ABSTRACT

The Mw 7.7 14 November 2007 Tocopilla earthquake occurred at the southern end of a known seismic gap in North Chile. Through modeling of Global Positioning System (GPS) and radar interferometer (InSAR) data we show that this event ruptured the deeper part of the seismogenic interface (30-50 km) and did not reach the surface. Our analysis of post-seismic deformation suggests that small but still significant post-seismic slip occurred within the first 10 days after the main shock, and that it was mostly concentrated at the southern end of the rupture, near an area already identified as an important inter-segment zone. The 2007 Tocopilla earthquake released only $\sim 2.5\%$ of the moment deficit that might have accumulated on the interface during the past 130 years and may be regarded as a possible precursor of a larger subduction earthquake rupturing partially or completely the 500-km-long North Chile seismic gap.

Key words: InSAR; GPS; northern Chile; subduction zone.

1. INTRODUCTION

The aim of this work is to contribute to the understanding of the regions where great earthquakes ruptures terminate, both at depth and laterally. To that end, we study the surface deformation associated with the Mw 7.7 Tocopilla subduction earthquake (North Chile). That region attracts scholars’ attention because the fast convergence of the Nazca and South American plates ($\sim 7$ cm in the $\sim 78^\circ$E direction) appears mostly accommodated by large interplate earthquakes ((Comte & Pardo 1991)). Indeed, the region between the Ilo Peninsula (South Peru) and the Mejillones Peninsula (North Chile) represents the remaining unbroken part of a previously identified major seismic gap not having experienced a significant subduction earthquake in the last 130 years ((Dorbath et al. 1990); (Comte & Pardo 1991)). The 1995 Mw 8.1 Antofagasta and the 2001 Mw 8.4 Arequipa earthquakes appear to have provided an extra load to the $\sim 500$ km length segment at its two extremities (Fig. 1). That was the situation when the Mw 7.7 Tocopilla earthquake occurred on November 14, 2007 (see Fig. 1). Rupture initiated in the subduction interface beneath the region of the city of Tocopilla and stopped to the south when it reached the region of the subduction interface beneath the Mejillones Peninsula, according to kinematic inversions of the rupture process ((Delouis et al. 2009); (Peyrat et al. 2009)). Most of the aftershocks following the 2007 event were concentrated immediately to the north of that peninsula, a large geomorphic feature that seems to act both as a barrier arresting rupture of large earthquakes (e.g. M 8.8 1877 Iquique earthquake) and as an asperity where large earthquakes nucleate (e.g. Mw 8.1 1995 Antofagasta earthquake, (Ruegg et al. 1996)). Here we focus on the coseismic and early post-seismic deformation associated with the 2007 Tocopilla earthquake, aiming at deciphering the role of this earthquake in the seismic cycle of mega-earthquakes in North Chile. We are particularly interested in:

- The extent of the Tocopilla rupture over the seismogenic interface and its relation with the segmentation of the subduction zone.

- The location and amount of afterslip following the Tocopilla main shock and its relation with both, the coseismic slip distribution and the afterslip following previous earthquakes in the area.

To address these questions we combine InSAR and GPS data covering the coseismic period plus one month of post-seismic deformation associated with the Tocopilla earthquake. As a first step we explore the geometric parameters of the rupture by assuming uniform slip on the fault. Then we estimate the slip distribution corresponding to the main shock, to the largest aftershock and to the post-seismic deformation observed during the first month following the main event.
Figure 1. Reference map of our study area in northern Chile. Rupture areas of historic and recent earthquakes are shown with their dates and magnitudes. Approximate ruptures areas of the two largest historic earthquakes in the region (the 1868 South Peru and the 1877 Iquique earthquakes) are represented as semi-transparent grey ellipses. Color filled areas represent rupture areas of large instrumental shallow interplate thrust earthquakes. For those earthquakes with known distributed-slip we use the outermost contour to represent the rupture area (for the 1995 earthquake from (Chlieh et al. 2004), for the 2001 Arequipa earthquake from (Pritchard et al. 2007) and for the 2007 earthquake from this work). Otherwise rupture area is represented by a colored ellipse. The relative Nazca - South American convergence rate and direction are shown by the black arrow ((Angermann et al. 1999)) and the trench is shown by the black barbed line.
2. DATA

2.1. InSAR data

We use 4 Envisat ASAR images from two descending tracks (track 96 and track 368, Fig. 2 a) to form two independent coseismic interferograms. Both interferograms span the date of the earthquake and they include some days after the main shock: 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 post-seismic deformation together with the coseismic deformation. Data were processed using the Caltech/JPL repeat-orbit interferometry package, ROI PAC (Rosen et al. 2004)). We construct each interferogram by calculating the phase difference between two ASAR images using the 2-pass approach (see Massonnet & Feigl 1998) for an overview of the method). The topographic phase contribution was removed using a 3-arc-sec (90-m) digital elevation model from the Shuttle Radar Topography Mission (SRTM) (Farr & Kobrick 2000)). The orbital information used in the processing was provided by the European Space Agency (DORIS orbits). Final results contain the relative displacement between the two dates in the radar LOS direction from ground to satellite, which is inclined 23 from the vertical. Therefore they are mostly sensitive to vertical displacements. The coherence of the interferograms is exceptionally high, because of the aridity of the Atacama Desert in northern Chile and the short time period in both interferograms ~ 1 month).

Figs 2 (b) and (c) show the observed displacements along the line of sight direction (LOS) for both unwrapped interferograms. Surface deformation pattern is characterized by two lobes: the western one shows a range decrease, corresponding to LOS displacement towards the satellite, with a maximum value of 30 cm; the eastern one represents a LOS displacement away from the satellite, with a maximum value of 15 cm.

2.2. GPS data

As our two interferograms include 10 to 26 days of post-seismic deformation following the Tocopilla earthquake, it is difficult to individualize the deformation associated with Tocopilla main shock from the deformation generated by the largest aftershocks (Mw 6.3 and Mw 6.8, 15 November 2007) and by the post-seismic afterslip. To separate the contribution of the big aftershocks and the post-seismic afterslip to the superficial strain field, we use continuous GPS (cGPS) data acquired in the frame of a Chilean-French-USA cooperation. The North Chilean cGPS network includes 24 cGPS stations (between 18S and 23.5S) embedded in solid bedrock outcrops, reinforced concrete buildings or concrete benchmarks where sediments are unconsolidated. In this network, 11 cGPS stations distributed between the coast line (80 km east from the trench) and 300 km east from the trench in the continent cover well the deformed zone identified with InSAR. We analyze coordinate time series of the cGPS records from 30 days before to 26 days after the earthquake using the GAMIT software (King 2000)).

Hereafter, displacements calculated for the hour of the main shock are referred as cGPS-main, displacements calculated for the hour around the two Mw > 6 aftershocks are referred as cGPS-15aft, displacements occurred between the 16 to 24 November 2007 are referred as cGPS-post1 and displacements occurred between the 25 November to 10 December 2007 are referred as cGPS-post2.

3. MODELING

In order to explain the pattern of deformation we try to reproduce it by modeling the earthquake as a dislocation in an elastic medium (Okada 1985)). We first invert for the geometric parameters by assuming a uniform slip on a rectangular fault. Although this simple model produces a first order fit to the observed deformation pattern, the observed GPS and InSAR displacements are poorly fit in the southern half of the rupture, arguing that the slip distribution is not spatially constant. Therefore models that allow for spatial slip variations along the fault plane are required. In a second step, we apply a linear inversion technique to estimate the slip distribution on the determined fault.

3.1. Results

Fig. 3 shows three coseismic slip distributions from two different data sets inverted independently and jointly. Only the first one corresponds to the purely coseismic interval, the other two include 10 to 26 days after the main shock.

All the models present two main areas where the slip reaches a maximum, which are interpreted as asperities. The northern one is located between 30 and 50 km in all the inversions and presents an elongated shape to the north. The southern asperity seems to be located below the northern half of the Mejillones Peninsula in all models and does not extend into its southern part.

The slip distribution corresponding to the surface displacement produced on November 15th 2007 is shown in Fig. 3 d. Most of the slip is concentrated in a patch NW of the Mejillones Peninsula (labeled 1 in Fig 3 d), which are coincident with the hypocenters of the two large aftershocks that occurred on November 15th 2007.

Finally, the slip distribution models corresponding to the two post-seismic periods studied (data cGPS-post1 and cGPS-post2) are shown in Figs 3 (e) and (f). The model for the first period of post-seismic deformation (16 to 24 November 2007), which is the closest to the main shock, shows less slip (up to 22 cm) than that associated with
Figure 2. InSAR and cGPS data used in this study. (a), (b) Unwrapped interferograms showing surface displacement associated with November 14th, 2007 Tocopilla earthquake. The two interferograms cover a 35 days period spanning the day of the earthquake. Track 368 interferogram (a) includes 10 days of post-seismic period (from October 10th to November 24th, 2007) and track 96 interferogram (b) includes 24 days of post-seismic period (from November 5th to December 10th, 2007). The color scale refers to change in the radar line of sight direction (LOS). Positive displacements are associated with a range decrease (movement towards the satellite). (c)- (f), Red arrows show the horizontal displacement and blue arrows show the vertical displacement in four different periods: (c) main shock coseismic displacements (cGPS-main), (d) displacement associated with the November 15th aftershock (cGPS-15aft), (e) first post-seismic period measured (cGPS-post1, from November 16th to November 24th, 2007) and (f) second post-seismic period measured (cGPS-post2, from November 25th to December 10th, 2007).
Figure 3. Distributed slip models for the Tocopilla main shock and the first month of post-seismic deformation. (a) - (c), Models for the Tocopilla earthquake using different data sets. (a) Slip distribution inverted from coseismic cGPS data. (b) Slip distribution from InSAR data. (c) Joint GPS-InSAR inversion. GPS in this case includes 26 days of post-seismic deformation to span a period comparable to InSAR. Colors and contours (0.5 m interval) show the magnitude of slip in meters. Slip patches labeled with “a?” are probably artifacts due to resolution problems. The Peyrat et al. 2009 locations for the main shock and largest aftershock are shown as stars. Depths on the fault interface are shown as black dotted lines labeled at top. The depth interval where the continental Moho intersects the subduction interface is 43-50 km (Patzwahl et al. 1999). (d)- (f), Slip distribution inverted from GPS data for (d) the largest aftershocks (November 15th, 2007), (e) 9-days of post-seismic deformation (November 16th to November 24th, 2007) and (f) 16-days of post-seismic deformation (November 25th to December 10th, 2007). The time interval of figure (e) corresponds to the postseismic interval included in the track 368 interferogram and the temporal span of (e) plus (f) (November 16th to December 10th, 2007) correspond to the postseismic interval included in the track 96 interferogram. Contours of slip (5 cm interval in a and 2 cm in b and c) are superimposed with a color scale.
the November 15th aftershocks, but with a very similar location (patch labeled 3 in Fig 3 e). The model corresponding to the second post-seismic period, which starts 10 days after the main shock, shows a patch of up to 2 cm of slip concentrated between 20 and 35 km depth, centered beneath the NW part of the Mejillones Peninsula (patch labeled 5 in Fig. 3 f).

In order to determine whether this post-seismic afterslip is aseismic, such as slow slip events, or a seismic process, we compare the geodetic moment release estimated for the two post-seismic periods with the cumulative moment release of aftershocks during the same time intervals. Our results suggest that 70 % of the post-seismic deformation during the first post-seismic period and 95 % of that during the second post-seismic period correspond to aseismic slip in the subduction interface.

4. DISCUSSION AND CONCLUSIONS

Our preferred models for the Tocopilla main shock show slip concentrated in two main asperities, located between 30 and 50 km depth. According to that, the shallow part of the seismogenic interface (from the trench to 30 km depth) remains unbroken, suggesting that the seismogenic zone is separated into a deep and a shallow area. That limit could be either materialized by a change in geometry or a change in the frictional properties.

The coseismic rupture initiated in the subduction interface beneath the region of the city of Tocopilla, offering a satisfying location to explain the triggering of Tocopilla earthquake. The Tocopilla rupture stopped to the south when it reached the region of the subduction interface beneath the Mejillones Peninsula, already identified as an important intersegment zone characterized by structural complexity and occurrence of aseismic slip after large earthquakes rupturing one or another of the segments located north and south of it.

The slip associated with the Mw 6.8 and Mw 6.3 aftershocks is concentrated updip the southern end of the main shock rupture. Our analysis of the post-seismic deformation observed from 2 to 26 days following the 2007 Tocopilla earthquake suggests that most of the post-seismic deformation recorded by GPS occurs during the first post-seismic period measured (from 16 to 24 November 2007). It is concentrated updip the southern termination of the rupture, and well correlated with the aftershocks distribution for the same period.

The Tocopilla earthquake only partially ruptured the deeper part of the southernmost 150 km of the North Chile seismic gap, releasing a 2.5 % of the deficit moment accumulated in the complete seismic gap since the 1877 Mw 8.8 earthquake. This suggests that the potential for a future event, ruptureing either partially or completely the 500-km-long North Chile seismic gap, remains similar than before the Tocopilla earthquake.

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