Coseismic Tectonic Surface Deformation during the 2010 Maule, Chile, M_w 8.8 Earthquake

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Tectonic deformation from the 2010 Maule (Chile) M_w 8.8 earthquake included both uplift and subsidence along about 470 km of the central Chilean coast. In the south, deformation included as much as 3 m of uplift of the Arauco Peninsula, which produced emergent marine platforms and affected harbor infrastructure. In the central part of the deformation zone, north of Constitución, coastal subsidence drowned supratidal floodplains and caused extensive shoreline modification. In the north, coastal areas experienced either slight uplift or no detected change in land level. Also, river-channel deposition and decreased gradients suggest tectonic subsidence may have occurred in inland areas. The overall north-south pattern of 2010 coastal uplift and subsidence is similar to the average crestral elevation of the Coast Range between latitudes 33°S and 40°S. This similarity implies that the topography of the Coast Range may reflect long-term permanent strain accrued incrementally over many earthquake cycles. [DOI: 10.1193/1.4000042]

INTRODUCTION

The effects of great subduction-zone interface earthquakes occur on a regional scale, as demonstrated by both the M_w 8.8 2010 Maule and the M_w 9.0 2011 Tohoku (Japan) megathrust earthquakes. Coastal communities may experience multiple, compounding seismic hazards (e.g., strong ground motions, liquefaction, tsunami), and inland areas may experience both strong ground motions and changes in surface elevations and gradients that affect lifelines (e.g., water conveyance facilities). The 27 February 2010 Maule M_w 8.8 earthquake resulted in strong ground motions and damage to man-made structures in central Chile over a distance along the coast of more than 600 km (375 mi) between Valparaíso in the north and Tirúa in the south, and over a distance of at least 100 km (60 mi) inland from the coast (Figure 1).

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Figure 1. Regional shaded relief map showing 2010 earthquake rupture source zone (from [Lorito et al. 2011](#)), locations of field-based measurements of land-level change, selected cities and towns, and topographic profiles AA' and BB'. Barbed line shows subduction zone trench.

Tectonic deformation resulting from the earthquake included uplift and subsidence along about 470 km of the central Chilean coast. To understand the pattern, style, and extent of tectonic surface deformation caused by the 2010 Maule earthquake, this paper summarizes our initial estimates of coseismic vertical displacement based primarily on reconnaissance observations within a few weeks after the earthquake.

This investigation involved both aerial reconnaissance and field measurements on the ground soon after the earthquake. Aerial reconnaissance included high-altitude flights with the Chilean Air Force on 7 March 2010 (from Constitución south to Arauco) and 10 March (from San Antonio to Concepción and Isla Santa María), and low-altitude flights on 9 March and 12 March along the coast near the main-shock epicenter south nearly to Tirúa (including reconnaissance over Isla Santa María), along the Andean foothills east of Curicó and Talca, and several traverses across the Central Valley and the Coast Ranges between the latitudes of Curicó and Lebu (GEER 2010). A flight on 12 March assessed the region surrounding Pichilemu following M_w 6.9 and 6.7 aftershocks (Ryder et al. 2012, Lange et al. 2011). Collectively, the flights covered approximately 460 km of the coastline of central Chile. Ground reconnaissance was conducted between 3 March and 18 March along several traverses that included coastline observations, as well as site visits in the coastal mountains and the Central Valley. Coastal field reconnaissance covered approximately 380 km of the central Chilean coastline between Lebu and Pichilemu, and focused on collecting data on the amount of vertical deformation (i.e., uplift, subsidence) produced by the earthquake (GEER 2010).

REGIONAL SEISMOTECTONIC AND GEOLOGIC SETTING

Central Chile is one of the most seismically active areas on Earth (Lomnitz 2004, Boroschek et al. 2012, this issue) because it overlies the plate boundary between the rapidly converging Nazca and South American tectonic plates. Along the central Chilean plate margin, the oceanic Nazca Plate is subducting beneath the South American continent at a convergence rate of about 62 to 68 mm/yr (Kendrick et al. 2003, Ruegg et al. 2009). Written records suggest that historical ruptures occurred along the central Chilean subduction zone in 1570, 1657, 1751, and 1822 (Graham 1823, Lomnitz 1970, Comte et al. 1986, Kolbl-Ebert, 1999, Ely et al. 2010). Detailed observations of the effects of the 1835 earthquake near Valparaíso are provided by FitzRoy (1839), and Darwin (1839, 1846). Large-magnitude earthquakes have since occurred along the central Chilean coast in 1928, 1960, 1985, and 2010, which collectively span a distance of about 1,500 km along the South American coastline (Lorito et al. 2011). In the area of the 2010 Maule earthquake, plate convergence is slightly oblique and probably has a secondary component of dextral slip, although the exact mechanism by which this strain is accommodated in the shallow crust is complex and incompletely understood (Melnick et al. 2009).

In central Chile, regional geologic characteristics reflect long-term cycles of crustal deformation, punctuated by coseismic coastal uplift and inland subsidence. These processes control onshore depositional environments and geologic deposits and thus affect geotechnical responses to strong vibratory motions and permanent ground deformation. Regionally, central Chile consists of four primary geologic domains (Melnick et al. 2009): (1) the Coastal Platform, consisting of Cenozoic marine deposits and terraces, (2) the Coastal Ranges,

consisting of Permo-Triassic metamorphic rocks and older granitic rocks, (3) the Central Depression, including Cenozoic volcanic rocks overlain by semi-consolidated and unconsolidated alluvial sediments in the Central Valley, and (4) the Main Andean Cordillera, consisting of Mesozoic and Cenozoic volcanic rocks. These rock types and sedimentary basins affect site-specific strong ground motions and thus affect geotechnical responses to earthquake shaking. As a rough generalization, the Coastal Platform is underlain by materials that are comparable (as a first approximation) with NEHRP soil classes (FEMA 2003) ranging from type B to C, to type D; the Coastal Ranges generally are underlain by soft bedrock in NEHRP soil classes B and B to C; the Central Valley is underlain by alluvial soils in classes C and D; and the Andean Cordillera consists of shallow-bedrock soils of mostly class B or perhaps both classes B and C. These relationships suggest that the thick alluvial soils underlying Chile's Central Valley may experience substantial amplification of strong ground motions with respect to the adjacent areas. These generalizations provide a framework to help understand site-specific geotechnical responses to the 2010 Maule earthquake that are documented elsewhere in this issue (Assimaki et al. 2012, this issue).

PATTERN OF LATE QUATERNARY DEFORMATION

Long-term geologic deformation is reflected by uplifted late Quaternary marine terraces along the central Chilean coastline (Campos et al. 2002, Melnick et al. 2009), which indicate long-term net uplift, and the depositional basin beneath the Central Valley of Chile between Santiago and Temuco (Figure 1), which reflects long-term regional subsidence. Melnick et al. (2009) document repeated deformation of the Arauco Peninsula during the Quaternary, showing progressive folding of increasingly older Quaternary marine terraces.

The historical record of large or great earthquakes in central Chile extends back approximately 500 years, as recently summarized by Melnick et al. (2009), who delineated three rupture segments in the region: the Valparaíso segment (which ruptured most recently in 1985), the Concepción segment (which ruptured in 1835), and the Valdivia segment (which ruptured in 1960; Figure 2a). Each of these three historical earthquakes produced substantial vertical deformation of the coastal and inland valley regions. Coseismic uplift during the 1835 earthquake, as measured from uplifted tidal organisms by FitzRoy (1839), included a maximum uplift of 3.0 m at Isla Santa María, 2.4 m at Isla Quiriquina in the Bay of Concepción, 1.8 m at Tubul (near Arauco), 1.5 m at the harbor of Talcahuano, and 0.6 m at Isla Mocha.

This pattern of coastal deformation is distinct from that produced by the 1960 M_w 9.5 Valdivia earthquake and its primary foreshock, as reported by Plafker and Savage (1970), which produced coastal subsidence over a distance of about 700 km southward from the town of Tirúa. Uplift in the 1960 earthquakes occurred only at the northern end of the ruptures, north of Tirúa; the town of Lebu was uplifted approximately 1.3 m, and both Tirúa and Isla Mocha were uplifted about 1 m.

REGIONAL PATTERN OF DEFORMATION FROM 2010 MAIN SHOCK

The 2010 shock produced a variable pattern of uplift and subsidence along the coast of central Chile, documented by spatially extensive satellite geodetic and tsunami waveform data (e.g., Tong et al. 2010, Lay et al. 2010, Moreno et al. 2010, Ryder et al. 2010,

Figure 2. (a) Surface displacements predicted by forward modeling the rupture slip distribution of [Lorito et al. \(2011\)](#). Color ramp shows vertical displacements (uplift/subsidence); barbed line shows subduction zone trench; dashed line indicates location of hinge line between areas of uplift and subsidence. Yellow stars are the epicenters of 1928, 1939, 1960, and 1985 earthquakes, with their approximate source zones outlined with thin black lines (from [Lorito et al. 2011](#)). (b) Plot of 2010 coseismic coastal land-level changes based on data from [GEER \(2010\)](#), [Farias et al. \(2011\)](#), and [Fritz et al. \(2011\)](#); uniform uncertainty of 50 cm assumed for all points.

[Delouis et al. 2010](#), [Lorito et al. 2011](#)). Inversion of these data provides an estimate of the fault-slip distribution pattern, including a large patch of slip roughly coincident with the 1928 earthquake rupture ([Lorito et al. 2011](#); Figure 2a). The level of detail available from these analyses far exceeds the precision of field measurements of vertical deformation produced by past ruptures (e.g., [FitzRoy 1839](#), [Plafker and Savage 1970](#)). The recent high-resolution

datasets confirm a variable pattern of uplift and subsidence along the central Chilean coastline that was identified during early field reconnaissance efforts (Farias et al. 2010, Vargas et al. 2011, GEER 2010). The deformation models show that the coastline crosses the line of no land-level change (the “hinge line”) in several locations (Lorito et al. 2011; Figure 2a). Coastal uplift occurred between Tirua in the south and Constitución in the north, with a maximum of 3.4 m of vertical uplift of the Arauco Peninsula (Fritz et al. 2011; Figure 2b). The regional data suggest as much as about 1 m of subsidence between Constitución and Pichilemu, and possible minor (<0.5 m) uplift near Pichilemu. In addition, the Lorito et al. (2011) model predicts as much as 1 m of subsidence in the Central Valley.

Geologic evidence of uplift and subsidence has been documented via field observations along the coastline between the towns of Pichilemu in the north and Tirua in the south (Figure 2b). Our reconnaissance data supplement the more extensive field campaigns presented by Farias et al. (2010), Castilla et al. (2010), Vargas et al. (2011), and Fritz et al. (2011). At selected coastal sites, the amount of uplift or subsidence was estimated from the upper growth limits of marine intertidal organisms, such as algae, mussels, and barnacles, whose growth is strongly influenced by tidal variation (Ortlieb et al. 1999, Castilla and Oliva, 1990). Our measurements of estimated uplift based on the uplifted marine organisms have uncertainties of ± 0.5 m, but nevertheless define broad spatial variations in the magnitude of vertical deformation along the coast. Observations also included interviews of local residents, fishermen, and public officials to gather anecdotal accounts of changes in sea level, noticeable shifts in the shoreline and surf breaks, and erosion features that may reflect earthquake-related vertical deformation. The combined field data suggest that, in a general sense, coastal coseismic deformation was characterized by coseismic uplift in the area between the towns of Tirua and Constitución (38.3°S to 35.3°S) and possibly between Pichilemu and Navidad (34.4°S to 33.9°S). Field data and subsequent deformation models also suggest the occurrence of coseismic subsidence between Constitución and Pichilemu (35.3°S to 34.4°S).

COSEISMIC COASTAL UPLIFT (38.0°S TO 35.3°S, AND 34.4°S TO 33.9°S)

Aerial reconnaissance on 9 March (10 days after the main shock) included observations of the Arauco Peninsula and the town of Lebu on the southwestern side of the peninsula and identified the presence of an uplifted (formerly active) tidal platform cut on bedrock (Figure 3). From the air, the tidal platform appears white because of dead, bleached intertidal organisms, and brown because of exposed kelp (Castilla and Oliva 1990). An island and its lighthouse northwest of the Lebu Harbor were uplifted enough to form a peninsula; the lighthouse was undamaged by tsunami waves (GEER 2010). Field observations near Lebu show that seawater drained from this platform without high flow velocities expected during tsunami surge, as indicated by the presence of attached kelp draped on the wave-cut platform, scattered buoyant trash, and several species of mobile intertidal organisms (e.g., crabs, starfish) preserved in a “life assemblage.” The coastline near Lebu experienced uplift of approximately 1.8 m based on measured elevations of uplifted tidal organisms attached to sandstone bedrock and the former high-tide level on the Lebu harbor wall. Local fishermen indicated that sea level went down (i.e., the coast was uplifted) approximately 1.8 m; fishing boats were stranded above high tide and a wooden jetty that is now above tidal level (Figure 4). Almost all of the boats in the Lebu Harbor, including a large ferry, were grounded as a result of the uplift; the absence of tsunami damage to wooden-frame residences at the same elevation as

Figure 3. Oblique aerial photograph looking north along the western coastline of the Arauco Peninsula, near the town of Lebu, showing uplifted wave-cut platform and exposed intertidal zone (S37.548111° W73.635672°; 03/09/2010). Tidal stage at time of photograph was about +1.0m above mean sea level.

Figure 4. Northeastern margin of Lebu Harbor, with stranded fishing boat and emergent wooden jetty; area to the left was a former tidal flat adjacent to harbor channel (S37.600789° W73.656317°; 03/10/2010). Tidal stage at time of photograph was about +1.0m above mean sea level.

the harbor docks show that the tsunami wave did not inundate areas outside of the harbor channel. Although originally only slightly above sea level, structures in Lebu were unaffected by tsunami waves. Pre-2010 inundation-hazard zonation maps generated using pre-earthquake bathymetry and topography (CITSU 2002) predict inundation in the low-lying parts of Lebu; the area actually inundated in 2010 was far smaller than expected (Figure 5). The pre-2010 inundation map was calculated based on detailed bathymetric, topographic and hydrographic data, and tsunami characteristics from the great 1835 and 1960 earthquakes (CITSU 2002). The relatively minor coastal damage in Lebu suggests that inundation may have been lessened by coastal uplift.

North of Lebu, coseismic uplift of the Arauco Peninsula near Punta Lavapie and of Isla Santa María exceeded 2 m (Farias et al. 2010, Vargas et al. 2011, Fritz et al. 2011), and probably represents the maximum amount of 2010 coseismic uplift. This area coincides

Figure 5. Pre-2010 tsunami inundation map of town of Lebu, showing interpreted inundation limit as dashed line (after CITSU, 2002); thick black line showing tsunami inundation extent interpreted from Google Earth imagery dated 2 October 2010; and location of uplift measurement sites by GEER (2010).

with the Arauco anticline, which [Melnick et al. \(2006\)](#) show has undergone long-term late Quaternary uplift and progressive folding of increasingly older Quaternary marine terraces. The long-term pattern of deformation is complex and appears related to segmentation of the subduction zone and upper crustal faults ([Melnick et al. 2006](#)); the peninsula experienced coseismic uplift both in 1960 ([Plafker and Savage 1970](#)) and in 2010. Northward from the Arauco Peninsula, coseismic uplift of at least 1 m occurred in 2010 over a stretch of coastline more than 100 km long, between the towns of Lebu and Concepción (Figure 2b).

Coseismic uplift of more than 0.5 m occurred from Concepción north nearly to the city of Constitución, a distance of approximately 160 km. Near the town of Pelluhue (Figure 1), anecdotal evidence from local fishermen and measurement of the upper growth limit of tidal marine organisms (adjusted for hourly tidal changes) suggests that the earthquake raised the shoreline by about 2 m ([GEER 2010](#)). Similarly, rocky intertidal areas exposed just after low tide at Los Pellines appear to be uplifted about 1.6 m based on upper growth limits of mussels and algae ([GEER 2010](#)). Our observations of substantial uplift at Pellehue and Los Pellines augment those of other workers ([Farias et al. 2010](#), [Vargas et al. 2011](#), [Fritz et al. 2011](#)), but are higher. At Los Pellines (latitude 35.471°S, Figure 2b), the [GEER \(2010\)](#) measurement is about 1.5 m higher than a nearby measurement at Las Canas (latitude 35.469°S; [Farias et al. 2011](#)). This difference is attributed to a possible overestimation at the rocky Los Pellines site because of direct exposure to wave activity that may have allowed intertidal organisms to grow to higher elevations. Nevertheless, the suite of coastal measurements indicate that coastal uplift extended nearly as far north as Concepción (latitude 35.33°S; Figure 2a). Overall, the 300 km stretch of coastline that experienced substantial uplift in 2010 essentially coincides with the 1835 earthquake source zone, and overlaps slightly on the north with the 1928 source zone and on the south with the 1960 source zone (Figure 2a).

Regional deformation models suggest that coseismic uplift decreases eastward from the coastline (e.g., [Lorito et al. 2011](#); Figure 2). Although there are very few field-based measurements that enable construction of an east-west profile, Figure 6 shows measurements at a latitude of 37°S, which crosses the northern tip of Isla Santa María, the northern

Figure 6. Plot of measured land-level changes along a transect at latitude 37°S (see Figure 1 for profile location AA'). Data points from [Farias et al. \(2011\)](#) and [Fritz et al. \(2011\)](#) within latitudes 36.7° and 37.3°S; uniform uncertainty of 50 cm assumed for all points.

Golfo de Arauco, and into the Coast Ranges east of the town of Lota. This profile shows that greater uplift occurred closer to the subduction zone (to the west, on Isla Santa Maria), lesser uplift to the east near the town of Arauco, and subsidence along the Rio Bío-Bío in the Coast Ranges (Figure 6). This deformation pattern is consistent with the uplift pattern modeled by Lorito et al. (2011) based on fault slip and tsunami characteristics.

COSEISMIC COASTAL SUBSIDENCE (35.3°S TO 34.4°S)

In contrast, the area from Constitución north to the town of Bucalemu experienced coseismic subsidence (Figure 1). Along the sparsely inhabited section of coastline directly south of Iloca (Figure 1), the area of tsunami inundation was the greatest observed during our reconnaissance in early March 2010, with evidence of tsunami scour and erosion present across the entire, 1- to 2-km-wide coastal plain. Prior to the earthquake, this coastal plain contained well-developed sets of active beach dunes, which were easily removed by tsunami waves in 2010. In contrast, similar coastal dune fields in areas that experienced coseismic uplift (e.g., Golfo de Arauco and Arauco Peninsula) remained intact and unaffected by tsunami waves. Fritz et al. (2011) indicate that the area near Iloca experienced tsunami flow depths of about 4 to 8 m, and areas directly to the north and south generally had flow depths of about 8 to 16 m. The uncertainty in tsunami flow depth near Iloca (1 to 3 m uncertainty) is equal to or larger than the amount of interpreted tectonic subsidence (less than 1 m).

At the mouth of Rio Mataquito near Iloca, erosion and/or subsidence lowered and submerged the barrier sand spit (GEER 2010, Villagran et al. 2011). The barrier spit at the mouth of Rio Mataquito was breached by the tsunami and suffered extensive erosion. Field observations in April 2010 showed that, after the March 2010 earthquake, ocean waves were breaking over a submerged remnant of the barrier spit. Evidence of seawater flooding along the post-seismic shoreline, formerly the left bank of the Rio Mataquito outlet, suggests the area subsided during the earthquake. Near the village of Iloca, field observations in April 2010 showed that ocean waves were encroaching onto lower parts of pasture fields that were not inundated prior to the earthquake (Figure 7). These features indicate the occurrence of coseismic coastal subsidence.

Evidence for coseismic subsidence at the town of Bucalemu (Figure 1) includes a 150-m eastward (landward) shift in the shoreline, extensive erosion of the beach, and a previously protected lagoon that is now fully connected with the ocean. Pre-earthquake images of Bucalemu show a 25-m-wide sandy beach that was submerged in April 2010 (GEER 2010). These changes probably are related to a combination of tsunami scour and tectonic subsidence; field observations in April 2010 favored an interpretation that the beach at Bucalemu was lowered about 0.5 m during the earthquake, and was inundated by the tsunami. The coincidence of areas affected by subsidence and tsunami inundation near Iloca and Bucalemu suggest that areas affected by subsidence also experienced relatively more extensive tsunami damage.

COSEISMIC INLAND SUBSIDENCE

The Central Valley of Chile represents the long-term development of a forearc depositional basin, which includes continued subsidence and sediment aggradation over geologic time scales. This long-term deformation is reflected by modern coseismic subsidence in the Central Valley produced by the 1960 and 2010 earthquakes, based on field observations

Figure 7. Ground photograph looking south from near Iloca, along the present coastline. Inundated grassy area in middle ground suggests subsidence (S34.982047° W72.181792°; 03/08/2010).

(Plafker and Savage, 1970) and teleseismic and geodetic data (Ryder et al. 2010, Lorito et al. 2011; Figure 2a). Our field reconnaissance supports the occurrence of coseismic tectonic subsidence in the western part of the Central Valley during 2010, as best exemplified by observations of the Rio Bío-Bío channel during aerial overflights and field reconnaissance from 9 March to 11 March 2010. Farias et al. (2010) estimate approximately 0.5 to 1.0 m of tectonic lowering based on changes to the Rio Bío-Bío about 35 km upstream of the coast. This location is directly upstream of the hingeline defined by Lorito et al. (2011). In this area, drowning of the channel and banks (without changes in river discharge and during seasonal discharge lows) suggests that the gradient of the Rio Bío-Bío decreased in March 2010. These changes appear to be a result of uplift of the coastal range and/or tectonic subsidence along the western part of the Central Valley. Systematic analysis of channel and terrace gradients along major rivers crossing the Central Valley may yield additional data on the amount and distribution of 2010 and older surface deformation.

DISCUSSION

The pattern of coseismic deformation along the central Chilean coastline is an important characteristic of the earthquake, both because it provides a physical basis for seismic-source zone modeling and because the pattern may have affected the distribution of damage to engineered structures. As shown in Figure 2a, the deformation pattern varied in both north-south and east-west orientations. Although the central Chilean coastline generally is parallel with the subduction zone and the NNE strike of the 2010 megathrust rupture plane, the spatial variability of 2010 coseismic deformation and the irregularity of the Chilean coastline together affected the pattern of onshore deformation. As a result, the amount of coseismic deformation was variable along the coastline.

The pattern of coseismic deformation appears to have a possible spatial relationship with pre-2010 earthquake source zones. The greatest amount of 2010 coseismic uplift occurred at the Arauco Peninsula, which coincides with the area of overlap of the 1960 and 2010 source zones. The area of 2010 coseismic coastal uplift generally coincides with the source zone of the 1835 earthquake (Figure 2a); the area of 2010 coseismic coastal subsidence generally coincides with the source zone of the 1928 earthquake (Figure 2a). The coastline north of Pichilemu to beyond Valparaíso lies in the source zone of the 1985 earthquake, and experienced either little or no coseismic land-level change.

There appears to be a spatial relationship between the pattern of coseismic coastal onshore uplift and subsidence measured following the 2010 earthquake and the generalized elevation of the Coast Ranges in central Chile. Figure 8 shows the 2010 coastal land-level changes, which reflect the short-term uplift/subsidence pattern in the most-recent earthquake, and the average elevation of the crest of the Coast Ranges, which is judged to reflect the overall uplift/subsidence pattern of the Coast Ranges over a longer, geologic time scale. The Coast Ranges along the profile shown on Figure 8 consist of primarily Mesozoic metamorphic rocks and older granitic rocks (CSNGM 2003); the effect of rock type on relative elevation along this profile is probably negligible. The elevation profile illustrates the relatively high relief associated with the Arauco Peninsula between latitudes 37° and 38°S (Melnick et al. 2009). The profile also shows a relatively high area between 35.5° and 36.5°S, which spatially coincides with the GEER (2010) measurements of more than 1 m of uplift between Los Pellines and Pellehue (Figure 8). The lowest part of the crestal elevation profile is near the town of Llico, which is inland of the towns of Bucalemu and Iloca where the greatest amount of coseismic subsidence occurred. As a basis for comparison, we generalize both the average crestal elevation and the field-based uplift/subsidence data using a fourth-order polynomial trendline (Figure 8), which appears to be the best fit for the two data sets. Interestingly, the polynomial trendline for the 2010 coastal deformation pattern generally parallels the trendline for the crestal elevation (Figure 8), with relatively low values

Figure 8. Plot of measured coastal land-level changes (see Figure 2b), and average elevation of Coast Range crest (see Figure 1 for profile location BB'). Elevation data are the 500-pt running averages from 90-m-resolution digital elevation model. Trendlines represent fourth-order polynomial regressions for both data sets.

(of uplift or average elevation) between latitudes 33° and 35°S, moderate values from 35° to 37°S, and high values from 37° to 39°S.

The parallelism of these two trendlines suggests that the 2010 coseismic deformation pattern generally reflects the overall long-term pattern of deformation of the Coast Ranges. Although individual earthquakes may produce variable patterns of coastal deformation, the long-term average range uplift appears to be similar to the 2010 deformation pattern. Considering that the extent of the 2010 rupture generally is coincident with the 1835 rupture (Lorito et al. 2011), we speculate that the deformation pattern of these two historical events may have been similar. However, because the variability in event-to-event deformation patterns in central Chile is not known, this interpretation only suggests that individual-rupture deformation patterns may be persistent through time.

The 2010 earthquake affected operations at several port and harbor facilities, primarily because liquefaction-induced ground failure displaced and distorted waterfront structures (GEER 2010, Bray et al. 2012, this issue), but also because of regional uplift. The uplift of harbor facilities in the town of Lebu (Figure 4) was significant because the fishing-industry fleet, which is a major component of the local economy, was unable to reach uplifted quay walls and loading platforms. Many boats were stranded in the uplifted harbor channel; others that were at sea during the earthquake could not return easily to the harbor, and were moored outside the harbor inlet. Observations made one year later indicate that several fishing boats remain on the uplifted harbor shoals. Similarly, the local fishing industries in the towns of Laraquete and Lota (as well as others bordering Golfo de Arauco) were affected by uplifted docks and exposed harbor shoals.

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REFERENCES

- Assimaki, D., Ledezma, C., Montalva, G. A., Tassara, A., Mylonakis, G., and Boroschek, R., 2012. Site effects and damage patterns, *Earthquake Spectra* **28**, this issue.

- Boroschek, R., Contreras, V., Kwak, D. Y., and Stewart, J. P., 2012. Strong ground motion attributes of the 2010 M_w 8.8 Maule Chile earthquake, *Earthquake Spectra* **28**, this issue.
- Bray, J. D., Rollins, K., Hutchinson, T., Verdugo, R., Ledezma, C., Mylonakis, G., Assimaki, A., Montalva, G., Arduino, P., Olson, S. M., Kayen, R., Hashash, Y. M. A., and Candia, G., 2012. Effects of ground failure on buildings, ports, and industrial facilities, *Earthquake Spectra* **28**, this issue.
- Campos, J., Hatzfeld, D., Madariaga, R., López, G., Kausel, E., Zollo, A., Iannacone, G., Fromm, R., Barrientos, S., and Lyon-Caen, H., 2002. A seismological study of the 1835 seismic gap in South Central Chile, *Phys. Earth Planet. Int.* **132**, 177–195.
- Castilla, J.C., and Oliva, D., 1990. Ecological consequences of coseismic uplift on the intertidal kelp belts of *Lessonianigrescens* in central Chile, *Estuarine, Coastal, and Shelf Science* **31**, 45–56, doi:10.1016/0272-7714(90)90027-O.
- Castilla, J. C., Manríquez, P. H., and Camano, A., 2010. Effects of rocky shore coseismic uplift and the 2010 Chilean mega-earthquake on intertidal biomarker species, *Mar. Ecol. Prog. Ser.* **418**, 17–23, doi: 10.335/meps08830.
- Chile Servicio Nacional de Geología y Minería (CSNGM) Subdirección Nacional de Geología, 2003. Mapa geológico de Chile: versión digital: Publicación geológica digital no. 4, versión 1.0, scale 1:1,000,000, available at <http://www.ipgp.fr/~dechabal/Geol-millon.pdf>.
- Comte, D., Eisenberg, A., Lorca, E., Pardo, M., and others, 1986. Chile earthquake of 3 March 1985, A repeat of previous great earthquakes in the region?, *Science* **233**, 449–453.
- Darwin, C., 1839. *Voyages of the Adventure and Beagle, Vol III, Journals and Remarks 1832–1836*: Henry Colburn, London.
- Darwin, C., 1846, *Geological Observations of South America*, Smith and Elder, London, 279 pp.
- Delouis, B., Nocquet, J-M., and Vallée, M., 2010. Slip distribution of the 27 February 2010 M_w 8.8 Maule earthquake, central Chile, from static and high-rate GPS, InSAR, and broadband teleseismic data, *Geophys. Res. Lett.* **37**, L17305.
- Ely, L. L., Cisternas, M., Wesson, R. L., and Lagos, M., 2010. Geological evidence of predecessors to the 2010 earthquake and tsunami in south-central Chile, *Abstract G32A-05 presented at 2010 Fall Meeting, AGU*, San Francisco, CA.
- 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* **329**, 916, DOI: 10.1126/science.1192094.
- Federal Emergency Management Agency (FEMA), 2003. *NEHRP Recommended Provisions and Commentary for Seismic Regulations for New Buildings and Other Structures*, 2003 Edition, <http://www.fema.gov/library/viewRecord.do?id=2020>.
- FitzRoy, R., 1839. *Voyages of the Adventure and Beagle, Vol III*, J. L. Cox & Sons, London.
- Fritz, H. M., Petroff, C. M., Catalán, P. A., Cienfuegos, R., Winckler, P., Kalligeris, N., Weiss, R., Barrientos, S., Mencses, G., Valderas-Bermejo, C., Ebeling, C., Papadopoulos, A., Contreras, M., Almar, R., and Dominguez, J. C., 2011. Field survey of the 27 February 2010 Chile tsunami, *Pure Appl. Geophys.* **168**, 1989–2010.
- Geoenvironment Extreme Events Reconnaissance (GEER) Team, 2010. *Geo-Engineering Reconnaissance of the 27 February 2010 Maule, Chile Earthquake*, available at http://www.geerassociation.org/GEER_PostEQReports/Maule_Chile_2010/Cover_Chile_2010.html.
- Graham, M., 1823. An account of some effects of the late Earthquakes in Chili, Extracted from a letter to Henry Warburton, Esq. V.P.G.S., in *Transactions of the Geological Society London*, Ser. II, v. 1, 413–415.

- Kendrick, E., Bevis, M., Smalley, Jr., R., Brooks, B., Barriga Vargas, R., Lauría, E., and Souto Fortes, L.P., 2003. The Nazca–South America Euler vector and its rate of change, *J. South Am. Earth Sci.* **16**, 125–131, doi:10.1016/S0895-9811(03)00028-2.
- Kolbl-Ebert, M., 1999. Observing orogeny—Maria Graham's account of the earthquake in Chile in 1822, *Episodes* **22**, 36–40.
- Lange, D., Tilmann, F., Barrientos, S. E., Contreras-Reyes, E., Methe, P., Moreno, M., Heit, B., Agurto, H., Bernard, P., Vilotte, J.-P., and Beck, S., 2012. Aftershock seismicity of the 27 February 2010 M_w 8.8 Maule earthquake rupture zone, *Earth and Planetary Science Letters* **317–318**, 413–425.
- Lay, T., Ammon, C. J., Kanamori, H., Koper, K. D., Sufri, O., and Hutko, A. R., 2010. Teleseismic inversion for rupture process of the 27 February 2010 Chile (M_w 8.8) earthquake, *Geophysical Research Letters* **37**.
- Lomnitz, C., 1970. Major earthquakes and tsunamis in Chile during the period 1935 to 1955, *Geologische Rundschau* **59**, 938–960.
- Lomnitz, C., 2004. Major earthquakes of Chile: A historical survey, 1535–1960: *Seismological Research Letters* **75**, 368–378.
- Lorito, S., Romano, F., Atzori, S., Tong, X., Avallone, A., McCloskey, J., Cocco, M., Boschi, E., and Piatenesi, A., 2011. Limited overlap between the seismic gap and coseismic slip of the great 2010 Chile earthquake, *Nature Geoscience*, doi:10.1038/NGEO1073.
- Melnick, D., Bookhagen, B., Echtler, H. P., and Strecker, M. R., 2006. Coastal deformation and great subduction earthquakes, Isla Santa Maria, Chile (37°S), *Geol. Soc. Amer. Bull.* **118**, 1463–1480, doi: 10.1130/B25865.1.
- Melnick, D., Bookhagen, B., Strecker, M. R., and Echtler, H. P., 2009. Segmentation of megathrust rupture zones from fore-arc deformation patterns over hundreds to millions of years, Arauco Peninsula, Chile, *J. Geophys. Res.* **114**, B01407, doi:10.1029/2008JB005788.
- Moreno, M., Rosenau, M., and Oncken, O., 2010. 2010 Maule earthquake slip correlates with pre-seismic locking of Andean subduction zone, *Nature* **467**, 198–202.
- Ortlieb, L., Barrientos, S., and Guzman, N., 1999. Coseismic coastal uplift and coralline algae record in northern Chile: The 1995 Antofagasta Earthquake Case, *Quat. Sci. Rev.* **15**, 949–960.
- Plafker, G., and Savage, J. C., 1970. Mechanism of the Chilean earthquake of May 21 and 22, 1960, *Geol. Soc. Amer. Bull.* **81**, 1001–1030, doi:10.1130/0016-7606(1970)81[1001:MOTCEO]2.0.CO;2.
- Proyecto CITSU Cartas de Inundacion por Tsunami (CITSU), 2002. *Puerto Lebu, Carta de Inundacion por Tsunami, Referida al Evento del Año 1835*, Servicio Hidrografico Y Oceanografico De La Armada De Chile, available at http://www.snamchile.cl/citsu/pdf/citsu_lebu.pdf.
- Ruegg, J. C., Rudloff, A., Vigny, C., Madariaga, R., de Chabalier, J. B., Campos, J., Kausel, E., Barrientos, S., and Dimitrov, D., 2009. Interseismic strain accumulation measured by GPS in the seismic gap between Constitución and Concepción in Chile, *Phys. Earth Plan. Int.* **175**, 78–85.
- Ryder, I. M. A., Rietbrock, A., Bevis, M. G., Bacz, J. C., Barrientos, S. E., Bataille, K., Parra, K., and Brooks, B. A., 2010. Postseismic investigation of the February Chile earthquake: relaxation processes and the relationship of seismic and aseismic activity, *Abstract G33A-0821 presented at 2010 Fall Meeting, AGU*, San Francisco, CA.
- Ryder, I., Rietbrock, R., Kelson, K., Burgmann, R., Floyd, M., Socquet, A., Vigny, C., and Carrizo, D., 2012. Large extensional aftershocks in the continental forearc triggered by the 2010 Maule earthquake, Chile, GJI DOI: 10.1111/j.1365-246X.2011.05321.x.

- Tong, X. D., Sandwell, K., Luttrell, Brooks, B., Bevis, M., Shimada, M., Foster, J., Smalley, Jr., R., Parra, H., Báez Soto, J. C., Blanco, M., Kendrick, E., Genrich, J., and Caccamise II, D. J., 2010. The 2010 Maule, Chile, earthquake: Downdip rupture limit revealed by space geodesy, *Geophys. Res. Lett.* **37**, L24311, doi: 10.1029/2010GL045805.
- Vargas, G., Farias, M., Carretier, S., Tassara, A., Baize, S., and Melnick, D., 2011. Coastal uplift and tsunami effects associated to the 2010 M_w 8.8 Maule earthquake in Central Chile, *Andean Geology* **38**, 219–238.
- Villagran, M. F., Cienfuegos, R., Almar, R., Catalán, P. A., and Camaño, A., 2011. Natural post-tsunami recovery of the Mataquito River mouth, after the 2010 Chilean tsunami, *Abstract OS44B-05 presented at 2011 Fall Meeting, AGU*, San Francisco, CA.

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