Andean Geology 39 (3): 558-563. September, 2012
doi: 10.5027/andgeoV39n3-a11

Andean Geology
formerly Revista Geológica de Chile
www.andeangeology.cl

GEOLOGICAL NOTE

Darwin seismic gap closed by the 2010 Maule earthquake

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ABSTRACT. The Maule earthquake (Mw 8.8) that affected south-central Chile on February 27, 2010 was preceded by the 1835 event documented by FitzRoy and Darwin. The relation between both events has been controversial. Fault slip in 2010 estimated by Lorito *et al.* (2011) is less than expected from 175 years of strain accumulation, leading them to conclude only limited overlap between the 2010 and 1835 events, and that a Mw 7.5-8 event could still strike the Concepción region. However, Lorito *et al.*'s model was based on displacements obtained from only 6 GPS stations and underpredicts observations from recent studies. Here we show that an alternative model based on 169 GPS displacements reproduces the data better, suggesting Lorito *et al.*'s main conclusion is not correct. Based on a slip deficit map, we suggest the seismic gap opened in 1835 was most likely closed in 2010.

Keywords: Maule earthquake, Coseismic slip distribution, Slip deficit, Seismic gap.

RESUMEN. Laguna sísmica de Darwin cerrada por el terremoto del Maule 2010. El terremoto del Maule (Mw 8.8) que afectó el centro-sur de Chile el 27 de febrero del 2010 fue precedido por el evento de 1835 documentado por FitzRoy y Darwin. La relación entre ambos eventos ha sido controversial. Los desplazamientos para el 2010 estimados por Lorito *et al.* (2011) son menores a los esperados en 175 años de acumulación de acortamiento, observación que los llevó a concluir que los eventos del 2010 y 1835 tenían una similitud restringida y que, por ende, un evento de Mw 7.5 a 8 podría afectar la zona de Concepción en el futuro cercano. El modelo de Lorito *et al.* (2011) usó desplazamientos obtenidos de solo 6 estaciones de GPS y subestima observaciones de estudios recientes. Aquí mostramos que un modelo alternativo basado en 169 estaciones de GPS reproduce los datos mejor, y sugiere que la principal conclusión de Lorito *et al.* (2011) no es correcta. Basados en un mapa de déficit de deslizamiento sugerimos que la laguna sísmica abierta en 1835 fue muy probablemente cerrada el 2010.

Palabras clave: Terremoto del Maule, Distribución de desplazamiento cosísmico, Déficit de desplazamiento, Laguna sísmica.

1. Introduction: The 2010 Maule earthquake

The Maule earthquake of moment magnitude (Mw) 8.8 struck south-central Chile on February 27, 2010 causing a devastating tsunami. Its predecessor on February 20, 1835 was famously documented by FitzRoy and Darwin (Darwin, 1851; Fitzroy, 1839). This fame has concealed additional less considered reports from the scientists' view. These sources tell that shaking distribution (El Araucano, 1835; Guzmán, 1836; Lozier *et al.*, 1835; El Mercurio de Valparaíso, 1835; Bonafous, 1835), tsunami inundation (Caldcleugh, 1836; Sutcliffe, 1839, 1841), and coastal uplift patterns (Dumont D'Urville, 1841; Caldcleugh, 1836; Guzmán, 1836) were rather similar in both events suggesting they ruptured an analogous segment of the plate boundary (Cisternas *et al.*, 2010).

Before 2010, this region had been long recognized as a mature seismic gap (Barrientos, 1987; Campos *et al.*, 2002), and surface velocities estimated from Global Positioning System (GPS) measurements suggested a high degree of coupling between the Nazca and South American plates (Ruegg *et al.*, 2009; Moreno *et al.*, 2010; Moreno *et al.*, 2011; Métois *et al.*, 2012). Theoretically, the average slip available for such a megathrust earthquake - the slip deficit - equals the plate convergence rate multiplied by the time since the last earthquake (175 years in this case) and the degree of plate coupling. This assumes that all the accumulated strain was released by the last earthquake (the 1835 event in this case) and neglects post-seismic deformation. Lorito *et al.* (2011) inverted geodetic and tsunami data to obtain plate-boundary slip during the Maule earthquake. Their modeled slip was lower than the theoretical slip deficit, particularly in a large area located immediately north of the city of Concepción, concluding that another damaging earthquake of M_w 7.5-8 could still strike this region (Lorito *et al.*, 2011). This was further highlighted by Lay (2011) who discussed differences among existing slip models.

2. Coseismic slip distribution and slip deficit after the 2010 earthquake

Because of the shallow dip of subduction faults, inversions for coseismic slip are mostly sensitive to horizontal displacements commonly obtained from Global Positioning System (GPS) stations in the near field (Okada, 1985). Lorito *et al.*'s model included only six GPS displacements, located mostly in the northern rupture sector (squares in Fig. 1a), and the adopted fault geometry was based on a single profile propagated along strike, discarding along-strike variations in dip and the complexity evident from a wealth of geophysical data (Tassara *et al.*, 2006). Oversimplified fault geometries may introduce significant artifacts in the slip distribution (Moreno *et al.*, 2009). Using near-field tsunami waveforms in the slip inversion requires detailed local bathymetry, data not included in Lorito *et al.*'s model. Their model failed to reproduce coastal uplift measurements in the southern part of the rupture (Farías *et al.*, 2010), where residuals from radar interferometry (InSAR) were also high (Fig. 3c and 3d of Lorito *et al.*, 2011), and it significantly misfits GPS displacements from other studies (Vigny *et al.*, 2011; Moreno *et al.*, 2012) (Fig. 1a). In addition, Lorito *et al.*'s model underpredicts their own GPS displacements by as much as 0.9 m at Constitución (Fig. 3b of Lorito *et al., 2011*). The main conclusions of Lorito *et al. (2011)*: 'limited overlap with the seismic gap' and 'zones of very high coupling in the Darwin gap remain unbroken' are likely incorrect because: **1.** their model underpredicts slip in the region where this coupled zone was located and **2.** the 1835 rupture was *a priori* assumed to be much smaller than suggested by historical data (Cisternas *et al.*, 2010).

An alternative slip model (Fig. 1b) has been derived from 169 GPS vectors covering the entire rupture zone and the far field (Moreno *et al.*, 2012), together with InSAR (Tong *et al.*, 2010) and land-level change data (Melnick *et al.*, 2012a). This new finite-element model integrates realistic fault and lithospheric geometries compiled from various geophysical data sets (Tassara and Echaurren, 2012), which include a seismic profile in the epicentral region of the Maule earthquake (Moscoso *et al.*, 2011). Compared to Lorito *et al.*, the new model reproduces the data with half the residuals standard error, resulting in more slip in the southern and less in the northern sectors.

Furthermore, a slip deficit map including: 1960 earthquake slip that overlapped ~150 km of the 2010 rupture (Moreno *et al.*, 2009); the 1928 and 1985 events; heterogeneous plate coupling (Moreno *et al.*, 2010, 2011); and the new slip distribution (Moreno *et al.*, 2012) shows null or negative values in most of the 2010 rupture with a small positive area (Fig. 1c). The slip deficit map obtained from this new slip

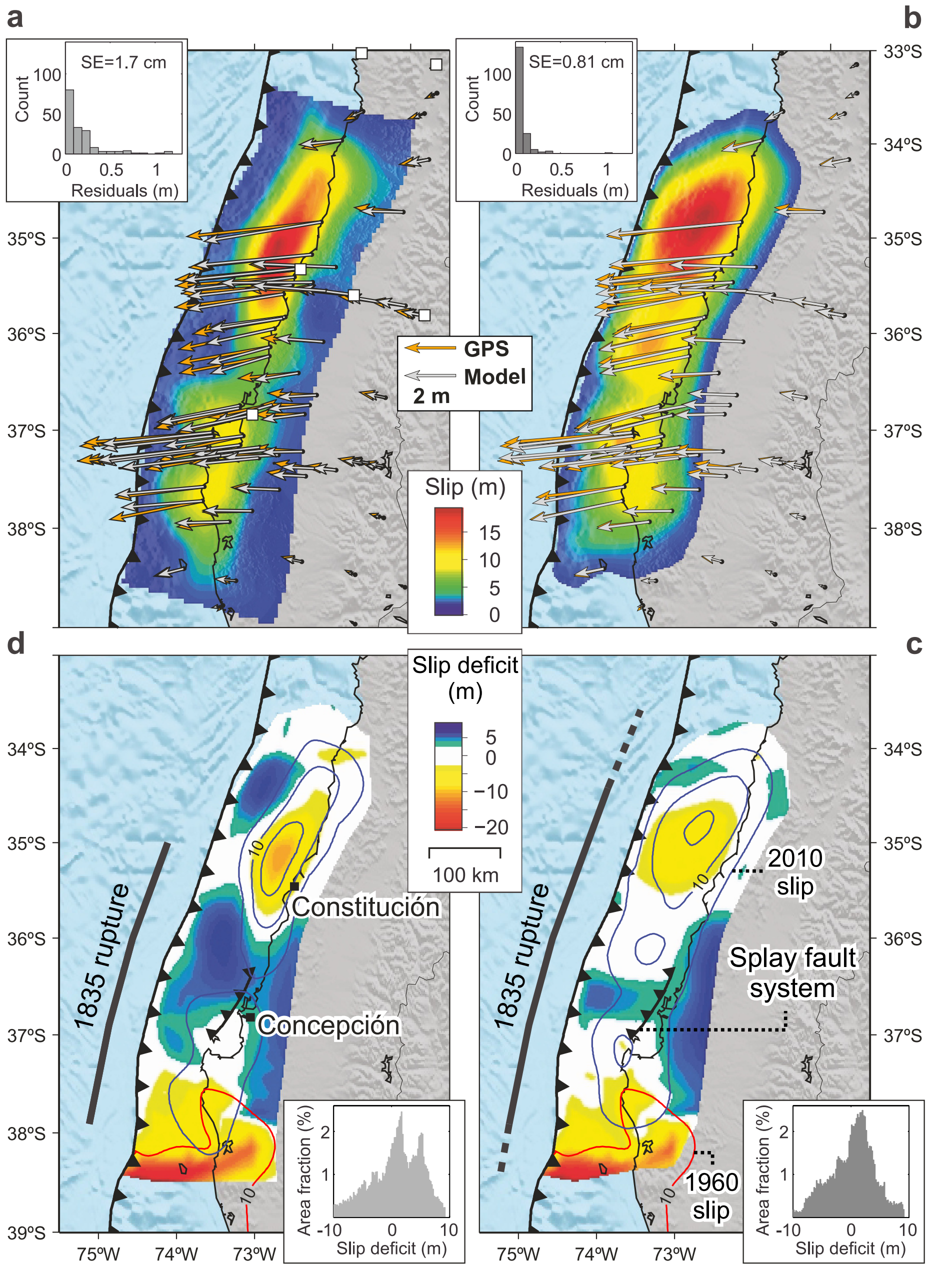

FIG. 1. Modeled plate-boundary slip during the 2010 Maule earthquake and slip deficit of Darwin seismic gap. **a.** Slip from Lorito *et al.* (2011) with computed (grey arrows) and GPS (orange arrows) displacements (Vigny *et al.*, 2011; Moreno *et al.*, 2012). White squares show GPS sites used by Lorito *et al.* (2011). Inset shows histogram of residuals between measured and modeled displacements. SE-standard error. Note that Lorito *et al.*'s model underestimates GPS displacements between 36-37.5°S where they forecasted a Mw 7.5-8 earthquake; **b.** Alternative slip distribution (Moreno *et al.*, 2012) with modeled and GPS displacements. Inset shows histogram of residuals; **c.** Slip deficit after the 2010 earthquake including plate coupling over 175 years at an heterogeneous rate (Moreno *et al.*, 2010; Moreno *et al.*, 2011), slip release by the 1960, 1928, and 1985 events (Moreno *et al.*, 2009; Moreno *et al.*, 2012), and the slip distribution of Moreno *et al.* (2012). Note that the deficit is negative or null over most of the rupture zone, suggesting the 2010 earthquake closed the gap opened in 1835. Extent of 1835 rupture inferred from a compilation of historical sources (see text). The Santa María splay fault system, which slipped during the Maule earthquake (Melnick *et al.*, 2012b), may be associated with the positive slip deficit near Concepción; **d.** Slip deficit using the same constraints as in (c) but with the slip model of Lorito *et al.* Note the large positive region northwest of Concepción. The extent of the 1835 rupture assumed by Lorito *et al.* (2011) is shown.

model results in a much smaller area of positive deficit in comparison with the slip deficit map obtained using the same constraints but the slip distribution of Lorito *et al.* (Fig. 1d). The small area of positive deficit might be associated with a splay fault that slipped during the 2010 earthquake (Melnick *et al.*, 2012b), not yet included in the model; in addition, deep afterslip occurred in this region immediately after the earthquake (Vigny *et al.*, 2011), and might also partly account for the positive deficit.

Thus, we propose that the 2010 event most likely closed Darwin seismic gap. Our re-analysis suggests the 34-38°S region is unlikely prone to the occurrence of another large plate-boundary earthquake in the near future. Potential earthquakes will rather occur on adjacent plate-boundary segments such as the Valdivia segment to the south (Moreno *et al.*, 2011) or the Central Chile segment to the north. Additional sources of future earthquakes within the Maule earthquake rupture could be the outer rise and faults in the upper-plate.

3. Discussion

The tenuous conclusion of Lorito *et al.* (2011), which was based on a basic model fed with limited data led to a premature alarm, rapidly divulgated by the media to the already scared population (Diario Cooperativa, 2011; El Mercurio, 2011; The New York Times, 2011). Although after a great earthquake the seismic hazard in neighbor regions usually increases (*e.g.*, Parsons and Velasco, 2011), the hazard assessment should be based on a thorough analysis of a comprehensive data set. On the other hand, two studies published before the Maule earthquake based on a wealth of data had shown that the area between Concepción and Constitución was highly locked and that it could produce a M>8.5 event anytime (Ruegg *et al.*, 2009; Moreno, 2010). Such alarms should be taken seriously, although their validity may be hard to judge for non-specialists, emphasizing the need for better communication and development of a tight link between scientists and local authorities.

Acknowledgements

This work was supported by German Science Foundation (DFG, Deutsche Forschungsgemeinschaft) grants ME3157/2-1 to Melnick and MO2310/1-1 to Moreno, Chilean Science Foundation (Conicyt) Fondecyt 1110848 to Cisternas and 1101034 to Tassara, and the GeoForschungsZentrum Potsdam. We thank Christophe Vigny and Eduardo Contreras-Reyes for constructive reviews.

References

Barrientos, S. 1987. Is the Pichilemu-Talcahuano (Chile) a seismic gap? Seismological Research Letters 61: 43-48.

Bonafous, M. 1835. Tremblement de terre au Chili. Bulletin de la Societe de Geographie IV: 415-416.

Caldcleugh, A. 1836. An account of the great Earthquake experienced in Chile on the 20th of February, 1835. Philosophical Transactions of the Royal Society of London. Part I: 21-26.

Campos, J.; Hatzfeld, D.; Madariaga, R.; Lopez, G.; Kausel, E.; Zollo, A.; Iannacone, G.; Fromm, R.; Barrientos, S.; Lyon-Caen, H. 2002. A seismological study of the 1835 seismic gap in south-central Chile. Physics of The Earth and Planetary Interiors 132: 177-195.

Cisternas, M.; Melnick, D.; Ely, L.; Wesson, R.; Norambuena, R. 2010. Similarities between the great Chilean earthquakes of 1835 and 2010: American Geophysical Union (AGU) Chapman conference on giant earthquakes and their tsunamis: p. 19.

Diario Cooperativa. 2011. Geofísico italiano explicó su presagio de nuevo gran terremoto en Chile, http://www.cooperativa.cl/prontus_nots/site/artic/20110131/pags/20110131135832.html.

Darwin, C. 1851. Geological observations of South America: Geological Observations on Coral Reefs, Volcanic Islands and on South America-Being the Voyage of the Beagle, Under the Command of Captain Fitzroy, R.N. During the years 1832 to 1836, Part III: London, Smith, Elder: 279 p.

El Araucano. 1835. The official newspaper of the government. It published all the 1835 earthquake's reports from the provincial governors and letters from civil and military servants. Issues: 233, 234, 235, 236, 238, 272, 274, 275.

El Mercurio de Valparaíso. 1835. Commercial newspaper based in Valparaíso. It published articles from El Araucano and additionally letters from educated citizens. Issues: 86, 88, 89, 90, 96, 97, 100.

Farías, M.; Vargas, G.; Tassara, A.; Carretier, S.; Baize, S.; Melnick, D.; Bataille, K. 2010. Land-level changes produced by the 2010 Mw 8.8 Chile earthquake. Science 329: 916.

Fitzroy, R. 1839. Proceedings of the Second Expedition, 1831-1836, under the Command of Captain Robert FitzRoy. Volume II of Narrative of the Surveying Voyages of His Majesty's Ships Adventure and Beagle between the Years 1826 and 1836. Describing their Examination of the southern shores of South America, and the Beagle's circumnavigation of the globe: London, UK: 695 p.

Guzmán, J. 1836. El chileno instruido en la historia topográfica, civil y política de su país II. Imprenta Araucana: 927 p.

Lay, T. 2011. Earthquakes: A Chilean surprise. Nature 471: 174-175.

Lorito, S.; Romano, F.; Atzori, S.; Tong, X.; Avallone, A.; McCloskey, J.; Cocco, M.; Boschi, E.; Piatanesi, A. 2011. Limited overlap between the seismic gap and coseismic slip of the great 2010 Chile earthquake. Nature Geoscience 4: 173-177.

Lozier, A.; Rodríguez, S.; Arteaga, J.J. 1835. Informe presentado a la Intendencia de la provincia de Concepción de Chile, por Ambrosio Lozier, Simón Rodríguez y Juan José Arteaga nom-brados para reconocer la Ciudad de Concepción y sus cercanías después del terremoto del 20 de Febrero de 1835. Archivo Nacional de Chile, Fondo Varios, Vol. 300, Pza. 8, fojas 67-100v.

Melnick, D.; Cisternas, M.; Moreno, M.; Norambuena, R. 2012a. Estimating coseismic coastal uplift with an intertidal mussel: calibration for the 2010 Maule Chile earthquake (Mw=8.8). Quaternary Science Reviews 42: 29-42.

Melnick, D.; Moreno, M.; Motagh, M.; Cisternas, M.; Wesson, R.L. 2012b. Splay fault slip during the Mw 8.8 2010 Maule Chile earthquake. Geology 40: 251-254.

El Mercurio. 2011. Zona central de Chile podría sufrir otro terremoto sobre magnitud 8 Richter, http://www.emol.com/noticias/nacional/2011/01/30/461464/estudio-zona-central-de-chile-podria-sufrir-otro-terremoto-sobre-magnitud-8-richter.html.

Métois, M.; Socquet, A.; Vigny, C. 2012. Interseismic coupling, segmentation and mechanical behavior of the central Chile subduction zone. Journal of Geophysical Research 117: B03406.

Moreno, M. 2010. Active Deformation in the Southern Andes from GPS and FEM Models. Technische Universität Berlin: 116 p.

Moreno, M.; Melnick, D.; Rosenau, M.; Báez, J.C.; Klotz, J.; Oncken, O.; Tassara, A.; Bataille, K.; Chen, J.; Socquet, A.; Bevis, M.; Bolte, J.; Vigny, C.; Brooks, B.; Ryder, I.; Grund, V.; Smalley, R.; Carrizo, D.; Bartsch, M.; Hase, H. 2012. Toward understanding tectonic control on the Mw 8.8 2010 Maule Chile earthquake. Earth and Planetary Science Letters 321: 152-165.

Moreno, M.; Melnick, D.; Rosenau, M.; Bolte, J.; Klotz, J.; Echtler, H.; Báez, J.; Bataille, K.; Chen, J.; Bevis, M.; Hase, H.; Oncken, O. 2011. Heterogeneous plate locking in the South-Central Chile subduction zone: Building up the next great earthquake. Earth and Planetary Science Letters 305: 413-424.

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: L16310.

Moreno, M.S.; Rosenau, M.; Oncken, O. 2010. Maule earthquake slip correlates with pre-seismic locking of Andean subuction megathrust. Nature 467: 198-202.

Moscoso, E.; Grevemeyer, I.; Contreras-Reyes, E.; Flueh, E.R.; Dzierma, Y.; Rabbel, W.; Thorwart, M. 2011. Revealing the deep structure and rupture plane of the 2010 Maule, Chile earthquake (Mw=8.8) using wide angle seismic data. Earth and Planetary Science Letters 307: 147-155.

Okada, Y. 1985. Surface deformation due to shear and tensile faults in a half-space. Bulletin of the Seismological Society of America 75: 1135-1154.

Parsons, T.; Velasco, A.A. 2011. Absence of remotely triggered large earthquakes beyond the mainshock region. Nature Geoscience 4: 312-316.

Ruegg, J.C.; Rudloff, A.; Vigny, C.; Madariaga, R.; de Chabalier, J.B.; Campos, J.; Kausel, E.; Barrientos, S.; Dimitrov, D. 2009. Interseismic strain accumulation measured by GPS in the seismic gap between Constitucion and Concepcion in Chile. Physics of the Earth and Planetary Interiors 175: 78-85.

Sutcliffe, T. 1839. The earthquake of Juan Fernandez as it occurred in the year 1835. Printed at the 'Advertiser' office. Manchester: 32 p.

Sutcliffe, T. 1841. Sixteen years in Chile and Peru. Fisher Son & Co. London: 563 p.

Tassara, A.; Echaurren, A. 2012. Anatomy of the Andean subduction zone: three-dimensional density model upgraded and compared against global-scale models. Geophysical Journal International 189: 161-168.

Tassara, A.; Götze, H.J.; Schmidt, S.; Hackney, R. 2006. Three-dimensional density model of the Nazca plate and the Andean continental margin. Journal of Geophysical Research 111: B09404.

Tong, X.; Sandwell, D.; Luttrell, K.; Brooks, B.; Bevis, M.; Shimada, M.; Foster, J.; Smalley, R. Jr.; Parra, H.; Báez, J.C.; Blanco, M.; Kendrick, E.; Genrich, J.; Caccamise, D.J.;

II. 2010. The 2010 Maule, Chile earthquake: Downdip rupture limit revealed by space geodesy. Geophysical Research Letters, 37: L24311.

The New York Times, 2011. Stress of Sliding Plates Builds Near Chile, http://www.nytimes.com/2011/02/08/science/08quake.html.

Vigny, C.; Socquet, A.; Peyrat, S.; Ruegg, J.-C.; Metois, M.; Madariaga, R.; Morvan, S.; Lancieri, M.; Lacassin, R.; Campos, J.; Carrizo, D.; Bejar-Pizarro, M.; Barrientos, S.; Armijo, R.; Aranda, C.; Valderas-Bermejo, M.-C.; Ortega, I.; Bondoux, F.; Baize, S.; Lyon-Caen, H.; Pavez, A.; Vilotte, J.P.; Bevis, M.; Brooks, B.; Smalley, R.; Parra, H.; Baez, J.-C.; Blanco, M.; Cimbaro, S.; Kendrick, E. 2011. The 2010 Mw 8.8 Maule Mega-Thrust Earthquake of Central Chile, Monitored by GPS. Science 332: 1417.

Manuscript received: March 20, 2012; revised/accepted: May 31, 2012; available online: June 19, 2012.