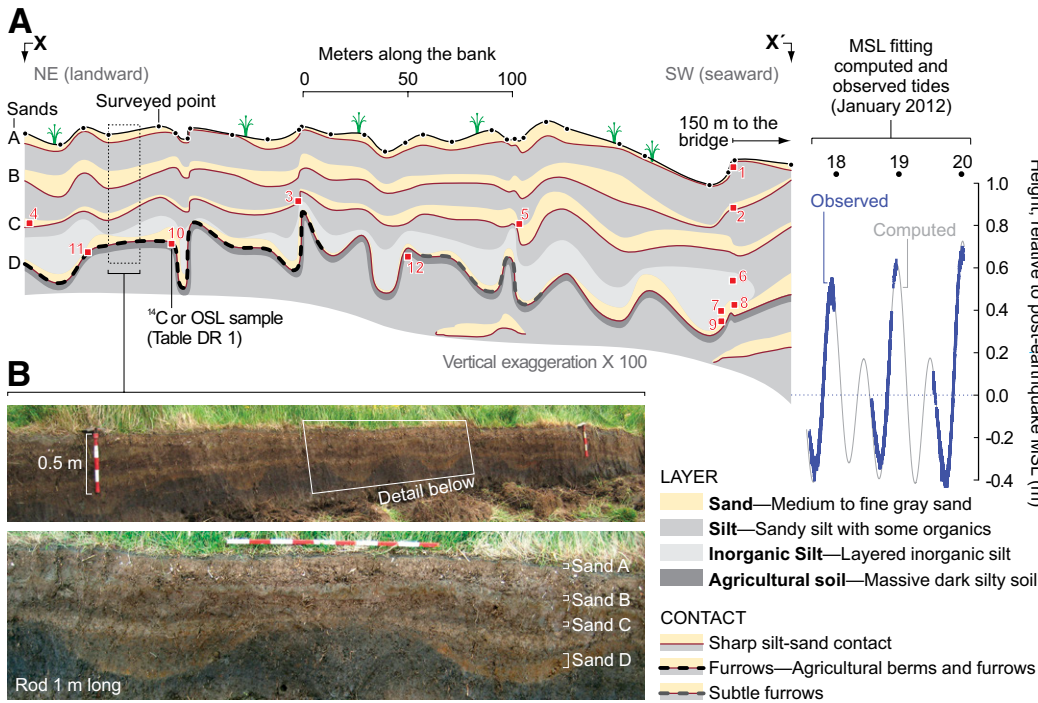
sands B and C were measured 5–70 m south of the river bank and 1.4–1.5 km upstream of the river mouth. The lower contacts are sharp and irregular. Minor amounts of overlying silt and organics are mixed with the sand layers over a 1–2 cm transition zone at the upper contacts. Sand C contains rip-up clasts resembling the underlying silt, indicating erosion. In contrast to these four gray sand layers, river bank deposits 2–10 km upstream of the river mouth are composed of light brown, angular, coarse sand and are not as laterally continuous.

Near the upstream end of the site, sand D conformably drapes over at least 20 buried furrows oriented perpendicular to the river bank (Fig. 4; Fig. DR6). The uniform amplitude (~30 cm) and spacing (~1.7 m) of the furrows suggest that they are agricultural features. Comparable agricultural furrows have been described and dated to as early as A.D. 1200 in this part of Chile (Dillehay et al., 2007). In 1862, the Chilean Navy surveyor Francisco Vidal Gormaz described strikingly similar abandoned agricultural furrows in the Lebu valley, 80 km north of Tirúa: “Wherever one looks there are still well marked furrows from the ancient agriculture of the Araucanian people [...]. The furrows always follow the down-slope water flow and are made with much uniformity at one and a half meters distance from each other.” (Vidal Gormaz, 1862, p. 45–46; Table DR3 in the Data Repository).

### DATING

Abundant evidence indicates that sand B was deposited by the 1960 tsunami. The main shock ( $M_w$  9.5) on May 22 nucleated nearly beneath Tirúa; it ruptured a 900 km segment to the south (Cifuentes, 1989) and was followed by the tsunami. Eyewitnesses to both the 1960 and 2010 tsunamis report that the maximum run-up elevation in the town of Tirúa was higher in 2010 than in 1960 (Fig. 2, label c), although the 1960 tsunami was large enough to strand the river ferry raft 3 km upriver. Sand B buries a trash pit containing recent historical objects (rope, glass, and cut wood). Non-natural  $^{137}\text{Cs}$ , introduced into the atmosphere by nuclear testing in the 1950s and 1960s, was detected in sediment samples above and closely below sand B, but not lower in the section (Fig. 3). OSL analyses on sands A and B yielded  $1\sigma$  age ranges that include 2010 and 1960 (Fig. 3; Table DR1b).

Sands C and D are constrained to the past 200–500 yr by radiocarbon ages (Fig. 3; Table DR1a). A thin layer of fragile, angular charcoal 1 cm above sand C yielded a  $2\sigma$  age range of A.D. 1640–1800, and is probably from an in situ vegetation fire that closely postdates sand C. Five  $^{14}\text{C}$  ages constrain the age of sand D to A.D. 1500–1630, which is consistent with the potential age range of the underlying agricultural furrows.



**Figure 4. A:** Correlated stratigraphic units 1.4–1.8 km inland from the mouth of the Tirúa River, Chile (X-X' in Fig. 2), including the four sands interpreted as tsunami deposits (Fig. 3; Fig. DR5 [see footnote 1]). Elevation relative to mean sea level (MSL) is based on fitting observed and computed tides (see Data Repository). **B:** Uniformly spaced furrows underlying sand D are interpreted as agricultural features (Fig. DR6).

**MATCHING HISTORICAL AND PALEOSEISMIC RECORDS**

Of the eight historically recorded tsunamis in the region, four were large enough to leave a detectable deposit 2 km upriver at this location, most likely in A.D. 1575, 1751, 1960, and 2010. Historic tsunamis in 1570, 1657, 1751, 1835, and 2010 affected areas to the north of Tirúa, particularly Concepción, while those in 1575, 1837, and 1960 mainly affected settlements to the south (Fig. 1; Montessus de Ballore, 1912; Lomnitz, 2004; Cisternas et al., 2005; Udías et al., 2012). An additional destructive earthquake occurred in southern Chile in 1737, but there is no known account of a tsunami in Chile (Cisternas et al., 2005) or Japan (Atwater et al., 2005). The 1837 earthquake and tsunami were much less severe north of Valdivia than those in 1575 and 1960 (Cisternas et al., 2005; Moernaut et al., 2014), and are thus unlikely to have had a significant effect even farther north at Tirúa.

The A.D. 1751 tsunami is the most plausible candidate for sand C, given the historical context and the bracketing radiocarbon ages of A.D. 1640–1800 (Fig. 3; Table DR1). The 1751 tsunami destroyed Concepción, leading to the inland relocation of the city, and the earthquake caused extensive damage from Santiago to Valdivia (Fig. 1; Lomnitz, 2004). Udías et al. (2012) inferred that the 1751 tsunami at Concepción was similar to that in 2010, and probably higher than those in 1657 and 1835. Written records of the 1751 tsunami are unknown south of Concepción (Fig. 1), as this region was largely under indigenous Mapuche control until the 1860s (Cisternas et al., 2012). However, the 1751 tsunami was large enough to destroy the

main settlement on the Juan Fernández Islands (675 km offshore), killing several people (Lomnitz, 2004), and to flood rice paddies in Japan (Atwater et al., 2005).

The 1835 tsunami (Darwin, 1839) is a slightly less likely source for sand C than the 1751 event. While the 1835 tsunami caused severe damage to coastal settlements near Concepción, descriptions of the tsunami at Juan Fernández Islands (Fig. 1; FitzRoy, 1839) and moderate damage in Hawaii (Lomnitz, 2004) suggest that it was not as great in distal locations. Seal hunters observed that the inundation at the southern tip of Mocha Island (30 km offshore from Tirúa) was higher than in any storm, but they safely weathered the tsunami on the small rocky islet where their boat had grounded (FitzRoy, 1839). In comparison, the 2010 tsunami reached elevations of 5 m on the southern shore of Mocha Island and >20 m on its northern end (Fritz et al., 2011).

The age range of sand D overlaps with historical tsunamis in 1570 and 1575. It is possible that deposits from both events are represented at Tirúa; however, historical records suggest that sand D was more likely deposited by the larger 1575 tsunami. The historical accounts and paleoseismic evidence of the 1575 earthquake and tsunami most nearly resemble those of the giant earthquake in 1960 (Cisternas et al., 2005; Moernaut et al., 2014). An eyewitness, Fernández de Córdoba (1575), described complete destruction by the 1575 earthquake as far north as Angol, 90 km northeast of Tirúa (Table DR3). Damage from the tsunami was widespread from Concepción southward (Cisternas et al., 2005). The tsunami flowed more than 10 km up the river at Puerto Saavedra, 50 km south

of Tirúa (Fig. 1), and the tides remained higher than usual even after the sea had retreated, implying coseismic subsidence consistent with our observations at Tirúa. In contrast with the numerous chronicles of the 1575 event, only two first-hand records have been found for the 1570 earthquake and tsunami.

**LAND-LEVEL CHANGES**

Using the surveyed difference in relative mean sea level before and after the 2010 earthquake, we calculated  $0.48 \pm 0.10$  m of coseismic uplift at Tirúa (Table DR2). Fariás et al. (2010) inferred <0.5 m of uplift at Tirúa using exposed coralline algae, Melnick et al. (2012) estimated  $0.91 \pm 0.17$  m of uplift using exposed intertidal mussels, and local fishermen interviewed shortly after the earthquake estimated 0.8–1.0 m of uplift. In contrast, net change at Tirúa during the earthquakes on 21–22 May 1960 was zero to slight subsidence:  $-0.2 \pm 0.4$  m based on surveyed evidence 8 yr later (Plafker and Savage, 1970), and  $-0.03 \pm 0.72$  m from diatom assemblages (Garrett et al., 2013).

Several features indicate subsidence associated with the deposition of sand D. The agricultural furrows buried by sand D lie below modern high-tide level and were probably abandoned after the deposition of the sand layer, as the stratigraphy shows no disruption by later use. The 8–10 cm layer of sticky gray to tan mud overlying sand D contrasts sharply with the organic-rich soil beneath sand D (Figs. DR5 and DR6), similar to other sites of coseismic subsidence (Nelson et al., 1996). This sequence is capped by thin, inorganic silt layers ( $\leq 1$ –2 mm thick) interbedded with occasional organic zones,

which we interpret as deposits from fluvial overbank flooding (Fig. 3; Fig. DR5). The proportion of freshwater diatom species is greatest in the soil below sand D, while marine and brackish species increase in the overlying silt units (Fig. DR7).

The stratigraphy spanning sand C is consistent with coseismic uplift. The underlying thinly bedded silt layers terminate in a sharp contact with sand C, which is consistently overlain by a 2–5 cm silty peat (Fig. DR5). The peat grades upward into increasingly abundant thin silt layers and fewer organics, similar to the layers below sand C. We interpret this gradational change as slow interseismic subsidence that gradually accommodated increasingly frequent fluvial overbank flooding. The interbedded thin silt and organic layers continue unaltered above sand B (A.D. 1960), consistent with little to no detectable coseismic land-level change in 1960.

### IMPLICATIONS FOR FUTURE EARTHQUAKES AND TSUNAMIS

Vertical displacements in great subduction earthquakes are controlled by the geometry of the megathrust surface, assumed to be relatively constant over millennia, and the amount and distribution of coseismic slip upon that surface, which may vary among earthquakes in both the strike and dip directions. Slip concentrated seaward of the coast will lead to subsidence at a coastal site. Slip extending landward beneath the coast, or distributed more evenly with depth, will lead to uplift at the same site (Fig. DR9; Segall, 2010). The two largest historical earthquakes in southern Chile are associated with subsidence (A.D. 1575) or slight land-level change (A.D. 1960) at Tirúa, while those in 1751 and 2010 exhibit evidence of coseismic uplift at the same site. The slip distributions inferred for 1960 and 2010 (Moreno et al., 2009 and 2012) and simple slip modeling (Fig. DR9) therefore suggest that the uplift at Tirúa in 2010 and likely 1751 was caused by slip extending farther landward and to greater depth than in 1960 and 1575.

The long and robust geological and historical records of tsunamis and land-level changes from this particularly well-documented location at Tirúa, Chile help to constrain the realistic range of behavior of these events, as required to inform models of earthquake and tsunami hazards. Only four of the eight historically recorded tsunamis in the region were large enough to leave a detectable deposit at this marginal location between the rupture zones, most likely in A.D. 1575, 1751, 1960, and 2010. In addition, the paleoseismic data, together with knowledge of the geometry of the megathrust, demonstrate the power of similar observations, even at a single site, to constrain inferences about the distribution of coseismic slip in pre-instrumental great earthquakes around the globe.

### ACKNOWLEDGMENTS

This research was funded by National Geographic Society Grant 8577-08, U.S. National Science Foundation grants EAR-1036057, EAR-1145170, and EAR1357756, Chile Fondo Nacional de Desarrollo Científico y Tecnológico N° 1110848 and the University of Pennsylvania Benjamin Franklin Fellowship. We thank B. Atwater, E. Garrett, I. Hong, B. Horton, M. Lagos, A. McConkey, A. Nelson, D. Nikitina, C. Orem, and D. Pineda for collaboration in the field or laboratory, Lorena Rebolledo for diatom identification, and Jessica Pilarczyk for grain-size tomography. The manuscript was improved by reviews from B. Atwater, J. Bourgeois, H. Kelsey, M. Kinoshita, A. Nelson, M.-T. Ramirez-Herrera, and R. Witter.

### REFERENCES CITED

- Atwater, B.F., Musumi-Rokkaku, S., Satake, K., Tsuji, Y., Ueda, K., and Yamaguchi, D.K., 2005, The Orphan tsunami of 1700: Japanese clues to a parent earthquake in North America: U.S. Geological Survey Professional Paper 1707, 133 p.
- Bourgeois, J., 2009, Geologic effects and records of tsunamis, in Bernard, E.N., and Robinson, A.R., eds., *The Sea*, Volume 15, Tsunamis: Cambridge, Massachusetts, Harvard University Press, p. 53–91.
- Cifuentes, I., 1989, The 1960 Chilean earthquakes: *Journal of Geophysical Research*, v. 94, p. 665–680, doi:10.1029/JB094iB01p00665.
- Cisternas, M., et al., 2005, Predecessors of the giant 1960 Chile earthquake: *Nature*, v. 437, p. 404–407, doi:10.1038/nature03943.
- Cisternas, M., Torrejón, F., and Gorigoitia, N., 2012, Amending and complicating Chile's seismic catalog with the Santiago earthquake of 7 August 1580: *Journal of South American Earth Sciences*, v. 33, p. 102–109, doi:10.1016/j.jsames.2011.09.002.
- Darwin, C., 1839, *Journal and Remarks, 1832–1836, Volume 3, Narrative of the Surveying Voyages of His Majesty's Ships Adventure and Beagle, Between the Years 1826 and 1836*: London, Henry Colburn (reprint: New York, AMS Press, Inc.), 615 p.
- Dillehay, T.D., Pino-Quivira, M., Bonzani, R., Silva, C., Wallner, J., and Le Quesne, C., 2007, Cultivated wetlands and emerging complexity in south-central Chile and long distance effects of climate change: *Antiquity*, v. 81, p. 949–960.
- Fariás, M., Vargas, G., Tassara, A., Carretier, S., Baize, S., Melnick, D., and Bataille, K., 2010, Land-level changes produced by the  $M_w$  8.8 2010 Chilean earthquake: *Science*, v. 329, p. 916, doi:10.1126/science.1192094.
- Fernández de Córdoba, P., 1575, Excerpt from Carta de Pedro Fernández de Córdoba al licenciado Calderón, fecha el 21 de Diciembre de 1575, Ciudad de los Infantes [Angol]: Biblioteca Americana José Toribio Medina, Fondo Manuscritos, tomo 88, manuscrito 1214 (microfilm ms. M2), p. 267–271.
- FitzRoy, R., 1839, Proceedings of the Second Expedition, 1832–1836 under the Command of Captain Robert FitzRoy, R.N., Volume 2, Narrative of the Surveying Voyages of His Majesty's Ships Adventure and Beagle, Between the Years 1826 and 1836: London, Henry Colburn (reprint: New York, AMS Press, Inc.), 695 p.
- Fritz, H.M., et al., 2011, Field survey of the 27 February 2010 Chile tsunami: *Pure and Applied Geophysics*, v. 168, p. 1989–2010, doi:10.1007/s00024-011-0283-5.
- Garrett, E., Shennan, I., Watcham, E.P., and Woodroffe, S.A., 2013, Reconstructing paleoseismic deformation, 1: Modern analogues from the 1960 and 2010 Chilean great earthquakes: *Quaternary Science Reviews*, v. 75, p. 11–21, doi:10.1016/j.quascirev.2013.04.007.
- Lomnitz, C., 2004, Major earthquakes of Chile: A historical survey, 1535–1960: *Seismological Research Letters*, v. 75, p. 368–378, doi:10.1785/gssrl.75.3.368.
- Melnick, D., Cisternas, M., Moreno, M., and Norambuena, R., 2012, Estimating coseismic coastal uplift with an intertidal mussel: Calibration for the 2010 Maule Chile earthquake ( $M_w = 8.8$ ): *Quaternary Science Reviews*, v. 42, p. 29–42, doi:10.1016/j.quascirev.2012.03.012.
- Moernaut, J., Van Daele, M., Heirman, K., Fontijn, K., Strasser, M., Pino, M., Urrutia, R., and De Batist, M., 2014, Lacustrine turbidites as a tool for quantitative earthquake reconstruction: New evidence for a variable rupture mode in south central Chile: *Journal of Geophysical Research*, v. 119, p. 1607–1633, doi:10.1002/2013JB010738.
- Montessus de Ballore, F., 1912, *Historia Sísmica de los Andes Meridionales al Sur del Paralelo XVI, Segunda Parte*: Santiago, Chile, Imprenta Cervantes, 236 p.
- Moreno, M.S., Bolte, J., Klotz, J., and Melnick, D., 2009, Impact of megathrust geometry on inversion of coseismic slip from geodetic data: Application to the 1960 Chile earthquake: *Geophysical Research Letters*, v. 36, p. L16310, doi:10.1029/2009GL039276.
- Moreno, M., et al., 2012, Toward understanding tectonic control on the  $M_w$  8.8 2010 Maule Chile earthquake: *Earth and Planetary Science Letters*, v. 321–322, p. 152–165, doi:10.1016/j.epsl.2012.01.006.
- Nelson, A.R., Shennan, I., and Long, A.J., 1996, Identifying coseismic subsidence in tidal-wetland stratigraphic sequences at the Cascadia subduction zone of western North America: *Journal of Geophysical Research*, v. 101, p. 6115–6135, doi:10.1029/95JB01051.
- Plafker, G., and Savage, J.C., 1970, Mechanism of the Chilean earthquakes of May 21 and 22, 1960: *Geological Society of America Bulletin*, v. 81, p. 1001–1030, doi:10.1130/0016-7606(1970)81[1001:MOTCEO]2.0.CO;2.
- Segall, P., 2010, *Earthquake and Volcano Deformation*: Princeton, New Jersey, Princeton University Press, 456 p.
- Udías, A., Madariaga, R., Buforn, E., Muñoz, D., and Ros, M., 2012, The large Chilean historical earthquakes of 1647, 1657, 1730, and 1751 from contemporary documents: *Bulletin of the Seismological Society of America*, v. 102, p. 1639–1653, doi:10.1785/0120110289.
- Vargas, G., Fariás, M., Carretier, S., Tassara, A., Baize, S., and Melnick, D., 2011, Coastal uplift and tsunami effects associated to the  $M_w$  8.8 Maule earthquake in Central Chile: *Andean Geology*, v. 38, p. 219–238.
- Vidal Gormaz, F., 1862, Reconocimiento de la Costa de Arauco, in *Memoria de Marina* (Report from the Navy Minister to the National Congress): Santiago, Chile, Imprenta Nacional, v. 140, p. 20–64.
- Vigny, C., et al., 2011, The 2010  $M_w$  8.8 Maule megathrust earthquake of central Chile, monitored by GPS: *Science*, v. 332, p. 1417–1421, doi:10.1126/science.1204132.

Manuscript received 1 May 2014

Revised manuscript received 19 August 2014

Manuscript accepted 27 August 2014

Printed in USA

## GSA Data Repository 2014349

### **“Five Centuries of Tsunamis and Land-Level Changes in the Overlapping Rupture Area of the 1960 and 2010 Chilean Earthquakes”**

Lisa L. Ely, Marco Cisternas, Robert L. Wesson, and Tina Dura

Methods for dating, grain-size distribution, and diatom analyses.

Table DR 1. Radiocarbon and optically-stimulated luminescence (OSL) ages from Tirúa sites.

Figure DR 1. Location map of photos and figures depicted in Data Repository.

Figure DR 2. Effects of the 2010 tsunami at Tirúa.

Figure DR 3. 2010 tsunami deposits and flattened vegetation at the Tirúa study site.

Figure DR 4. Photographs of stratigraphy and tsunami sand deposits along the Tirúa River.

Figure DR 5. Stratigraphic description of depositional units exposed in the Tirúa River bank.

Figure DR 6. Agricultural furrows overlain by Sand D, exposed in the bank of the Tirúa River.

Figure DR 7. Diatom assemblages from Tirúa Section 2.

Estimation of the Change in Relative Mean Sea Level Associated with the 2010 Earthquake

Table DR 2. Estimates of MSL and associated errors.

Figure DR 8. Results of simulation comparing estimates of MSL.

Figure DR 9. Schematic dependence of vertical displacement at Tirúa for two positions of the coseismic slip zone.

Table DR 3. Translations of written records of historical earthquakes cited in the text and that were not transcribed in previous publications.

Record 1: Vidal Gormaz, 1862

Record 2: Fernández de Córdoba, 1575

## Methods for Dating, Grain-size and Diatom Analyses

### Dating

Samples for radiocarbon dating were manually cleaned of modern roots and sediment in the laboratory and submitted to either Beta Analytic or the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at Woods Hole Oceanographic Institution for AMS dating analysis. The 2-sigma age in Years BC/AD was calibrated using OxCal version 4.2.1 with southern hemisphere calibration curve SHCal04 (Bronk Ramsey, 2009; McCormac et al., 2004). One radiocarbon sample (012403-2), a seed, was submitted to Paleoresearch Laboratory in Golden, Colorado for identification and subsequent AMS dating.

Samples for Optically Stimulated Luminescence (OSL) dating were collected by pushing a 1.5" diameter, 8" long metal tube into the center of each sand layer and capping both ends after extracting the tube, to keep the sediments isolated from light. Sediment surrounding the sample site was collected separately for measurement of background radiation levels. The OSL analysis was conducted at the University of Illinois at Chicago Luminescence Dating Research Laboratory (LDRL), directed by Dr. Steven Forman.

The OSL ages of the pre-1960 sand layers were consistently several hundred years older than multiple radiocarbon ages from the surrounding stratigraphic horizons, as well as the most probable historic ages of the tsunamis. We are more confident in the radiocarbon results, as OSL has not been widely used to date tsunami deposits. For those reasons, we did not rely on the OSL results from Sands C and D to constrain the age ranges of those units. Research into the most effective methods to collect and analyze OSL samples from tsunami deposits is currently underway. We believe that the anomalously older OSL ages could result from the electron traps of the sand not becoming fully 'bleached' by adequate exposure to light before they were redeposited in the tsunami deposit.

Samples for detection of  $^{137}\text{Cs}$  were collected from multiple stratigraphic horizons above and below the assumed 1960 sand layer, Sand B.  $^{137}\text{Cs}$ , with a half-life of 30.3 years, is a thermonuclear byproduct. Its presence is directly related to the atmospheric testing of nuclear devices during the latter half of the 1950s and early 1960s. Its presence in the stratigraphy indicates deposition after the initiation of nuclear testing. The  $^{137}\text{Cs}$  is typically not mobile in sediments containing clay or silt (Ely et al., 1992), rendering them suitable for this method of dating. Analysis of  $^{137}\text{Cs}$  in the tsunami sands and intervening silt deposits from Tirúa was conducted at Microanalytica Laboratory in Miami, Florida. Samples with a high organic content were heated to leave only noncombustible ash prior to analysis with a gamma spectrometer.

### Grain-Size Analysis

Grain-size analysis was conducted on stratigraphic monoliths excavated from Section 2 on the southern Tirúa River bank (Figs. 2, 3, 4, DR 5). Subsampling was conducted at 5-cm resolution except around lithologic contacts where sampling was conducted at 2-cm resolution. Samples were treated with hydrogen peroxide (30%) to remove organic material and analyzed using a Beckman Coulter LS230 laser diffraction grain-size analyzer. Grain size interpretations are based on the Wentworth Phi Scale (1922) and reported as differential volume (the percentage of total volume that each size class occupies). The grain-sizes were interpolated and gridded using a triangular irregular network (TIN) algorithm (Sambridge et al. 1995) and plotted as color surface plots using Geosoft Oasis TM software (Donato et al., 2009).

### Diatom Analysis

The diatom identification was conducted by Lorena Rebolledo of the Universidad de Concepción, Chile. Seventeen samples were collected from representative stratigraphic layers at

Section 2 on the southern Tirúa River bank (Figs. 2, 3, 4, DR 5, DR 7). Samples were prepared based on the methods described by Scharader and Gersonde (1978). Samples were treated with hydrogen peroxide (30%) to remove organic material and mounted on permanent slides. The fossils were identified and counted using an Axioscope 2 plus microscope at 400x and 1000x magnification. Identification of the species was based mainly on Cupp (1943), Round et al., (1990), Sims (1996), and Witkowski et al., 2000). The diatoms were divided into groups according to their principal ecological affinity: Marine (M), Marine and Brackish (M&B), Brackish (B), and Freshwater (FW), as established by Vos and de Wolf (1993).



**Table DR 1a.** Radiocarbon ages from Tirúa, Chile. Samples are in stratigraphic order (Figs. 3 and 4, main text).

Sample #	Sample Name	Lab # <sup>1</sup>	Meters upstream of bridge <sup>2</sup>	Depth (cm)	Stratigraphic Unit	Sample Type <sup>3</sup>	$\delta^{13}\text{C}$	<sup>14</sup> C Yrs BP $\pm 2\sigma$ error <sup>4</sup>	Calibrated Age Yrs AD or BP <sup>5</sup>
3	Tirúa 24a	OS-94872	355	35	1 cm above Sand C	C IS burned layer	-27.8	250 $\pm$ 25	AD1640-1800
4	Tirúa 21a	OS-94873	511		Within Sand C	C, T	-27.8	2030 $\pm$ 50	BC 160-AD 130
6	011010-2	Beta-276184	150	53	Below Sand C	C, T	-25.9	360 $\pm$ 40	AD 1460-1640
7	Tirúa-2	Beta-261094	154	75	Above Sand D	W	-25.5	430 $\pm$ 40	AD 1440-1630
9	Tirúa-1	Beta-259608	154	83	Sand D	C, T	-22.7	650 $\pm$ 40	AD 1300-1410
10	011511-8	OS-86736	415	62	Sand D	W	-25.5	655 $\pm$ 25	AD 1300-1400
11	Tirúa 20a	OS-94871	459	1 cm below D	Below Sand D	Rh, IS	-25.3	530 $\pm$ 25	AD1410-1450
12	012413-2	PRI-Tirúa 012413-2	305	53	5 cm below Sand D	<i>Calystegia</i> seed	-	365 $\pm$ 15	AD 1500-1630

<sup>1</sup>AMS analysis laboratories: OS = National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole Oceanographic Institution; Beta = Beta Analytic; PRI = PaleoResearch Institute, Golden, Colorado.

<sup>2</sup>Surveyed distance along the river bank upstream of the bridge that is 1.3 km upstream of the river mouth (Fig. 2).

<sup>3</sup> Sample Type: C=charcoal, W=wood, Rh=Rhizome; Subset organic type: T=transported; IS=in situ.

<sup>4</sup>Reported ages are conventional <sup>14</sup>C ages in years before AD 1950, corrected for isotopic fractionation using  $\delta^{13}\text{C}$ .

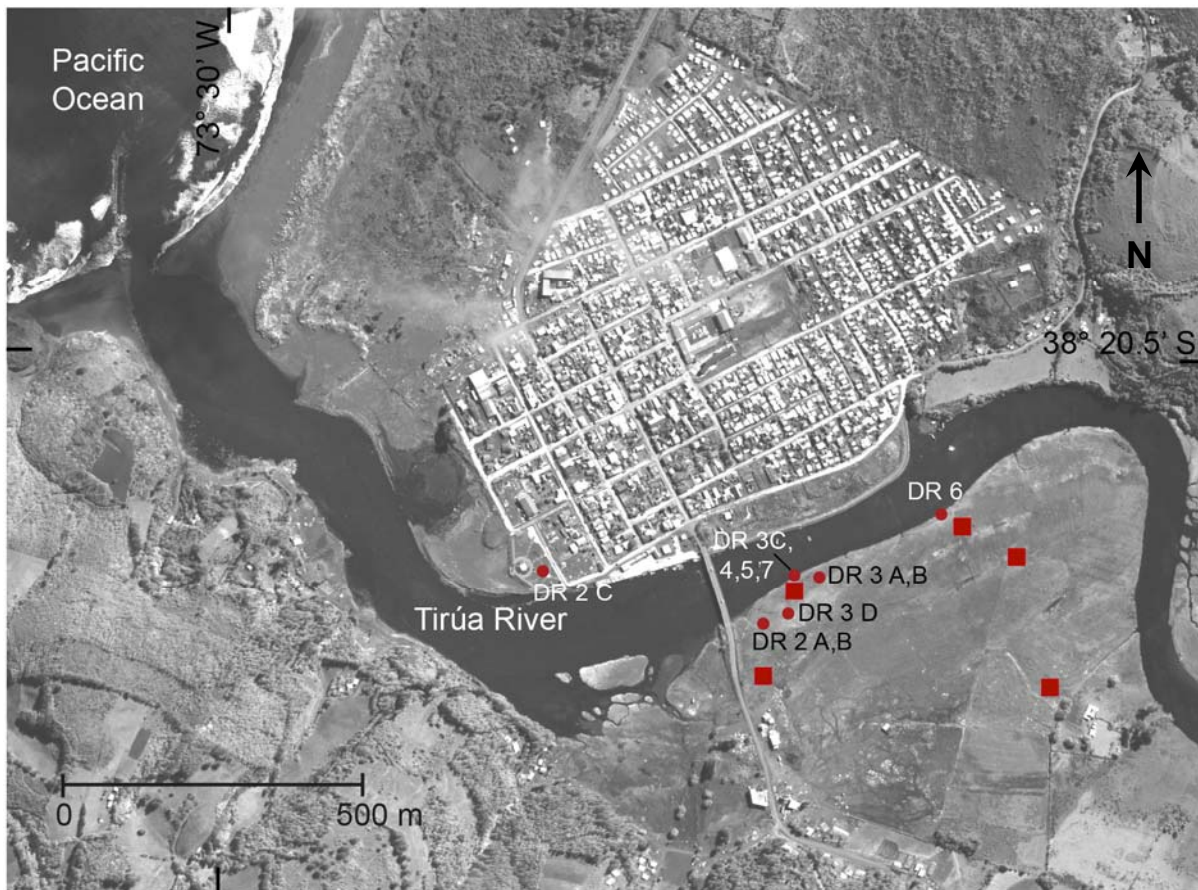
<sup>5</sup>Calibrated 2-sigma age in Years BC/AD using OxCal 4.2.1 with southern hemisphere calibration curve SHCal04 (Bronk Ramsey, 2009; McCormac et al., 2004).

**Table DR 1b.** Optically stimulated luminescence (OSL) ages from Tirúa, Chile. Samples are in stratigraphic order (Figs. 3 and 4, main text).

Sample #	Sample Name <sup>6</sup>	Lab # <sup>6</sup>	Meters upstream of bridge <sup>7</sup>	Depth (cm)	Stratigraphic Unit	Sample Type	Years AD $\pm 1\sigma$ error
1	082610-OSL-2	UIC2848	150	16-19	2010 Sand A	Sand	AD 2005 $\pm$ 50
2	082610-OSL-1	UIC2847	150	16-20	Sand B 1960	Sand	AD 1950 $\pm$ 40
5	041209-OSL-1	UIC2523	250	30	Sand C	Sand	AD 1280 $\pm$ 50
8	041209-OSL-2	UIC2524	150	75	Sand D	Sand	AD 810 $\pm$ 250

<sup>6</sup>OSL analysis laboratory: UIC = University of Illinois at Chicago Luminescence Dating Research Laboratory.

<sup>7</sup>Surveyed distance along the river bank upstream of the bridge that is 1.3 km upstream of the river mouth (Fig. 2).



**Figure DR 1.** Locations of photographs and diagrams included in the Data Repository. Red squares = locations of additional pits that were excavated to expose the tsunami deposit stratigraphy inland of the river bank.

Red circles = location of Data Repository figures, denoted by DR number as follows:

- DR 2 A and B = sand and debris scattered by the 2010 tsunami
- DR 2 C = light post toppled by inflowing tsunami in 2010
- DR 3 A and B = vegetation flattened by inflowing tsunami in 2010
- DR 3 D = 2010 tsunami sand deposit buries flattened vegetation
- DR 4 = river bank stratigraphy exhibiting prominent sand layers
- DR 5 = description of sample stratigraphic section exposed in river bank
- DR 6 = buried agricultural berms and furrows
- DR 7 = sampling site for diatom analysis

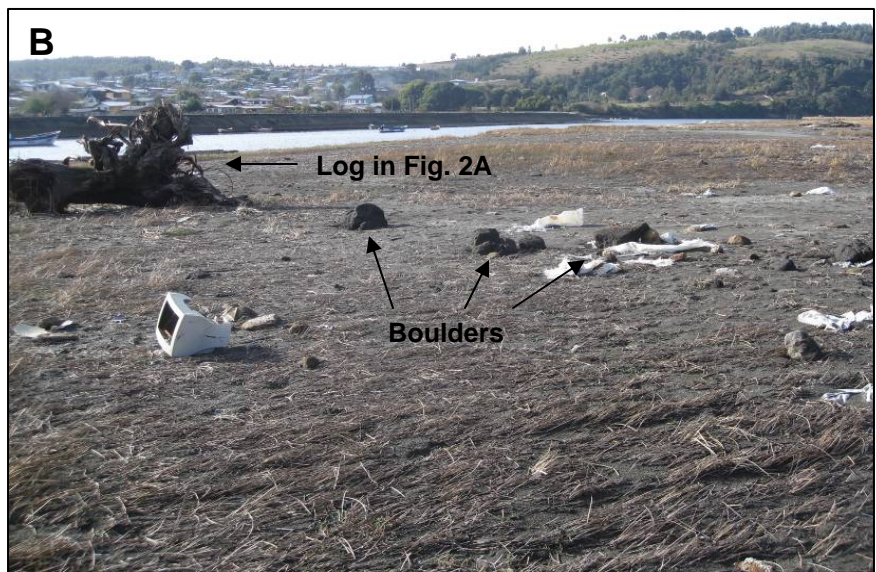


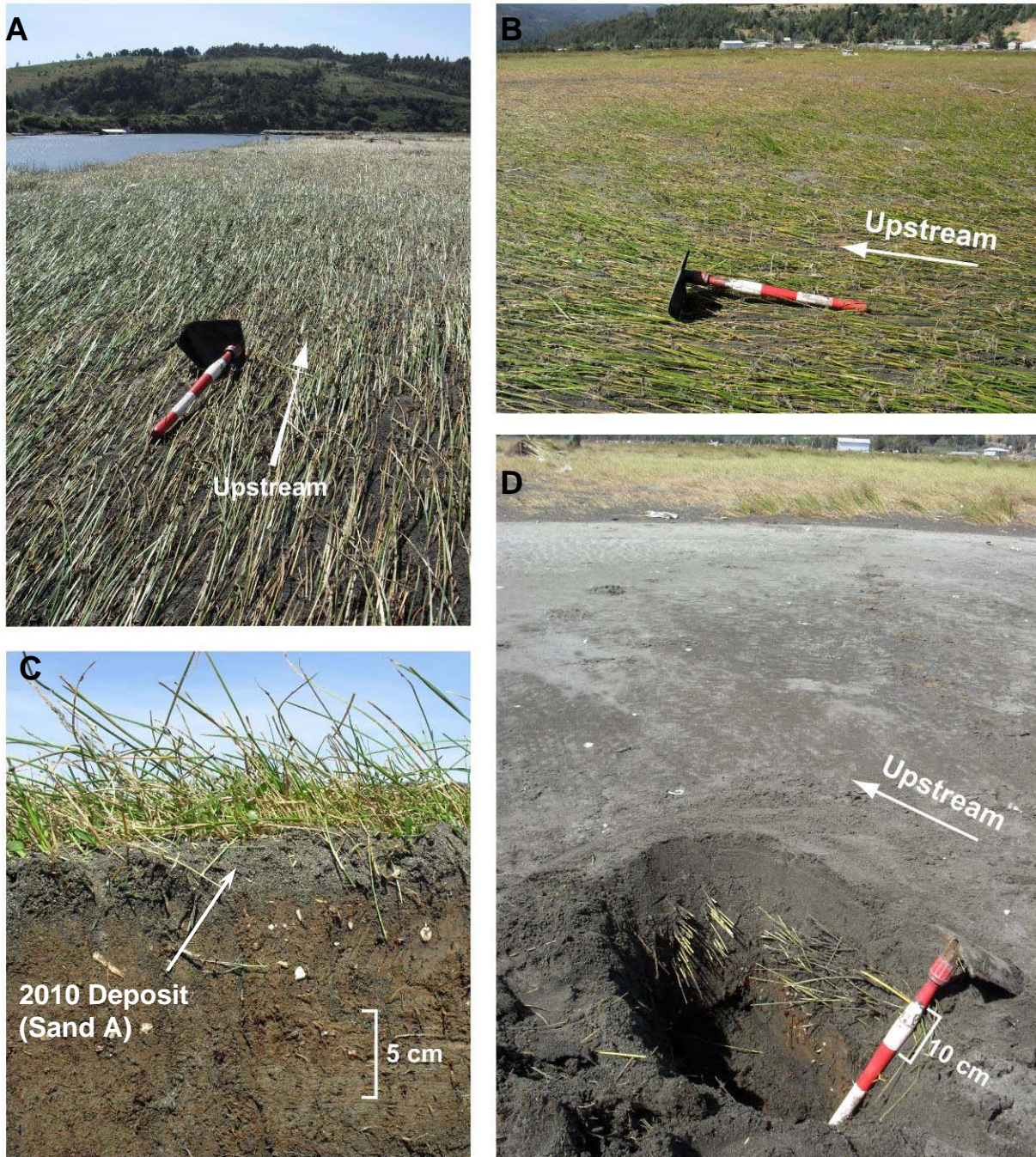
**Figure DR 2.** Effects of the 2010 tsunami at Tirúa.

**A)** Sand spread by the 2010 tsunami in patches across the surface of the study site on the south side of the Tirúa River. Boulder at lower right was carried 20 m from the bridge abutment (Fig. 2).

**B)** Sand and debris deposited by the 2010 tsunami on the floodplain south of the Tirúa River. The >50-cm boulders in the center were entrained from the bridge abutment ~50 m downstream.

**C)** Damage from the 2010 tsunami in the Tirúa town square north of the river 3 months after the tsunami (location b in Fig. 2, main text). Flow depth at this location was > 7 m, based on height of kelp hanging from toppled electrical poles.





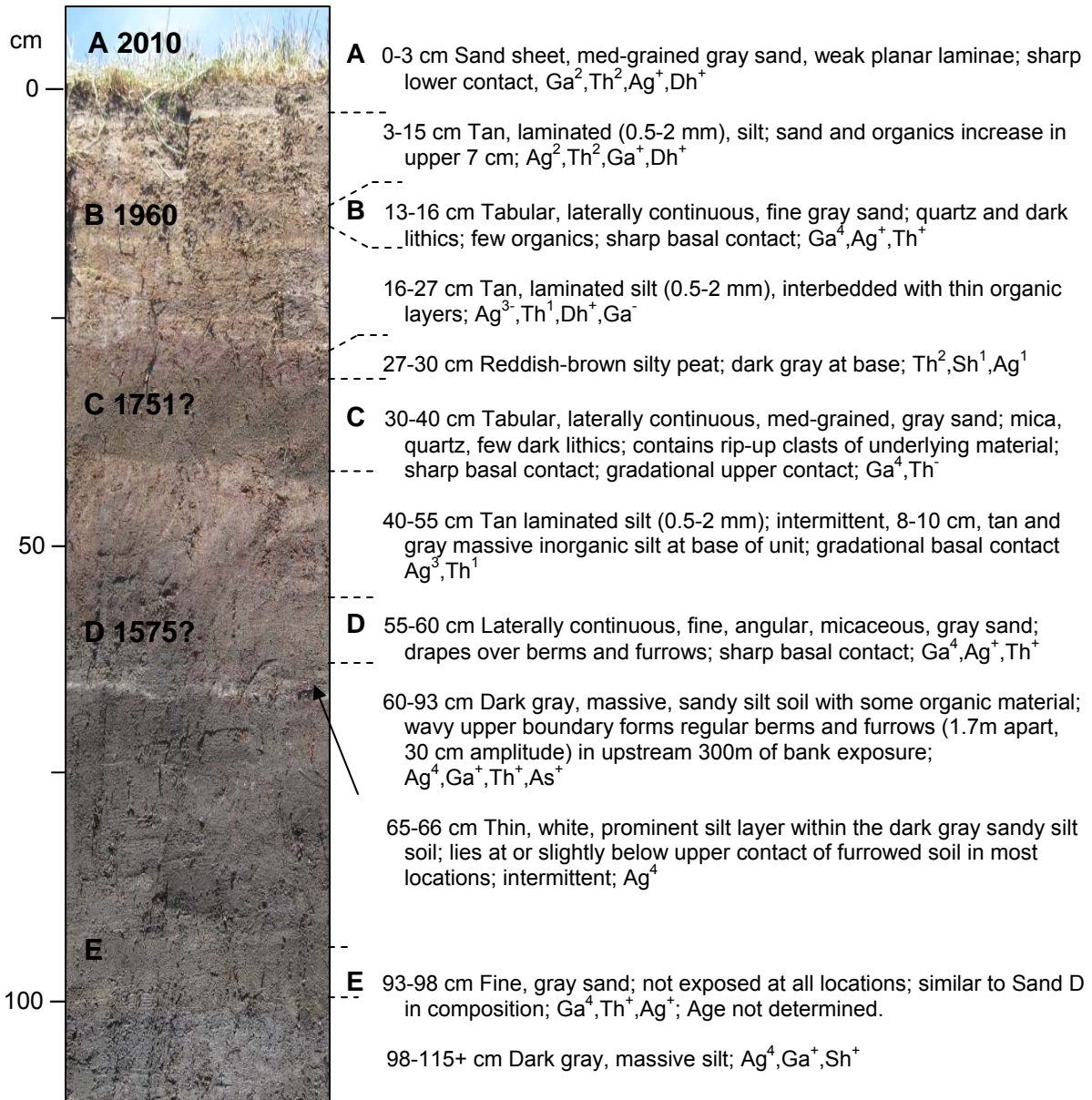
**Figure DR 3.** 2010 tsunami deposits and flattened vegetation at the Tirúa study site. The floodplain vegetation was buried by sand and/or flattened in the upstream direction by the inflowing tsunami wave. The tsunami backflow was concentrated in the river channel. **Photos A and B** are in the zone where the tsunami sand deposit was <10 cm thick. **Photo C** is in the cut bank exposure along the Tirúa River bank, where the tsunami sand deposit was generally 1-3 cm thick. **Photo D** is in one of the thickest patches of tsunami sand deposits, 10-30 cm thick, ~100 m upstream of the bridge. An isopach map of the 2010 tsunami deposit at this site is shown in Fig 2, main text.



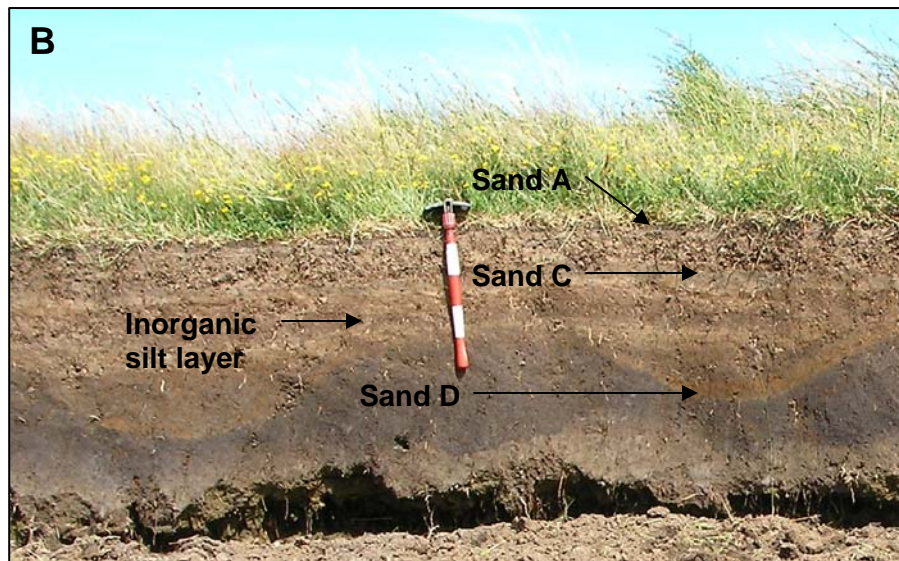
**Figure DR 4.** Photographs of stratigraphy and tsunami sand deposits along the Tirúa River bank. The sand layers are dark gray, in contrast to the light tan intervening silt units. **Photos A and B** show the laterally continuous, tabular Sand layers B, C and D (erosional notches marked by flags) in January, 2010, prior to deposition of Sand A by the February, 2010 tsunami.

**Photo C** shows the four sand layers and intervening silt units after the 2010 tsunami. Scale interval = 10 cm.

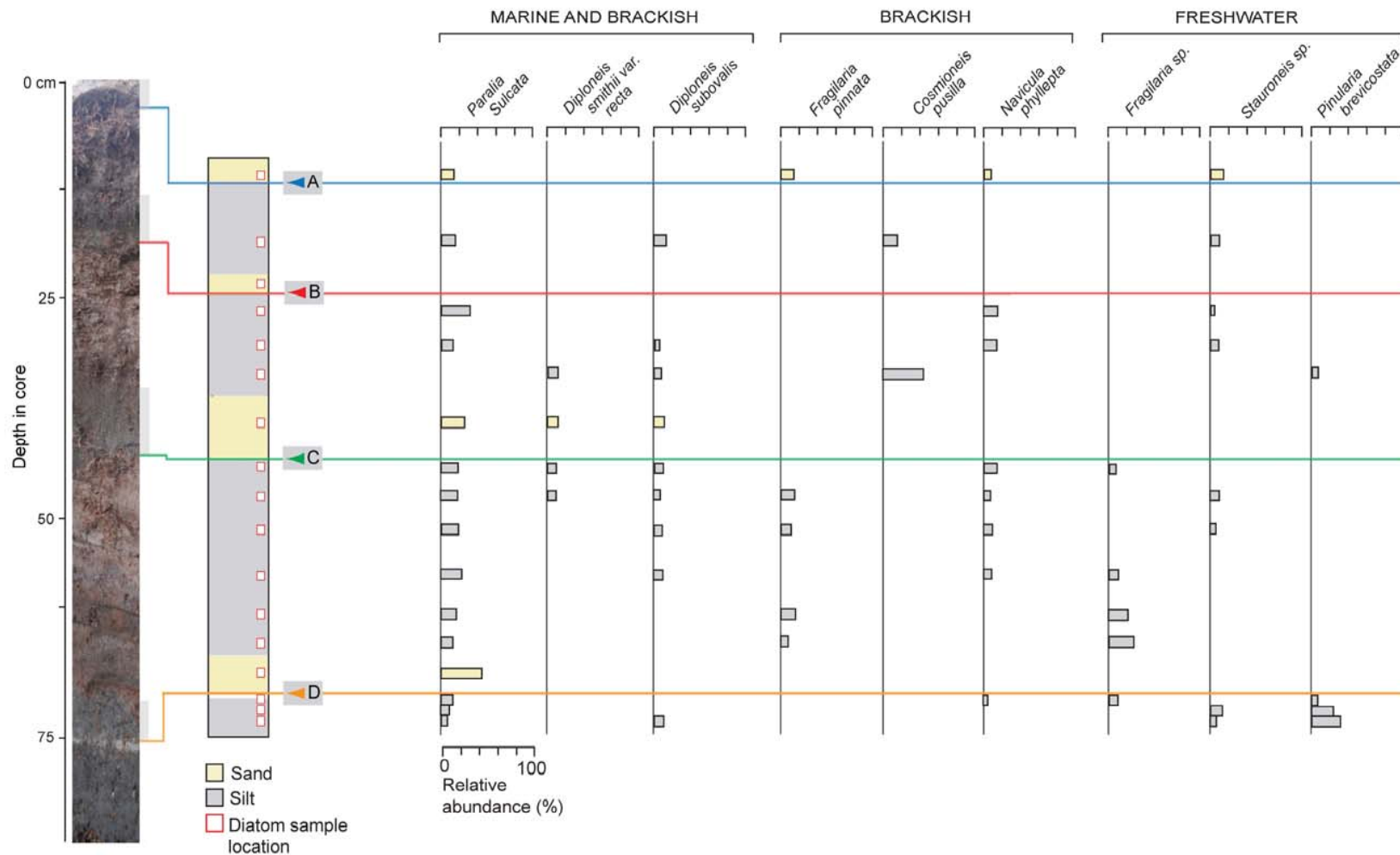




**Figure DR 5.** Stratigraphic description of depositional units exposed in the Tirúa River bank near Section 2, 1.45 km inland from the coast (Figs. 2, 3, 4 and DR 4). Five sand layers (A-E) are interbedded with massive and laminated silt deposits and organic-rich layers. The dates in calendar years AD are our interpretation of the historical tsunamis that deposited each sand layer. Sand E may represent an earlier tsunami, but it was not been thoroughly described or dated for this study. Lithologic descriptions and abbreviations for each unit follow the Troels-Smith (1955) nomenclature system for organic sediments.



**Figure DR 6.** Series of regularly-spaced agricultural berms and furrows below Sand D, 1700 m upstream from the river mouth. Average spacing = 1.7 m, average amplitude = 30 cm. Sand D is draped across the undulating topography of the furrows (50-60 cm depth), and is overlain by a horizontal, 8- to 10-cm-thick, inorganic, gray to tan silt layer (Fig. DR 5), capped by laminated silt and organic layers. Sand C is 3-5 cm thick, medium gray, and lies horizontally at a depth of 20-25 cm, directly overlying a light tan silt layer in both DR 6A and DR 6B. Sand A is at the surface; Sand B is not visible in these photos. Scale intervals on shovels = 10 cm.



**Figure DR 7.** Most abundant diatom species from Tirúa Section 2 (Figs. 2, 3, 4, and DR 5). Sand layers A–D are yellow. Inferred tsunami sand layers C and D contain diatoms from marine and brackish environments, while the 2010 tsunami deposit contains both marine and freshwater diatoms. This difference might result from recent changes to the landscape, such as construction of the bridge in 1962 and levees on the northern bank, possibly constricting the flow path of the 2010 tsunami and causing additional erosion of freshwater sediment and microfauna en route. There is a slight upward decrease in freshwater diatoms and an increase in marine and brackish species from the agricultural soil underlying Sand D up through the overlying package of silty sediments to the base of Sand C. This trend supports the sedimentological and archaeological evidence of coseismic subsidence coincident with Sand D. The diatom evidence for land-level changes in the section above Sand C is inconclusive, partly due to lower sampling density. The diatom identification was conducted by Lorena Rebolledo of the Universidad de Concepción, Chile.



## Estimation of the Change in Relative Mean Sea Level Associated with the 2010 Earthquake

We estimated mean sea level (MSL) at Tirúa through measurements made in January, 2010 (before the earthquake on February 27, 2010), and in January, 2012, and in January, 2013. These estimates provided a datum for our stratigraphy and permitted an estimate of crustal uplift at Tirúa associated with the 2010 earthquake.

In January, 2010, we measured the water level in the tidally influenced Tirúa River estuary near the Tirúa River bridge (Figs. 2 and DR 1) relative to a fixed point on the bridge abutment using a level and rod about every half hour for a period of seven hours. In January, 2012, and again in 2013, we measured the water level in the river using a portable acoustic tide gauge referenced to the same fixed point on the bridge abutment. In 2012 the tide gauge reported water level measurements about every eight seconds; in 2013 it reported averages every minute of about fifteen measurements taken at four-second intervals.

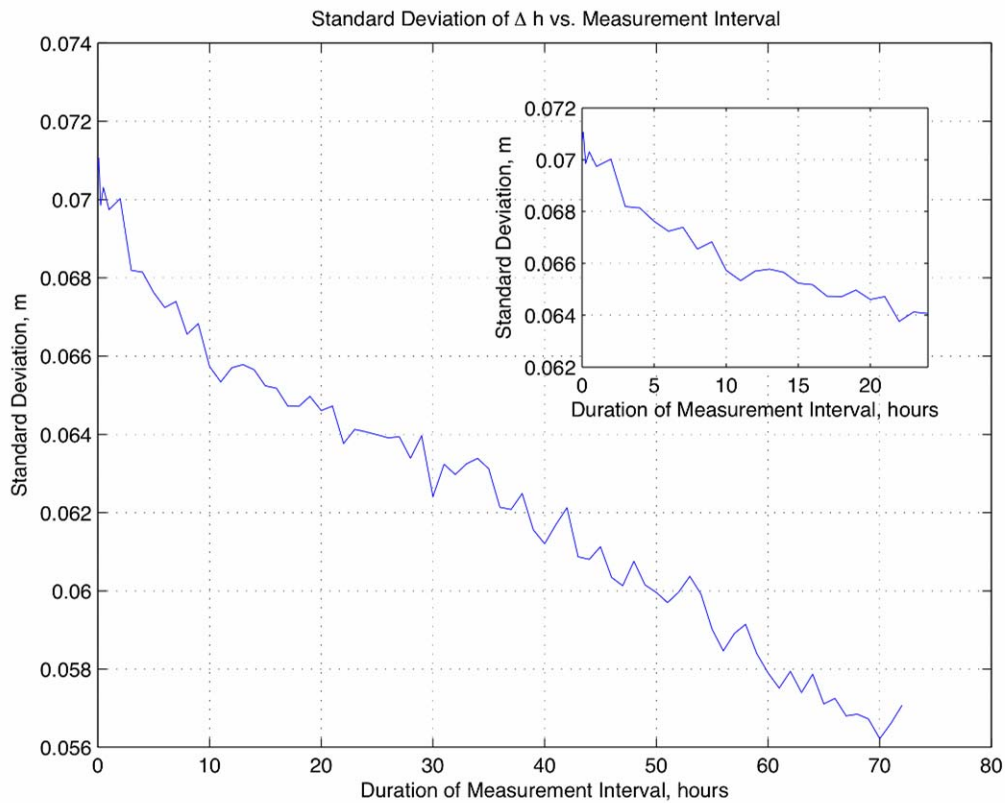
Ideally, estimation of a tidal datum such as MSL would be based on measurements over at least one month. However, we used an approximate approach in which we compared observations of water level over a shorter period with the tidal predictions computed from the TPX08-atlas tidal model ([http://volkov.oce.orst.edu/tides/tpxo8\\_atlas.html](http://volkov.oce.orst.edu/tides/tpxo8_atlas.html); Egbert et al, 1994; Egbert and Erofeeva, 2002). This tidal model combines a global model of tides based on satellite measurements together with high-resolution models for coastal areas with tide gauge measurements. Figure 4A (main text) shows a sample comparison between the surveyed tidal levels at Tirúa on January 18-20, 2012 and the tidal model predictions for those dates. Our estimates of the error bounds associated with this approach are described in detail below.

Our preferred estimates for MSL (relative to an arbitrary datum in which a notch on the southern abutment of the Puente Tirúa has an elevation of 8.75 m) are  $6.86 \pm 0.07$  m before the earthquake, and  $6.38 \pm 0.07$  m after the earthquake. Thus our estimate of the uplift associated with the earthquake is  $0.48 \pm 0.10$  m. These results along with our estimates of the associated errors are shown in Table DR 2.

**Table DR 2.** Estimates of MSL and Associated Errors (m).

	January, 2010	January, 2012	January, 2013
Mean Estimate of MSL (TP=10 m) (Assuming TP-BN = 1.25 m)	6.86	6.40	6.38 (Preferred Post-Earthquake Value)
Standard Error of Mean	0.0078	0.0006	0.001
Estimate of Error in Mean From Model (Estuarine Effects)	0.01	0.02	0.01
Estimate of Error in Mean from Model (Short Sampling Period)	0.07	0.07	0.07
Estimate of Systematic Error (Temperature Compensation)	0	0.03	0.01
Estimate of Survey Error	0.01	0.05 ??	0.01
Estimate of Total Error in Mean Estimate of MSL (S.D.)	0.072	0.093	0.072
Estimate of Uplift Owing to Earthquake			0.48±0.10

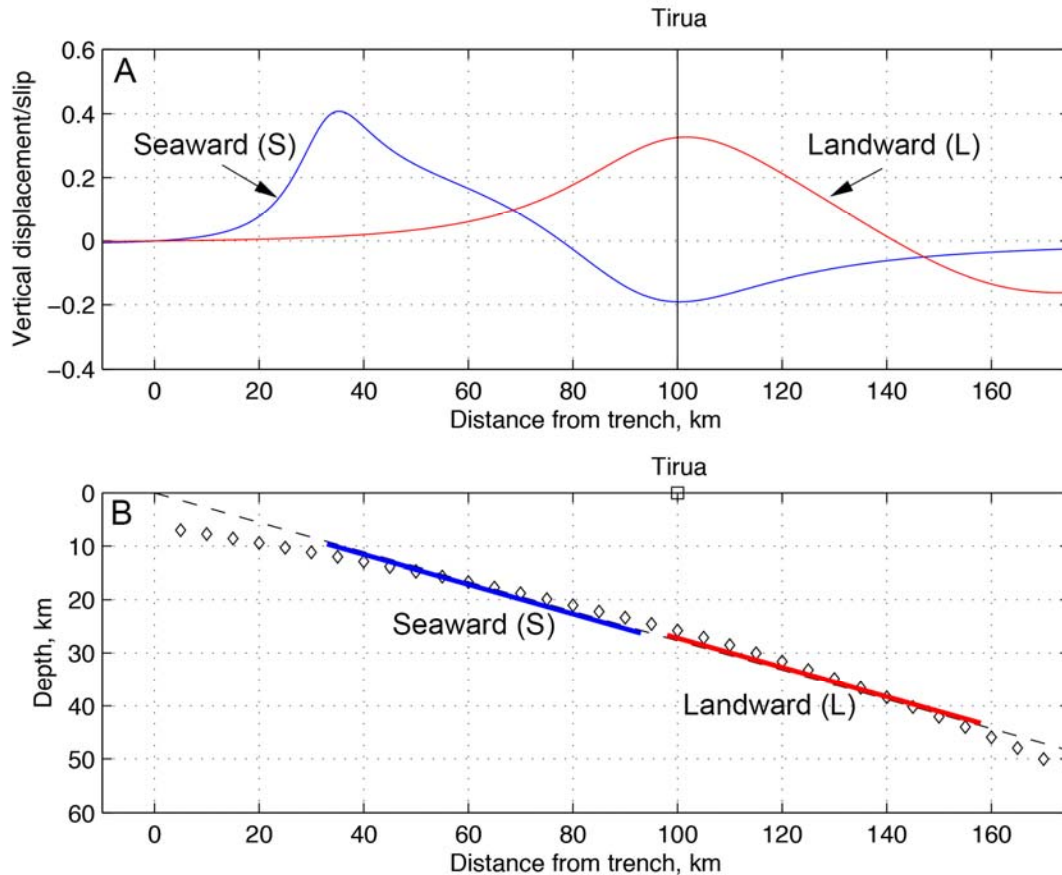
We considered five sources of error in our estimates of MSL. The largest source of error arises from the fact that our tidal observations covered only a short time period. We used a simulation to estimate the resulting error in our estimate of MSL in which we used real data from a permanent tide gauge at Lebu (85 km north of Tirúa) to estimate MSL by fitting samples of the data to the model at that site. The simulation involved taking 10,000 random samples of real data with a given time length during the calm water conditions of summer months and estimating MSL by fitting these samples to the model, then repeating for a range of sample lengths. The standard deviation of the differences between estimates of MSL from the trials and the estimate made from two years of data indicate that for observation periods comparable in length to that of our measurements at Tirúa, the error is about 7 cm (Figure DR 8).



**Figure DR 8.** Results of simulation comparing estimates of MSL at Lebu, Chile, derived from short observation periods in the summer months versus the best values estimated over two years.

We estimated the errors introduced by variations of the observed tide by estuarine effects, temperature compensation of the acoustic tide gauge, and survey errors to about 1 cm each. The estuarine effects included a lag of a fraction of an hour in the observed tide with respect to the predicted; a reduction in the amplitude of the tide; and possibly a slight tendency for the observed rising tides to be steeper, and the falling tides to be less steep, than predicted by the model. The smallest error is the standard error of the mean involved in the fit of the observations to the TPXO model.

The estimated total error in the estimates of MSL is taken as the square root of the sum of the squares on the errors from all sources. The error estimate for the uplift is also taken as the square root of the sum of the squares of the error estimates on the two means.



**Figure DR 9. A)** Schematic dependence of vertical displacement at Tirúa for two positions of coseismic slip zone for **B)** a simple model of constant coseismic slip in which slip is confined to a zone 60 km wide measured horizontally. The blue curve (S) shows slip entirely seaward of Tirúa, the red curve (L), entirely landward. As the interval containing the slip is moved landward and deeper along the megathrust, the displacement at Tirúa shifts from subsidence to uplift. Increasing the width of the slip zone will broaden the regions of uplift and subsidence. Thus, for example, a coseismic slip zone including both the red (L) and blue (S) regions in (B), comparable to the A+B+C scenario of Lay et al. (2013), would have a region of uplift extending landward from the trench including Tirúa; the region of subsidence would be located even farther landward. The calculations are based on Segall (2010). The megathrust is modeled as a plane dipping at 15.5°. The megathrust geometry of Moreno et al. (2012) is shown by the small diamonds in (B).

The minor differences between the simple plane approximation and the more realistic geometry should not affect the conclusion. Slip inhomogeneity will be a key factor in a real earthquake. Tirúa experienced little or no vertical change in 1960, and the slip zone was largely offshore but extended beneath Tirúa. Tirúa was uplifted in 2010 implying that the slip zone extended landward and to greater depth than in 1960. Moreno et al. (2009) and Moreno et al. (2012) present more realistic calculations showing the relation between slip and uplift at Tirúa for 1960 and 2010 respectively.

### Table DR 3. Written Records of Historical Earthquakes and Tsunamis

The records transcribed in this section include only those that were not transcribed in previous publications cited in the main text. Additional transcriptions of historical records referred to in the text can be found in Cisternas et al., 2005 and 2012. We kept the original 16<sup>th</sup> and 19<sup>th</sup> century Spanish orthography.

#### Table DR 3, Record 1. Vidal Gormaz, 1862.

Excerpt from Vidal Gormaz, 1862. Reconocimiento de la Costa de Arauco. In: Memoria de Marina (Report from the Navy minister to the National Congress). Imprenta Nacional, Santiago, Chile. v. 140, p. 20-64.

In 1862 Vidal Gormaz was sent by the Chilean Government to conduct a reconnaissance of the Arauco region that was under the control of the indigenous Mapuche people, including our field area at Tirúa. In his report, he describes ubiquitous abandoned agricultural furrows made by earlier generations of indigenous farmers that are remarkably similar in appearance and spacing to the furrows exposed in the stratigraphy of the river bank at Tirúa. The furrows at Tirúa were buried by Sand D, which we interpret as deposited by the tsunami in AD 1575.

The bold text highlights the portions that are most directly relevant to our study.

#### TERRENOS QUE AVECINAN EL RIO I SUS PRODUCTOS NATURALES

“Los terrenos que avecinan el rio [Lebu<sup>1</sup>] son, como todos los del territorio araucano, de una fertilidad proverbial. [...].

Esos campos de desolacion como se ven ahora, ofrecen todavía fidedignos testimonios que atestiguan i recuerdan épocas mas felices i abundantes: por donde se estienda la vista se hallan aun bien marcados los surcos de la antigua agricultura del pueblo araucano: en los valles i colinas, en las vegas i montañas, i aun en los barrancos mas pendientes, se nota el trabajo de la mano del hombre, que revela la intelijencia agrícola de las anteriores jeneraciones de ese pueblo tan valiente como hospitalario.

Los surcos siguen siempre el declive de las aguas i son formados con mucha uniformidad a un metro i medio de distancia unos de otros, cambiando de direccion siempre que el terreno lo damandaba. Estas muestras solo han desaparecido en los lugares que la actual jeneracion cultiva los campos con el auxilio del arado introducido por los españoles.”

#### LANDS SURROUNDING THE RIVER AND THEIR NATURAL PRODUCTS

The lands bordering the [Lebu] river are, like all of the Araucanian territory, proverbial in fertility. [...].

These fields now appear desolate, but they still offer reliable testimonies that attest to and recall happier and more prosperous times: **wherever one looks there still are well marked furrows from the ancient agriculture of the Araucanian people:** in the valleys and hills, in the marshes and mountains, and even in the steepest ravines can be noted the hand of man, which reveals the agricultural intelligence of the past generations of these people who were as brave as hospitable.

**The furrows always follow the down-slope water flow and are made with much uniformity at one and a half meters distance from each other, changing direction as the terrain demanded.** These samples have only disappeared in the places where the present generation cultivates the fields with the help of the plow introduced by the Spaniards.

---

<sup>1</sup> The Lebu River is located 85 km north of the Tirúa River

**Table DR 3, Record 2. Pedro Fernández de Córdoba, 1575.**

Excerpt from “Carta de Pedro Fernández de Córdoba al licenciado Calderón, teniente é capitán general deste reyno por su Magestad, fecha en 21 de Diciembre de 1575, Ciudad de los Infantes [Angol]”. Biblioteca Americana José Toribio Medina, Fondo Manuscritos, Tomo 88, Manuscrito 1214 (Microfilm Ms. M2), p. 267-271.

In this letter, Pedro Fernández de Córdoba describes the complete destruction of the city of Angol by the 1575 earthquake in southern Chile. Because Angol lies inland about 80 km northeast of Tirúa, this account supports the interpretation that major shaking should have affected our study site in 1575. Devastation from the earthquake and tsunami is described in numerous historical records along the southern coast of Chile from Chiloé Island to Imperial (now Puerto Saavedra; Fig. 1). See Table S1 of Cisternas et al. (2005) for additional historical descriptions of this event. The 1575 earthquake has been compared in size and extent to the giant  $M_w$ 9.5 Chilean earthquake of 1960 (Cisternas et al., 2005).

f.269. “En quince deste á la tarde hubo un torbellino de viento el mas brabo que jamas e visto y crei que se llevara las casas y al anochecer murio badajoz [sic] rrepentinamente y otro dia viernes [f. 270] diez y seis acudio el mas brabo y largo temblor de tierra que jamas se ha visto y lo que dejó de llevar el torbellino el temblor lo derribó no ay casa que todas no estan unas por el suelo y otras cascadas para caerse el dormir es en el campo y huertas y no ay dia ni noche que despues acá no tiembla mas de doce veces [...], cayo gran parte del fuerte [...].”..

f.269. “On the afternoon of the fifteenth, there was the wildest whirlwind that I have ever seen, and I believed that it was going to bring the houses[.] and at night badajoz<sup>2</sup> suddenly died[.] and the next day Friday [f. 270] sixteenth came the most wild and long quake of earth that has ever been seen[.] and what was left by the whirlwind was demolished by the earthquake[;] most houses were left on the ground and the rest are ready to fall[.] Sleeping is in the field and gardens and afterward there is no day nor night with less than twelve quakes[...]. A large part of the fort fell down[...].

---

<sup>2</sup> Badajoz is a surname

## DATA REPOSITORY REFERENCES

- Bronk Ramsey, C., 2009, Bayesian analysis of radiocarbon dates: *Radiocarbon*, v. 51, p. 337/360.
- Cisternas, M., Atwater, B.F., Torrejón, F., Sawai, Y., Machuca, G., Lagos, M., Eipert, A., Youlton, C., Salgado, I., Kamataki, T., Shishikura, M., Rajendran, C.P., Malik, J.K., Rizal, Y. and Husni, M., 2005, Predecessors of the giant 1960 Chile earthquake: *Nature*, v. 437, p. 404-407.
- Cisternas, M., Torrejón, F., and Gorigoitia, N., 2012, Amending and complicating Chile's seismic catalog with the Santiago earthquake of 7 August 1580: *Journal of South American Earth Sciences*, v. 33, p. 102-109.
- Cupp, E. E., 1943, Marine plankton diatoms of the west coast of North America: *Bulletin of the Scripps Institution of Oceanography*, v. 5, p. 1-238.
- Donato, S. V., Reinhardt E.G., Boyce, J.I., Pilarczyk, J.E. and Jupp, B.P., 2009, Particle-size distribution of inferred tsunami deposits in Sur Lagoon, Sultanate of Oman: *Marine Geology*, v. 257, p. 54-64.
- Egbert, G. D., Bennett, A. F., & Foreman, M. G., 1994, TOPEX/POSEIDON tides estimated using a global inverse model: *Journal of Geophysical Research Oceans*, v. 99, C12, p. 24821-24852.
- Egbert, G. D., & Erofeeva, S. Y., 2002, Efficient inverse modeling of barotropic ocean tides: *Journal of Atmospheric and Oceanic Technology*, v. 19, p. 183-204.
- Ely, L. L., Webb, R. H., and Enzel, Y., 1992, Accuracy of post-bomb  $^{137}\text{Cs}$  and  $^{14}\text{C}$  in dating fluvial deposits: *Quaternary Research*, v. 38, p. 196-204.
- Farias, M., Vargas, G., Tassara, A., Carretier, S., Baize, S., Melnick, D., and Bataille, K., 2010, Land-Level Changes Produced by the Mw 8.8 2010 Chilean Earthquake: *Science*, v. 329, p. 916. doi:10.1126/science.1192094.
- Fernández de Córdoba, 1575, Excerpt from Carta de Pedro Fernández de Córdoba al licenciado Calderón, teniente é capitán general deste reyno por su Magestad, fecha en 21 de Diciembre de 1575, Ciudad de los Infantes [Angol]: Biblioteca Americana José Toribio Medina, Fondo Manuscritos, Tomo 88, Manuscrito 1214 (Microfilm Ms. M2), fojas 267-271.
- Lay, T., Kanamori, H., Ammon, C.J., Koper, K. D., Hutko, A. R., Ye, L., Yue, H., and Rushing, T. M.(2012). Depth-varying rupture properties of subduction zone megathrust faults. *Jour. Geophys. Res.*,117, B04311, doi:10.1029/2011JB009133
- McCormac, F. G., Hogg, A. G., Blackwell, P. G., Buck, C. E., Higham, T. F. G., & Reimer, P. J., 2004, SHCal04 Southern Hemisphere calibration, 0-11.0 cal kyr BP: *Radiocarbon*, v. 46, no. 3, p. 1087-1092.
- Melnick, D., Cisternas, M., Moreno, M., & Norambuena, R., 2012, Estimating coseismic coastal uplift with an intertidal mussel: calibration for the 2010 Maule Chile earthquake (Mw 8.8): *Quaternary Science Reviews*, v. 42 C, p. 29-42. doi:10.1016/j.quascirev.2012.03.012.

- Moreno, M. S., Bolte, J., Klotz, J., & Melnick, D., 2009, Impact of megathrust geometry on inversion of coseismic slip from geodetic data: Application to the 1960 Chile earthquake: *Geophysical Research Letters*, 36(16), L16310. doi:10.1029/2009GL039276.
- Moreno, M., Melnick, D., Rosenau, M., Baez, J., Klotz, J., Oncken, O., et al., 2012, Toward understanding tectonic control on the Mw 8.8 2010 Maule Chile earthquake: *Earth and Planetary Science Letters*, 321-322, 152–165. doi:10.1016/j.epsl.2012.01.006
- Round, E. E., Crawford, R. M., Mann, D. G. (Eds.), 1990, *The Diatoms: Biology and Morphology of the Genera*: Cambridge University Press, Cambridge, 747 pp.
- Sambridge M., Braun, J. and McQueen, H., 1995, Geophysical parametrization and interpolation of irregular data using natural neighbors: *Geophysical Journal International*, v. 122, p. 837–857.
- Schrader, H., Gersonde, S., 1978. Diatoms and silicoflagellates in the eight meters section of the lower Pliocene on Campo Rosello: *Utrecht Micropaleontological Bulletin*, v. 17, p. 129–176.
- Segall, P., 2010, *Earthquake and Volcano Deformation*: Princeton University Press, 456 p.
- Sims, P.A. (Ed.), 1996. *An Atlas of British Diatoms*: Biopress Ltd, Bristol United Kingdom, 601 pp.
- Troels-Smith, J., 1955, Characterization of unconsolidated sediments: *Geological Survey of Denmark, Series IV*, v. 3, no. 10, 73 p.
- Vidal Gormaz, 1862. Reconocimiento de la Costa de Arauco, *in Memoria de Marina* (Report from the Navy minister to the National Congress): Imprenta Nacional, Santiago, Chile, p. 20-64.
- Vos, P. C. and de Wolf, H., 1993, Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; methodological aspects: *Hydrobiologia*, v. 269/270, p. 285-296.
- Witkowski, A., Lange-Bertalot, H., Metzeltin, D., 2000. *Diatom flora of marine coast I. Iconographia diatomologica annotated diatom micrographs, Vol. 7. Diversity taxonomy-identification*: Koeltzs Scientific Books, Königstein, Germany, 925 pp.