The Mw=7.7 Tocopilla Earthquake (North Chile) of November 14, 2007: First results from space geodesy (InSAR)

El Terremoto de Tocopilla de Mw=7.7 (Norte de Chile) del 14 de Noviembre de 2007: Resultados preliminares de la geodesia especial (InSAR)

M. Béjar Pizarro[1], A. Socquet[2], R. Armijo[2] y J.B. de Chabalier[2]

1 Dpto. Geodinámica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, c/José Antonio Novais s/n, 28940 Madrid. mbejarpi@geo.ucm.es

2 Tectonic Laboratory, Institute de Physique du Globe de Paris, 4 place Jussieu, 75252 Paris cedex 05, France

Abstract: A Mw 7.7 subduction earthquake occurred on November 14, 2007 in Tocopilla (northern Chile). This region (between 16.5ºS and 23.5ºS) had been identified as major seismic gap (~1000 km length) since the South Peru (Mw= 9.1, 16 August 1868) and the Iquique (Mw=9.0, 10 May 1877) megathrust earthquakes. This gap was reduced to 500 km after the Arequipa (Mw = 8.3, 23 June 2001) and the Antofagasta (Mw = 8.1, 30 July 1995) earthquakes. We compute interferograms using Envisat ASAR images acquired before and after the Tocopilla earthquake to infer the location, geometry and slip of the rupture. Elastic modeling of this data allows us to infer that the 2007 main rupture extended over an area of ~150 x 60 km2, between 35 and 55 km depth, with a mean displacement of ~ 1.3 m. That means that the Tocopilla earthquake ruptured the deeper part of the seismogenic interface, probably within the transition zone. This earthquake released a little portion of the slip deficit accumulated in the seismic gap during the last 130 years (~ 10m). Hence the Tocopilla event may constitute a precursor of a future large thrust event in the current 500 km seismic gap that continues accumulating elastic strain from 1877.

Key words: earthquake, subduction,Chile, InSAR, elastic models.

***Resumen**: Un terremoto de subducción de Mw 7.7 tuvo lugar el 14 de Noviembre de 2007 en Tocopilla (norte de Chile). Esta región (entre 16.5ºS y 23.5º S) había sido identificada como una gran laguna sísmica (de ~ 1000 km de longitud) desde los terremotos del Sur de Perú (Mw = 9.1, 16 de Agosto de 1868) y de Iquique (Mw = 9.0, 10 de Mayo de 1877). La extensión de la laguna se redujo después de los terremotos de Arequipa (Mw = 8.3, 23 de Junio de 2001) y de Antofagasta (Mw=8.1, 30 de Julio de 1995). Hemos calculado interferogramas a partir de imágenes ASAR Envisat adquiridas antes y después del terremoto de Tocopilla para deducir la localización, geometría y deslizamiento asociados a la rotura. La modelización elástica de estos datos indica que la ruptura principal de 2007 se propagó sobre un área de ~150 x 60 km2, entre 35 y 55 km de profundidad, con un deslizamiento medio de ~1.3 m. Esto significa que el terremoto de Tocopilla rompió la parte profunda de la interfase sismogéncia, probablemente dentro de la zona de transición. Este terremoto relajó una porción muy pequeña del déficit de deslizamiento acumulado en la laguna sísmica durante los últimos 130 años (~10 m). Por lo tanto, el evento de Tocopilla podría constituir un precursor de un gran terremoto de subducción en la laguna sísmica actual de 500 km que continua acumulando deformación elástica desde 1877.*

***Palabras clave:** terremoto, subducción, Chile, InSAR, modelos elásticos.*

INTRODUCTION

We use InSAR data to explore the source parameters of the November 14th 2007 Mw 7.7 Tocopilla earthquake, North Chile. Our primary goal is to determine which plane ruptured (extent, dimensions?), Did it rupture the subduction interface? If so, which part? And more important for the seismic hazard assessment of North Chile region, was the deficit of slip in this zone equilibrated by this earthquake? Answering these questions is fundamental to understanding rupture and earthquake mechanics, and necessary to estimate seismic hazard in this area.

The Tocopilla earthquake is the consequence of subduction of the Nazca plate beneath South America along the Chilean trench. The subduction zone here presents one of the highest levels of seismic activity in the world, with a large earthquake of M>8 every five to ten years. The fast convergence rate between Nazca and South America, 79 mm/yr in the N 78°E direction (Demets *et al.*, 1990, 1994), is accommodated by large interplate earthquakes.

North Chile has been identified as a seismic gap with high potential for large earthquakes in the near future. The region between 16.5ºS and 23.5ºS had been quiescent since the occurrence of the South Peru (Mw= 9.1, 16 August 1868) and the Iquique (Mw=9.0, 10 May

1877) earthquakes. Figure 1 shows the most recent large subduction earthquakes along the North Chile trench and the extension of this seismic gap (~1000 km). The Arequipa earthquake (Mw = 8.3, 23 Jue 2001) reduced this seismic gap 300 km in his northern end and the Antofagasta earthquake (Mw = 8.1, 30 July 1995) reduced 200 km its southern end, leaving still ~ 500 km to rupture. All these events may have affected the stress regime of the region.

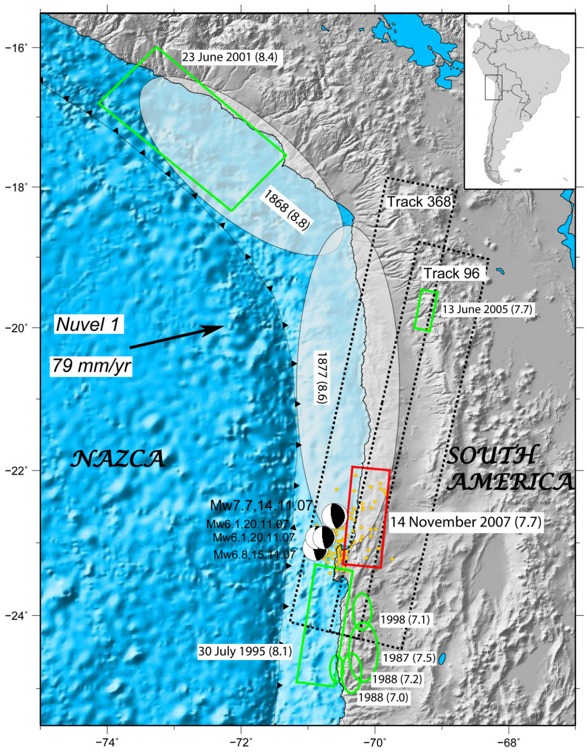

FIGURE 1. *Reference map of our study area. Large subduction earthquakes along the Peru-Chile trench are represented by green rectangles and ellipses. Grey ellipses represent the approximate extent of 1877 and 1868 rupture zones. The Harvard CMT solution for the mainshock and the 3 biggest aftershocks are indicated. Aftershocks are indicated by yellow dots (NEIC catalog). Dashed squares outline the tracks of Envisat data used in this study. Red rectangle represents the approximate extent of the 2007 Tocopilla earthquake studied here.*

The Mw 7.7 November 14th 2007 Tocopilla earthquake ruptured the segment just north of the 1995 Antofagasta rupture. The epicenter was located near the Tococopilla city (Lat:22.25° S, lon: 69.91° W, according to the National Earthquake Information Center (NEIC)), where two people were reported to have been killed and most of the buildings were damaged. Most of the aftershocks were concentrated in the south end of the rupture, northwest of the Mejillones Peninsula. Three strong aftershocks occurred withing the 6 days following the mainshock and a Mw 6.4 occurred one month later (Fig. 1). In the north end of the rupture, the seismic activity has been low, but recently (on February 4th 2008), a Mw 6.3 earthquake occurred 50 km of Iquique, 200 km north of the Tocopilla earthquake and just in the middle of the seismic gap, raising the question about the evolution of this gap.

The crustal deformation during the different phases of the seismic cycle in North Chile has been described by InSAR data in the past: coseismic deformation associated to the 2001 Arequipa earthquake (Pritchard *et al.*, 2007, Ruegg *et al.*, 2001) and to the 1995 Antofagasta earthquake (Pritchard *et al.*, 2002, Ruegg *et al.*, 1996), interseismic deformation (Chlieh *et al.*, 2004) and postesimic deformation after the Antofagasta earthquake (Chlieh *et al.*, 2004). Chlieh *et al.* (2004) proposed a model for the seismic cycle in North Chile with a transition zone located between 35 and 55 km depth, separating the fully coupled shallower interface from the deeper interface, where continuous sliding occurs.

INSAR PROCESSING

Interferometric Synthetic Aperture Radar (InSAR) is a space geodetic technique that has been widely used for the detection of surface deformation due to natural processes such as earthquakes (Massonnet and Feigl, 1998). InSAR provides high spatial resolution of surface deformation and can provide good constraints on the epicenters and depths of events (Dawson and Tregoning, 2007). To form a coseismic interferogram we combine two or more SAR images acquired before and after an earthquake in order to get the relative surface deformation within the images. This technique only measures one component of the deformation field, in the direction of the radar line of sight (LOS). For the ENVISAT SAR images this direction is approximately 23° from vertical and therefore has significantly bigger sensitivity to vertical than horizontal motion. This is especially well adapted to the kind of deformation we want to measure, because the coesismic deformation associated to a subduction earthquake has an important vertical component.

Interferogram	Track	Date	Baseline
1	368	2007 October 20	232
		2007 November 24	
2	96	2007 November 5	155
		2007 December 10	

TABLE I. *SAR data used to compute interferograms 1 and 2.*

Here we use 4 Envisat ASAR images (Table I) from two descending tracks (track 96 and track 368, Fig. 1) to form two independent coseismic interferograms. The images from the track 96 are ~ 600 km long and the images from the track 368 are 700 km long what allows us to control the far field deformation. Both interferograms span the date of the earthquake and they include some days after the mainshock: 10 days in the case of the track 368 interferogram and 26 days in the case of the track 96 interferogram. It is therefore probable that they include some postseismic deformation together with the coseismic deformation.

Data were processed using the Caltech/JPL repeat-orbit interferometry package, ROI PAC (http://www-radar.jpl.nasa.gov/roi pac/). The topographic phase contribution was removed using a 3-arc-sec (90-m) digital elevation model from the Shuttle Radar Topography Mission (SRTM). The orbital information used in the processing was provided by the ESA (DORIS orbits). After processing, the interferograms presented a linear ramp, probably due to uncertainties in the orbital ephemeris. A plane was adjusted to this ramp and removed from each interferogram.

Figures 2a and 2b show both interferograms with the observed displacement along the line of sight direction. Surface deformation pattern is characterized by two lobes: the western one shows a LOS displacement towards the satellite, with a maximum value of ~30 cm and the eastern one represents a LOS displacement away from the satellite, with a maximun value of ~15 cm.

Uplift and eastward movements decrease the LOS distance while the subsidence and the westward horizontal displacement increase this distance. In subduction earthquakes we have typically a deformation pattern with an uplift of the part above the thrust plane and subsidence down this pane. Horizontal displacements converge towards the ruptures area inland and diverge at sea. Therefore, the displacement in the west lobe of the interferograms represents a combined uplift and westward displacement of the ground surface when the east lobe represents a subsidence and westward displacement. The position of the neutral line separating the lobes is particularly critical to compute the model since it can be taken as a good indicator of the horizontal position of the downdip end of the fault plane.

MODELLING AND DISCUSSION

Observed surface displacements are modeled using Okada's formulation of a dislocation buried in an infinite elastic half-space (Okada, 1985). We determine a simple fault model, consisting in uniform slip on a rectangular fault plane. 3D surface deformation is projected into the satellite line of sight and compared to the original data set. We performed a series of forward models to assess the dislocation parameters that are best fitting the deformation pattern. We started by exploring the length of the plane, that is well constrained by the extension of the deformation in the north-south direction. The dislocation length that better reproduces the deformation pattern is ~150 km, extending from latitude -22 to latitude 23.3 (Fig. 2c). The horizontal position of the downdip end of the fault plane is determined at the first order by the location of the neutral line of deformation. The plane width (~ 60 km) is mostly constrained by the sharpness of the deformation lobes. Using this fault geometry we test different possible locations of the plane at depth. As we only have one displacement component (in the LOS direction) the dip of the fault plane is poorly resolved, so we started by using the CMT Harvard value of 20º. A trade-off between depth and slip is observed: the deeper the plane is, the more slip is allowed to fit the surface deformation, and the higher is the equivalent magnitude of the model. The equivalent seismic moment of the

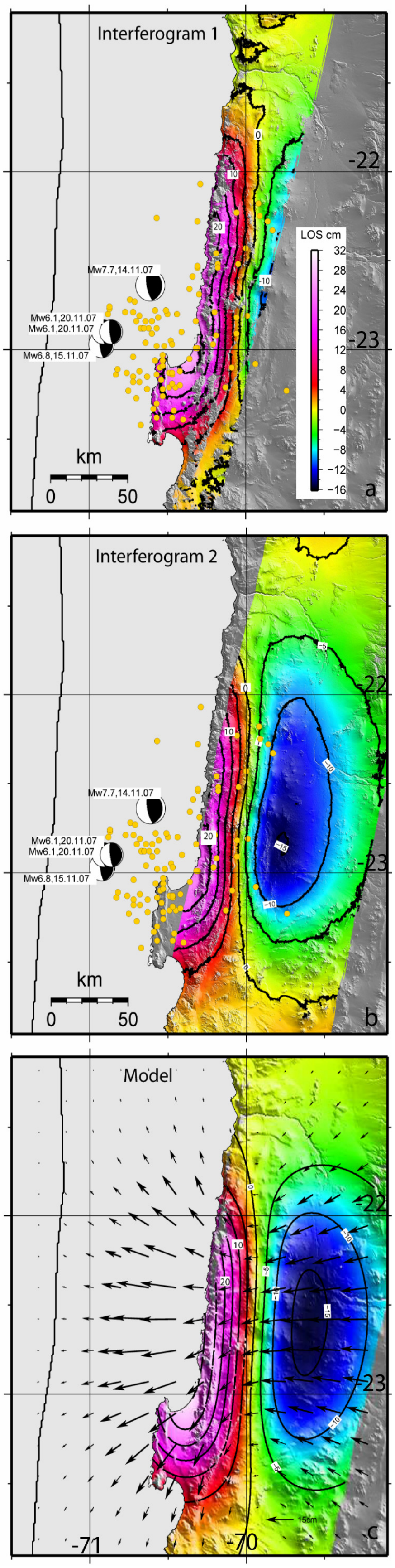

FIGURE 2. *Coseismic surface displacements from a) Interferogram 1 (track 368) b) Interferogram 2 (track 96). c) Synthtetic model. Black vectors in figure 2c represent the modelled horizontal component of displacement. The contour interval is 5 cm in the LOS direction.*

earthquakes that occurred between the SAR data acquisition dates (Mo=4.88x10^{20} N.m) is best fit for a deep plane (between 55 and 65 km depth). However this generates a deformation field too spread out, so we lose the shape of our deformation field. The best compromise between seismic moment and depth is found for a plane that lies between 35 and 55 depth, with a total slip of 1.30 m and a geodetic moment of 3.86 x10^{20} N.m.

The resulting model is shown in Figure 2c. It accounts for first order coseismic deformation associated with the 2007 Tocopilla earthquake. Residuals are still significant, arguing that the slip distribution is not spatially constant. This can be seen in both interferograms, since more deformation is present in the south than in the north. Linear inversions of slip using the fixed fault geometry deduced in this study will tell us more about the earthquake source.

CONCLUSIONS

Our data point out to a rupture within this transition zone as defined by Chlieh *et al.* (2004). The question about why it didn't continue rupturing updip (the seismogenic zone) remains open. On the other hand, the slip released by the Tocopilla earthquake, estimated by our models (~ 1.3 m) represents a minor part of the slip deficit in the North Chile seismic gap (approximately 10 m, for a convergence rate of 79 mm/yr and ~130 years since last great subduction earthquake). Thus the Tocopilla event ruptured only partially the southern end of the seismic gap. The 1995 Mw 8.1 Antofagasta earthquake was preceded by a deeper Mw 7.5 earthquake in 1987, similar to the 2007 Tocopilla earthquake, so the current earthquake raises the possibility of a shallower, larger subduction earthquake, that might rupture the seismogenic interface in this zone of gap.

ACKNOWLEDGMENTS

M.B.P acknowledges support of Universidad Complutense de Madrid grant. This work was supported by the ANR-05-CATT-01402 project of the French National Research Agency. We acknowledge the support of the European Agency (ESA) for programming Envisat satellite (research project AO-720).

REFERENCES

Chlieh, M., Chabalier, J.B.,Ruegg, J.C.; Armijo, R., Dmowska, R., Campos, J. and Feigl, K. (2004): Crustal deformation and fault slip during the seismic cycle in the north Chile subduction zone, from GPS and InSAR observations, *Geophys. J. Int.*, 158, 695–711.

Dawson, J. and Tregoning, P. (2007): Uncertainty analysis of earthquake source parameters determined from InSAR: A simulation study, *Journal of Geophysical Research,* vol. 112, B09406, doi:10.1029/2007JB005209

DeMets C, Gordon RG, Argus, DF. and Stein, S. (1990): Current plate motions. *Geophysical Journal International* 101:425-478.

DeMets, C., Gordon, R.G.; Argus, D.F. and Stein, S. (1994): Effect of recent revisions to the geomagnetic reversal timescale on estimates of current plate motions, *Geophys. Res. Lett.*, 21,2191-2194.

Massonnet, D. and Feigl, K..(1998): Radar interferometry and its application to changes in the earth's surface, *Rev. Geophys*., 36, 441–500.

Okada, Y. (1985): Surface deformation to shear and tensile faults in a half space, *Bull. seism. Soc. Am*., 75, 1135–1154.

Pritchard, M.E., Simons, M., Rosen, P.A., Hensley, S. and Webb, F. H. (2002): Co-seismic slip from the 1995 July 30 Mw = 8.1 Antofagasta, Chile, earthquake by constrained by InSAR and GPS observations, *Geophys. J. Int,* 150, 362-376.

Pritchard, M. E., Norabuena, E.O., Ji, C., Boroschek, R., Comte, D., Simons, M., Dixon, T.H. and Rosen, P.A. (2007): Geodetic, teleseismic, and trong motion constraints on slip from recent southern Peru subduction zone earthquakes, *Journal. Geophys. Resear.* vol 112, B03307, doi 10.1029/2006JB004294.

Ruegg, J.C., Campos, J., Armijo, R., Barrientos, S., Briole, P., Thiele, R., Arancibia, M., Cañuta, J., Duquesnoy, T., Chang, M., Lazo, D., Lyon-Caen, H., Ortlieb, L., Rossignol, J.C. and Serrurier, L. (1996): The Mw =8.1 Antofagasta (North Chile) earthquake July 30, 1995: first results from teleseismic and geodetic data, *Geophys. Res. Lett*., 23, 917–920.

Ruegg, J. C., Olcay, M. and Lazo, D. (2001): Co-, post- and pre (?)-seismic displacements associated with the Mw = 8.4 southern Peru earthquake of 23 June 2001 from continuous GPS measurements, *Seismol. Res. Lett.,* 72, 673–678.