Source characterization of the San Juan (Argentina) crustal earthquakes of 15 January 1944 (Mw 7.0) and 11 June 1952 (Mw 6.8)

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Abstract

The backarc region of the Andes in the vicinity of San Juan, Argentina, is one of the most seismically active fold and thrust belt regions in the world. Four large damaging crustal earthquakes (1894, 1944, 1952 and 1977) occurred during the last 111 yr between 30°S and 32°S. We have determined the source parameters for two of these important earthquakes, the 1944 and 1952 events, using historic seismic records. The earthquake on 15 January 1944 had an epicentral location between the eastern thin-skinned Precordillera fold and thrust belt and the thick-skinned Sierras Pampeanas basement-cored uplifts. The 11 June 1952 earthquake occurred in the eastern Precordillera about 35 km southwest of the 1944 epicenter location. The P-wave first motions, long-period teleseismic P waveform modeling, and SV/SH amplitude ratio indicate a thrust focal mechanism for the 1944 event (strike N45°E, dip 35° to the southeast, and rake 110°) with M0 = 3.01×10 19 N m and Mw = 7.0. The 1952 earthquake focal mechanism solution indicates a more oblique mechanism (strike N40°E, dip 75° to the southeast, and rake 30°) with M0 = 2.20×10 19 N m and Mw = 6.8. Both the 1944 and 1952 earthquakes have focal depths <12 km and simple source time functions with one pulse of moment release with durations of 10 s and 8 s, respectively. Both the shallow focal depth and the east-dipping fault plane in the focal mechanism solution for the 1944 earthquake are consistent with the parameters observed along the La Laja fault in the frontal part of the eastern Precordillera that generated a 6–8-km-long coseismic surface rupture. The 1952 earthquake focal mechanism solution and its shallow source depth suggest it is related to faults in the eastern Precordillera, but a particular fault association is difficult. The 1944 earthquake was clearly the most destructive event because its proximity to the most populated area in San Juan, large size and shallow focal depth.

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1. Introduction and regional tectonics

The seismically active Andean backarc between 28°S and 33°S results from the convergence between the oceanic Nazca plate and the continental South American plate at a rate of 6.3 cm yr⁻¹ [1] (Fig. 1a). In this region, the Nazca slab subducts to ~100 km depth and then extends near horizontal several hundred kilometers to the east before descending into the mantle. The flattening of the subducted Nazca plate initiated at 8–10 Ma [2,3]. This process is linked to the shut off of the volcanic arc, the eastern migration of the thin-
skinned Precordillera and the uplift of the Sierras Pampeanas basement-cored blocks in the broad region of the foreland [2,3] (Fig. 1). Although there is a large number of earthquakes with depths of \( \sim 100 \) km which define the flat slab geometry in the Andean backarc at about 31\(^\circ\)S and correlate with the projection of the subducting Juan Fernández Ridge [4–7] (Fig. 1a), the most destructive earthquakes are the moderate-to-large
events generated in the South American upper plate with depths <35 km. Large crustal earthquakes in 1894, 1944, 1952, and 1977 associated with the Precordillera and the Sierras Pampeanas have caused extensive damage in the vicinity of San Juan, Argentina (Fig. 1b).

The Precordillera is a thin-skinned fold and thrust belt that makes up the foothills of the high elevation Andes (Fig. 1). Based on the deposits, timing and style of deformation, it is divided in the western, central and eastern Precordillera [8,9] (Fig. 2). The western and central Precordillera are a series of mainly Paleozoic ranges and linear valleys bounded by roughly N–S east verging reverse faults [8,12] (Fig. 2). In contrast, the eastern Precordillera is made up of Paleozoic, Triassic and Cenozoic rocks with both thin-skinned and thick-skinned structures and west verging thrust faults with a similar style to the Laramide structures in the western U.S.A. [13] (Fig. 2). The Precordillera and the Sierras Pampeanas are separated by broad internally drained retroarc basins that include the Bermejo and Tulum Valleys, which receive much of their sediments from the Andes but whose structures are controlled by the Sierras Pampeanas active tectonics [12,14]. The Tulum Valley contains San Juan, a city with a population of about 350,000, and other smaller communities (Figs. 1b and 2). This transition between the Precordillera and the Sierras Pampeanas structures corresponds to the region of many of the large devastating crustal earthquakes in the last 111 yr and hence, it is a region with high seismic hazard.

There is uncertainty in both the continuation at depth of exposed Precordillera and Sierras Pampeanas structures and in how the structures are related. Regional seismic studies around San Juan have shown crustal seismicity to depths of ~35 km related to the Precordillera and the Sierras Pampeanas [15–17]. In the Precordillera, this seismicity is mainly restricted to the central and eastern subprovinces with almost no seismic activity in the western Precordillera [16,18]. A similar pattern of seismic activity is observed from global catalogs (Fig. 1). Smalley et al. [16] have determined small to moderate sized earthquakes of depths between 5 and 35 km, which correlate with a broad diffuse N–NE striking plane dipping to the northwest in the region between the Sierra Villicum and the Sierra Chica de Zonda, which is interpreted as a basement structure. As these authors pointed out, this structure (labeled as structure b in Fig. 2b) does not match the exposed east-dipping faults (structures 1 and 2 in Fig. 2a) in the eastern Precordillera [16] (Fig. 2). At the surface, the eastern Precordillera has a major 145-km-long east-dipping reverse fault system composed of several segments from north to south: Villicum, Las Tapias, Chica de Zonda and Pedernal [8,9]. Along each segment, the reverse faults uplift the range of the same name in the hanging wall (Fig. 2).

Farther east, the Sierra Pie de Palo (uplift in the Sierras Pampeanas) (Figs. 1 and 2) is seismically active with crustal events located at depths between approximately 10 and 35 km [15,17]. Studies by Regnier et al. [15] revealed seismicity at 20–25 km beneath the Sierra Pie de Palo which may represent a décollement that connects the eastern Precordillera with the Sierras Pampeanas structures at depth [19–21] (Fig. 2b).

The only major crustal seismic event in the vicinity of San Juan studied using local, regional and teleseismic records is the most recent 1977 earthquake (Ms =7.4) that killed 65 people [22]. This thrust earthquake [23] was located in the Sierra Pie de Palo [22] and was composed of two shocks separated by 64 km and 20 s with focal depths of ~17 km and ~25–30 km, respectively [24,25] (Fig. 1b). The geometry of the fault activated during the mainshock is still debated [25–28] (Fig. 2).

The earthquake on 15 January 1944 (Ms =7.3) was by far the most damaging. Its epicenter is located between the eastern Precordillera and the western Sierras Pampeanas [29]. The event devastated San Juan and caused numerous deaths [30,31] (Fig. 1b). A surface rupture of 6 to 8 km long was observed immediately after this large earthquake in the Precordillera along the La Laja fault [30,32,33] (Figs. 1b and 2). The relatively short exposed rupture and the existing middle to lower crust seismicity detected by local seismic studies [16] (Fig. 2) have given rise to debate about interpreting the La Laja reverse fault as the main fault activated during the 1944 earthquake or as a secondary structure [16,20,21,24,26,30,33–37].

Earthquakes in 1894 (Ms =7.6) and 1952 (Ms =7.0) are generally associated with the Precordillera [35,38] (Fig. 1b). Although less damaging events, their study is important to characterize the large crustal seismicity around San Juan related to the Precordillera. The study of the 1894 event using seismic records is difficult because of its occurrence during the early stages of the instrumental period. In contrast, there are a large number of seismic records for the 1944 and 1952 earthquakes that can be analyzed to extract useful quantitative information.

We have collected, digitized and analyzed mainly long-period teleseismic records for the 1944 and 1952
San Juan earthquakes. We determined P-wave first motion focal mechanisms and carried out a depth-phase analysis for both events. We have also done a grid search to determine the best focal mechanism and source depth and obtained the source time function and seismic moment by modeling teleseismic P-waves. We have...
compared these results with neotectonic studies and seismic intensity information. The study of the 1944 and 1952 earthquake sources completes the characterization of the large crustal earthquakes in the vicinity of San Juan during the last century. This is useful for the understanding of the crustal earthquake backarc deformation related to different major geological and structural provinces over the flat-slab Andean subduction segment. It is also important for the assessment of the seismic hazard in this region.

2. Data and methods

We have collected paper seismograms and instrument responses from seismic observatories around the world for the 1944 and 1952 earthquakes (Fig. 3a and Table 1). We have scanned and digitized all available analog seismograms using the interactive software SeisDig [39] (Fig. 3b, c). We used as many records as possible to estimate the first-motion focal mechanism for each event. In some cases, we utilized horizontal components and P-diffracted waves in order to increase the usable records. We also included available local and regional P-wave data to place more constraints on the focal mechanism for both events as shown in Fig. 4a for the 1944 earthquake.

To help determine the focal mechanism and source depth for both earthquakes, we identified possible depth phases and used their relative amplitudes and timing. We tested a set of possible fault planes and source depths previously determined by predicting the observed relative P-wave and depth-phase amplitudes (P, pP, sP) and timing at each teleseismic station [40]. However, for earthquakes with magnitudes of near 7 it can be difficult...
Information for seismic stations used in this study of the 1944 and 1952 San Juan, Argentina earthquakes including the instrument responses

<table>
<thead>
<tr>
<th>Event</th>
<th>Station</th>
<th>Comp.</th>
<th>Lat. (°)</th>
<th>Long. (°)</th>
<th>H (m)</th>
<th>Δ (°)</th>
<th>Az (°)</th>
<th>Baz (°)</th>
<th>Instrument</th>
<th>$T_0$ (s)</th>
<th>$T_g$ (s)</th>
<th>Damp</th>
<th>$V_m$ (mm/min)</th>
<th>Speed (mm/min)</th>
<th>Take-off (°)</th>
</tr>
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<td>TUC</td>
<td>z</td>
<td>32.25</td>
<td>-110.83</td>
<td>770</td>
<td>75.1</td>
<td>323.8</td>
<td>143.4</td>
<td>Benioff</td>
<td>1</td>
<td>77</td>
<td>0.8</td>
<td>3000</td>
<td>30</td>
<td>18</td>
</tr>
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<td>SJP</td>
<td>s</td>
<td>18.38</td>
<td>-66.11</td>
<td>80</td>
<td>49.5</td>
<td>2.9</td>
<td>182.5</td>
<td>Wenner M-1</td>
<td>9.8</td>
<td>17</td>
<td>–</td>
<td>1280</td>
<td>16</td>
<td>24</td>
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<td>295</td>
<td>80.3</td>
<td>320</td>
<td>13.8</td>
<td>Benioff</td>
<td>9.8</td>
<td>14.5</td>
<td>–</td>
<td>1180</td>
<td>16</td>
<td>–</td>
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<tr>
<td>1944–1952</td>
<td>DBN</td>
<td>z</td>
<td>52.1</td>
<td>5.17</td>
<td>2</td>
<td>105</td>
<td>37.8</td>
<td>238.1</td>
<td>Galitzin</td>
<td>12</td>
<td>12</td>
<td>–</td>
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<td>30</td>
<td>12</td>
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<tr>
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<td>BRK</td>
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<td>37.87</td>
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<td>49</td>
<td>85.3</td>
<td>320.1</td>
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<td>42.38</td>
<td>-71.32</td>
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<td>73.5</td>
<td>357.7</td>
<td>177.4</td>
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<td>0.8</td>
<td>3000</td>
<td>30</td>
<td>19</td>
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<tr>
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<td>CHR</td>
<td>z</td>
<td>-43.5</td>
<td>172.62</td>
<td>8</td>
<td>86.8</td>
<td>219.2</td>
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<td>Galitzin</td>
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<td>12.9</td>
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<td>30</td>
<td>16</td>
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<td>SIT</td>
<td>e</td>
<td>57.05</td>
<td>-135.32</td>
<td>19</td>
<td>104.5</td>
<td>328.7</td>
<td>125.6</td>
<td>Wenner</td>
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<td>8</td>
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<td>1000</td>
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<td>159</td>
<td>113.7</td>
<td>332.7</td>
<td>113.4</td>
<td>Benioff</td>
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<td>0.45</td>
<td>0.01</td>
<td>8000</td>
<td>15</td>
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<tr>
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<td>HUA</td>
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<td>-12.04</td>
<td>-75.34</td>
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<td>20.3</td>
<td>340.1</td>
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<td>8000</td>
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<td>1952</td>
<td>HUA</td>
<td>n</td>
<td>-33.44</td>
<td>-70.64</td>
<td>595</td>
<td>2.5</td>
<td>222.7</td>
<td>43.7</td>
<td>Bosch-Omori</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<td>STL</td>
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<td>25</td>
<td>9</td>
<td>114.7</td>
<td>289.3</td>
<td>Wiechert</td>
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<td>–</td>
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<td>1944</td>
<td>BAA</td>
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<td>-68.85</td>
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<td>1.5</td>
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<td>–</td>
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<td>1952</td>
<td>SLM</td>
<td>z</td>
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<td>-90.24</td>
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<td>342.4</td>
<td>143.6</td>
<td>Macelwane-Sprengnether</td>
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<td>1.3</td>
<td>–</td>
<td>15,000</td>
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<tr>
<td>1952</td>
<td>FLO</td>
<td>z</td>
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<td>-90.37</td>
<td>160</td>
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<tr>
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<td>7.76</td>
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<td>11.6</td>
<td>0.2</td>
<td>710</td>
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<td>14</td>
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</tbody>
</table>

Comp. is the seismic component (z, vertical component; n, north–south, e, east–west), Lat. the station location latitude, Long. the station location longitude, H the station altitude, Δ the epicentral distance, Az the azimuth to the station, Baz the back-azimuth from the station, $T_0$ the period of the seismometer, $T_g$ the period of the galvanometer, Damp the damping [67], $V_m$ the instrument amplification, Speed the rotating drum velocity and Take-off the angle for a seismic ray leaving the source.

*a Used only P-wave first motion.
to separate out the depth phases because of the duration of the source time function or the instrument response. Hence, we also did a grid-search inversion using the full teleseismic P-waveforms to constrain the focal mechanism and depth.

We carried out a long-period teleseismic P-wave inversion using the multistation omnilinear technique of Ruff [41] (Fig. 4b). We initially assumed a focal mechanism and a source depth previously determined with P-wave first motions and depth-phase analysis. As a result, we obtained the source time function and seismic moment. The technique minimizes scatter in the amplitudes, which results in a better match between observed and synthetic seismograms. We used a 2-s interval for the source time function and 40 s of record, and a crustal velocity structure of P-wave velocity $6.6 \text{ km s}^{-1}$ and density $2.7 \text{ g cm}^{-3}$. We then performed a grid search for the focal mechanism and source depth by stepping through a full suit of possible strike, dip and rake values to determine the best source parameters for each earthquake.

3. Results and discussion

3.1. The 15 January 1944 earthquake

The earthquake on 15 January 1944 that occurred on a late Saturday evening (23:49:27 GMT) was the most destructive event during the last century in the vicinity of San Juan, Argentina. The mainshock and an aftershock that occurred 36 h later produced the collapse of $\sim$13,000 houses and historical sites, and devastated 80% of downtown San Juan [30]. Many reports were immediately published describing the effects of this earthquake, eyewitness accounts, and the local geology [30–33]. This earthquake caused $\sim$5000 deaths in a population of 80,000–90,000 people. For this reason, the 1944 earthquake is considered the largest natural disaster in the Argentinean history [42]. Residents of downtown San Juan and Albardón (Figs. 1b and 2a) reported one very sharp shock of short duration [30,33]. We interpolated the Modified Mercalli (MM) seismic intensities reported for 39 localities in Argentina for the 1944 earthquake [30,33,43]. The intensities show a small area of maximum MM intensity IX in the vicinity of San Juan (Fig. 1b). For completeness, we list all the reported seismic locations published for the 1944 earthquake in Table 2. Most likely none of the earthquake depths are very well constrained. The INPRES seismic location [29] lies in the region of maximum intensity and used local and regional seismic data; hence, this is our preferred epicenter. From this
The 1944 earthquake was well recorded at teleseismic distances and the P-wave first motions are consistent with a thrust focal mechanism but neither plane is well constrained. All of the teleseismic P-wave records we obtained show a compressional first arrival. We also used horizontal seismic records which are plotted in Fig. 4a to be consistent with the convention that a downward motion on the seismogram corresponds to a P-wave dilatation. Local and regional components from stations in Mendoza (MEN) and Buenos Aires (BAA) in Argentina and Huancayo (HUA) in Perú (Table 1) show dilatational first motions. More information reported in the LPA bulletin from the three component seismic station in La Plata (LPA), Argentina, located at 34.91°S and 57.93°W, also indicates a dilatational P-wave arrival [45]. These data from closer stations to the 1944 epicenter (Fig. 3a and Table 1) are consistent with a thrust focal solution (Fig. 4a). Because we have so few records compared to modern events and of the importance of determining the focal mechanism and depth, we have used several approaches to constrain the source parameters.

Previous depth-phase analysis results using the vertical component of the stations with epicentral distances between 50° and 87° indicate a thrust focal mechanism of fault planes oriented in a north direction and a shallow focal depth <12 km, approximately [40].

We have performed a grid-search for a range of strike, dip and rake values by inverting the data at a series of fixed focal depths for the source time function using P-waves recorded on the vertical component at stations PAS, TUC, WES, BRK and CHR. All of these records are observed at teleseismic distances and have clear first arrivals (Fig. 4a). We carefully examined the predicted phases for each waveform modeling, the normalized error between observed and synthetic amplitudes, and the source time function results in the grid search. We started exploring fault planes with dip between 0° and 90°, rake between 30° and 150°, using a grid spacing of 10° and a fixed strike for different focal depths. The best results occur for a dip of 30°–40° to the east and a rake of 100°–130°. We then fixed the rake and varied the dip between 0° and 90°, and the strike between 340° and 100°, in steps of 10°. Acceptable solutions have a strike between 20° and 50° and a dip of ∼30–40°. For simplicity, we present amplitude-misfit error results of modeling for the best depth (11 km) using a fixed strike

Table 2
Summary of published locations and depths for the 1944 and 1952 San Juan, Argentina earthquakes

<table>
<thead>
<tr>
<th>Reference</th>
<th>Lat. (°)</th>
<th>Long. (°)</th>
<th>Depth (km)</th>
<th>MM intensity</th>
</tr>
</thead>
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<td>LPA Bulletin [45]</td>
<td>−31.51</td>
<td>−68.55</td>
<td>12</td>
<td>IX</td>
</tr>
<tr>
<td>Kadinsky-Cade [24]</td>
<td>−31.60</td>
<td>−68.50</td>
<td>Shallow</td>
<td>IX</td>
</tr>
<tr>
<td>INPRES (on-line catalog) [29]</td>
<td>±0.4°</td>
<td>±0.6°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Castellanos [30]</td>
<td>−31.40</td>
<td>−68.40</td>
<td>30</td>
<td>IX</td>
</tr>
<tr>
<td>CALTECH Pasadena Bulletin (1945)</td>
<td>−31.50</td>
<td>−68.00</td>
<td>50</td>
<td>VIII</td>
</tr>
<tr>
<td>Jesuit Seismological Asoc. Bulletin (1944) a</td>
<td>−31.50</td>
<td>−67.60</td>
<td>40–50</td>
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<td>50</td>
<td>IX</td>
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<td>ISS a</td>
<td>−31.50</td>
<td>−68.60</td>
<td>50</td>
<td>IX</td>
</tr>
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<td>Gutenberg and Ritcher (1945) a</td>
<td>−31.25</td>
<td>−68.75</td>
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<tr>
<td>1952 Earthquake</td>
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<td>35</td>
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</table>

MM intensities for the 1944 earthquake [43] represent the Maximum Modified Mercalli intensity that would correspond to each hypocentral location. We used the epicentral location from INPRES [29] for the 1944 and the 1952 events in our study (Figs. 1b and 2).

a References from reports in the ISC archive data.

information alone it is difficult to estimate source parameters for this large earthquake.

All of the reports are consistent describing a 6- to 8-km-long fault scarp forming with the east side up on the La Laja reverse fault after the 1944 earthquake (Fig. 2). The La Laja fault has been interpreted as a thrust fault system of N–NE trend and west vergence, composed of several segments between 31°S and 32.30°S [16,20] (Fig. 2a). The surface rupture which appeared after the occurrence of the 1944 event showed a dip-slip displacement of 0.30 m immediately after the earthquake, which increased to 0.60 m in the following days [30,33]. Harrington [33] also observed a horizontal right-lateral strike-slip displacement of 0.25 m on the same segment. Based on scaling relationships, the expected rupture and average displacement for an earthquake of magnitude ∼7.0 might be of 40 to 50 km and ∼1.4 m, respectively [44].
of N45°E in Fig. 5a and rake of 110° in Fig. 5b, respectively. Our preferred solution (source time function mostly positive and best comparison between observed and synthetic waveforms with normalized error 0.53) has a strike of N45°E, a dip of 35° to the southeast, and a rake of 110° as shown in Fig. 4b.

Another constraint used to test the focal mechanism consisted of the S-wave amplitude ratio and polarity observed at station SJP (Puerto Rico Observatory). The back-azimuth from SJP to the earthquake is 182.5° (Fig. 3a and Table 1), hence, the S waves are almost naturally rotated to SV and SH waves. Both SV and SH phases have impulsive arrivals with opposite polarities at SJP (Fig. 6). At SJP, the ratio of the initial pulse of the SV to SH is 0.52 with SV polarity up (north) and SH polarity down (west). Most of the focal mechanisms that produced the correct SV/SH ratio and P-wave first motion polarities have a thrust focal mechanism with a strike of 350–85°, a dip of 20–65° to the east, and a rake of 70–140°, including our preferred focal mechanism solution (Fig. 4a).

Fig. 5. Example of the grid-search results for the focal mechanism parameters of the 1944 earthquake using the multistation P-wave inversion. (a) Map of the normalized errors between synthetic and observed seismograms for each inversion varying the dip and rake of the fault plane in steps of 10°, for a fixed strike of N45°E and a source depth of 11 km. (b) Same as (a) but varying the dip and the strike of the fault plane in steps of 10°, for a fixed rake of 110°. (c) Amplitude-misfit errors between observed and synthetic seismograms as a function of fixed focal depths from the P-wave inversion assuming our preferred focal mechanism of strike 45°, dip 35° and rake 110°. Error bar in the focal depth is based on acceptable synthetic fits to the observed teleseismic P-waveform data.

Fig. 6. Plot of the SH and SV components recorded at station SJP for the 1944 earthquake. The S waveforms are naturally rotated for this station (Fig. 3a).
We evaluated the best focal mechanism at a series of fixed focal depths using P-waveform inversions (Fig. 5c). The normalized error versus focal depth shows a minimum at a depth of 11 km, although acceptable synthetic P-waveforms occur in the depth range between 9 km and 13 km (Figs. 2b and 5c). The resultant source time function indicates one simple pulse with duration of 10 s (Fig. 4b). For comparison, we present the results for a focal depth of 20 km in Fig. 4c which show a higher amplitude misfit, a more negative source time function (corresponding to a smaller seismic moment and a smaller moment magnitude) and synthetic P-waveforms more inconsistent with the observed waveform data.

We also investigated the behavior of the source time function with increasing depth. We find that at depths greater than 13 km, the source time function begins to exhibit the periodic ringing indicative of a depth overestimation [46] (Fig. 7). In fact, at the best depth (11 km), the seismic moment is concentrated toward the beginning of the deconvolved source time function (Fig. 4b). It seems likely that the local residents did feel one single event of short duration. We concluded that the majority of the seismic moment release occurred at shallow depths with the best point source at 11 km, although we cannot rule out small amounts of moment release further down-dip.

The source time function for the 1944 earthquake has one simple pulse with duration of 10 s, suggesting that most of the moment release occurred near the epicenter. Assuming a rupture velocity of 2.5 km s\(^{-1}\), and a 10-s duration, we estimate that most of the seismic moment was released within approximately 25 km of the epicenter. Depending on if the earthquake had a unilateral or bilateral rupture, the fault length should be between 25 km and 50 km, respectively. We determined a seismic moment \(M_0 = 3.01 \times 10^{19}\) N m which gives a moment magnitude \(M_w = 7.0\) (using the equation \(M_w = 0.67 \times \log M_0 - 6.0\)). We can calculate the average displacement \(D\) using \(M_0 = \mu DA\). For this purpose, we used two possible fault areas (12 km × 25 km for a unilateral rupture and 12 km × 50 km for a bilateral rupture) and a rigidity \(\mu\) of \(3 \times 10^{10}\) N m\(^{-2}\), and obtained an average slip of 3.3 m and 1.7 m, respectively.

According to Wells and Coppersmith [44], an empirical scaling relationship between the moment magnitude and the surface rupture length (SRL) is given by \(M_w = 5.08 + 1.16 \times \log (\text{SRL})\). This relationship predicts a surface rupture length of 45 km for the 1944 event rather than the 6–8 km observed. However, there is a large amount of scatter in this relationship for continental shallow thrust or reverse fault earthquakes especially with magnitudes near 7.0. There are many examples of intraplate earthquakes related to blind thrusts not reaching the surface despite magnitudes between 6.5 and 7.0 [47]. Another empirical regression curve indicates a maximum displacement of 2.5 m for a magnitude \(M_w 7.0\) [44], which is similar to our estimate based on the seismic moment and fault areas assumed above.

We have observed that the teleseismic P-waveform inversion is not sensitive to the different epicentral locations reported for the 1944 earthquake (Table 2). However, the hypocentral location determined using local and regional seismic data by INPRES [29] (Table 2) is consistent with the east dipping fault-plane
geometry suggested by the observed surface rupture (Fig. 2), and by our focal mechanism solution (Fig. 4a). Our results are consistent with the 1944 earthquake rupturing upward mostly or in part on the La Laja fault. In fact, the fault parameters measured on the 1944 fault scarp by Perucca and Paredes [36] yield a strike of N45°E, a dip between 25° and 45° to the southeast and a rake of 90°, as measured in Neogene strata and a Quaternary terrace. These parameters are comparable to those observed by INPRES [48] and Costa et al. [26]. Our solution is also consistent with the sense of coseismic displacement vectors (vertical thrust dip-slip and horizontal right-lateral strike-slip) observed on the La Laja fault after the 1944 earthquake [30,33]. Hence, we suggest the southeast-dipping nodal plane (strike N45°E, dip 35°, rake 110°) is the fault plane that ruptured and the northwest-dipping plane (strike 201°, dip 57°, rake 76°) is the auxiliary plane in the focal mechanism solution.

Besides the clear 6–8-km-long coseismic rupture [30,32,33], Castellanos [30] describes another less well-developed break further south in the vicinity of Ullum related to the 1944 earthquake. It was observed in soft sediments of ~1.5-m vertical displacement with orientation along the strike of the La Laja fault (Fig. 2a). Harrington [33] also pointed out that the La Laja fault might have ruptured for more than 20 km during the 1944 event but the presence of sediments and agricultural sites makes its trace confusing. In addition, Smalley et al. [16] have observed a LANDSAT lineament of N45°E-trending near La Laja fault that continues to the south ending at the Villicum-Zonda segment in the eastern Precordillera fault (Fig. 2a). Taken together this suggests that the La Laja fault might be 40 to 50 km long and capable of a magnitude 7.0 earthquake (Fig. 2).

Based on the regional crustal seismicity around San Juan, the 50-km focal depth reported by the ISS for the 1944 earthquake (Table 2), and the 1977 earthquake source studies, several authors have suggested a deep source (~20–30 km) for the 1944 earthquake [16,20,21,24,34,37]. Smalley et al. [16] investigated the local seismicity in this area and found an active planar structure dipping 35° to the northwest between 19 km and 35 km depth and more diffuse seismicity between 5 km and 15 km beneath the eastern Precordillera (Fig. 2). Thus, these authors speculated that the 1944 event probably had a deep crustal source located to the west of the eastern Precordillera, and may have ruptured in multiple faults, like the 1977 earthquake in the Sierras Pampeanas [24,25] (Fig. 2a), without generating a main surface rupture and interpreting the La Laja fault as a secondary feature [16,34]. For focal depths greater than 15 km and fault planes dipping 35° to the northwest, which are 22° less inclined than our estimated dip (57°) for the auxiliary fault plane, we find significantly worse fits to the observed P-waveforms (Figs. 4b,c, 5 and 7). In fact, we note that the dip is the best constrained parameter in our focal mechanism grid-search with an uncertainty of ±5° (Fig. 5a, b). The simple source time function (Fig. 4b) also indicates that the 1944 earthquake occurred most likely as a single event. Hence, we suggest the 1944 earthquake is unlikely to have ruptured on the deep west-dipping fault and as a complex multiple event.

Siame et al. [20,21] consider the La Laja fault as part of the N40°E-trending fault system that branches from the main eastern Precordillera fault composed of several segments. The same authors used structural geology, geomorphology and exposure age dating analysis in this area to suggest the 1944 earthquake may have ruptured at depth on the Villicum–Las Tapias segment. According to their study, this segment is a 65-km-long reverse fault, oriented in a N20°E direction with a dip of 60° (±15°) to the east at the surface but becoming much shallower at a depth of 20–25 km [20,21] (Fig. 2). The strike N20°E is consistent with the waveforms but not the high angle (60°) dip. We note that if we assume this focal mechanism with a high angle east dipping fault plane for modeling, larger errors result between our observed and synthetic P-waveforms (Fig. 5). These authors also suggested a seismic source for the 1944 earthquake located at 20–25 km depth but with the focus to the east of the eastern Precordillera in a flat-lying part of the Villicum–Las Tapias fault that did not produce any surface rupture along this fault and distributed the deformation in secondary fractures [20,21]. Our results for an inversion of the P-waves with the moment release at depths >13 km (Figs. 4c, 5c and 7) do not produce the best results. Our evidences indicate that it is more likely that it ruptured on a shallower thrust fault with a geometry similar to that observed for the La Laja fault. However, it is possible that the 1944 event also produced coseismic folding and faulting deformation and related ground features. The 1971 (Mw 6.7) San Fernando, California earthquake is another example of a shallow (~12 km) thrust event that ruptured spreading out along several minor structures as it approached the surface [50,51]. Given that we do not know the subsurface geometry of active faults beneath the Tulum valley (Fig. 2) from supporting industry oil-well or seismic reflection data we cannot rule out rupture on the Villicum–Las Tapias segment. But if the seismic moment
release occurred at a shallow depth then we would expect some surface rupture on the Villicum–Las Tapias fault which is clearly not observed [20,21,26,52,53].

Our preferred solution is consistent with the geologic model proposed by Ramos et al. [19] between the Precordillera and the Sierra Pie de Palo (Fig. 2). These authors inferred one major east-dipping thrust basement fault extending up to 10–15 km depth beneath the Tulum valley with several thrust branches as it becomes shallower. We note that the crustal seismicity observed in the same region by Smalley et al. between 5 km and ~15 km in a diffuse distribution [16] may be related to the same east-dipping thrust structures. Our interpretation, together with the already recognized deeper active basement structure of a 35°-northwest dip by Smalley et al. [16] (Fig. 2), can have direct implications in the seismic risk around San Juan from both concealed and exposed faults. A comparable example was evidenced in the San Fernando Valley, California after the 1971 and 1994 earthquakes [51,54].

3.2. The 11 June 1952 earthquake

After the 1944 earthquake San Juan was rebuilt quickly using a modern building code for earthquake-resistant design [55]. Another damaging crustal earthquake occurred in 1952 [29]. However, the smaller magnitude of this event, its location further away from densely populated centers, and improved buildings prevented widespread destruction.

The 1952 earthquake occurred on June 11 at 00:31:37 GMT. Its epicenter was located ~15 km to the S–SW of downtown San Juan, in the vicinity of the Sierra Chica de Zonda (Figs. 1b and 2 and Table 2). Almost 1000 houses collapsed or suffered severe damage in Carpintería, Pocito, and Zonda localities, among others, reaching a maximum MM intensity VIII in this area [43] (Fig. 1b). Beyond this area, damage was minor to moderate and mostly limited to old non-earthquake-proof design constructions as shown by our interpolation for the MM intensities reported in Argentina [43]. The mainshock caused 1 death in Carpintería (Fig. 2) and 14 injured people [56,57]. The reports indicate that the local residents felt 11 aftershocks during that night and point out the strongest one at 03:00:33 GMT [57,58].

We used first motion P-waves (stations STL, HUA, SJP, SLM, FLO, WES, TUC, BRK, CHR), P-diffracted waves (stations STR, DBN), and the SV/SH ratio (0.49) and positive polarities (SV north and SH east) observed at station SJP as input to estimate the focal mechanism. In general, possible solutions have a strike of 0–120°, a dip of 30–90° and a rake of 5–70°. We used these focal mechanisms in the depth-phase analysis. The relative depth phase amplitudes were well predicted when using a roughly northeast fault plane of a steep dip of at least 50° with an important left-lateral strike-slip component (Fig. 8a). We estimated a focal depth of 10–12 km from the predicted depth-phase arrivals.

Teleseismic records at stations TUC, FLO, WES, BRK and CHR (Fig. 3a and Table 1) were used in the simultaneous inversion for the source time function following the same methodology used for the 1944 event. In this grid search, we explored a wide range of fault-plane focal mechanisms and focal depths. Fig. 9
shows the results of the normalized errors between observed and synthetic data obtained for each inversion. In the first step, we varied the dip from 10° to 90° and the rake from 0° to 120° in steps of 10°, respectively, maintaining the strike at N40°E (Fig. 9a). Secondly, we fixed the rake at 30° and varied the dip as before and the strike from 340° through 90°, using a grid spacing of 10°. The minimum amplitude-misfit errors, best comparison between predicted and observed P-waveforms, and source time function mainly positive, are found for a focal mechanism with a fault plane of strike of 20–40°, dip of 70–80° to the southeast, and rake of 20–40° (Figs. 8b and 9a,b).

Fig. 9c shows the behavior of our preferred focal mechanism solution (strike N40°E, dip 75°, rake 30°) when varying the source depth from 1 km to 25 km, in steps of 1 km. The best fit between observed and synthetic data (amplitude-misfit error of 0.402) occurs at a point source depth of 12 km, but acceptable fits result between 10 km and 13 km focal depth, which is in agreement with the depth-phase identification. In addition, solutions with depths larger than 15 km produce a ringing in the source time function indicative of a depth overestimation [46].

Our best results (Fig. 8b) indicate a single pulse for the source time function with a duration of 6 to 8 s and seismic moment $M_0 = 2.2 \times 10^{19}$ N m, which corresponds to a moment magnitude $M_w = 6.8$.

Although there are uncertainties in the epicentral location of the 1952 earthquake, we can speculate on the association of this event with the local geology. Considering the epicentral information from INPRES, NEIC and ISS (Table 2) and the maximum MM intensities for this earthquake [43] (Fig. 1b), it is possible that it is related to the structures in the Sierra Chica de Zonda in the eastern Precordillera as suggested by [26,48,52] (Fig. 2). This portion of the eastern Precordillera has shown little crustal seismicity in a very disperse pattern during local seismic deployments [16,59]. However, neotectonic studies of the interaction between the Precordillera and the Sierras Pampeanas by Martinez and Perez [60] have identified important left-lateral horizontal displacements along active faults of N–NE orientation in this sector of the Precordillera. The NE striking plane in our focal mechanism solution is consistent with this style of deformation.

Interestingly, both the 1944 and the 1952 earthquakes seem to be related to the active eastern Precordillera system and separated by 8 yr and a distance of about 35 km. Recent studies about earthquake interaction, based on the Coulomb stress transference and seismicity rate changes, have proposed that the occurrence of one earthquake contributes to the next on an adjacent segment [61,62]. It is likely that both earthquakes are related to the interaction of the Precordillera and Sierras.
Pampeanas fault systems. Our constraints might help to test this possibility which requires further study.

4. Conclusions

We have analyzed waveforms for the historical earthquakes in 1944 and 1952 in San Juan, Argentina. We have used a combination of several seismic techniques to constrain the source parameters for both crustal events. We obtained a thrust focal mechanism (strike 45°, dip 35°, rake 110°), a seismic moment $M_0 = 3.01 \times 10^{19}$ N m, a moment magnitude $M_w = 7.0$ and a focal depth of 11 km for the 1944 earthquake. The results for the 1952 event indicate an oblique focal mechanism solution (strike 40°, dip 75°, rake 30°), with $M_0 = 2.20 \times 10^{19}$ N m, $M_w = 6.8$ and focal depth of 12 km. We found one single pulse for the source time function of each event with duration of 10 s and 8 s, respectively. Although it is difficult to make a formal error analysis, we estimate the uncertainty in the strike, dip and rake, and focal depth by trial-and-error sensitivity tests using teleseismic P-waveform modeling. This gives uncertainties of about $\pm 15^\circ$ in the strike and rake, and $\pm 5^\circ$ in the dip. The same analysis for the focal depth gives a total range of uncertainty of 5 km, approximately.

Based on our results and the geological observations, we think that the 1944 earthquake is a thrust event that occurred on a northeast striking plane, dipping $\sim 35^\circ$ to the southeast. The 1952 earthquake, of a more oblique focal mechanism, is consistent with the active N–NE faults of the eastern Precordillera that show left-lateral neotectonic displacements [60] in the Sierra Chica de Zonda segment, but a particular association to the active faults in the area is difficult (Fig. 2). We note that the relocation study of some of the larger aftershocks mentioned in the historical reports could help to constrain the fault plane activated during each earthquake. Unfortunately, we do not have seismic records for them.

We find good agreement between the exposed La Laja thrust fault and the seismogenic fault that produced the 1944 $M_w = 7.0$ earthquake. This is mainly based on the following reasons:

- The focal depth and geometry of the east-dipping thrust fault plane solutions are consistent with the parameters (strike, dip and rake) observed for the La Laja fault.
- The east-dipping focal mechanism fault plane solution is compatible with the sense of the slip vectors (thrust and right-lateral) observed at the surface on the La Laja fault scarp during the 1944 earthquake.
- Given the shallow focal depth ($\sim 11$ km) of this large earthquake, it is likely to have occurred on a fault plane that ruptured to or near the surface.
- Some reports of disruption at Ullum during the 1944 earthquake might be an indication of additional activity along the same (La Laja) fault.
- The La Laja fault has been predicted to continue to the south for about 40 km until it meets the Villicum–Zonda fault segment in the eastern Precordillera [16,33,52], although the presence of unconsolidated sediments and agriculture sites to the south of the La Laja fault scarp make it difficult to map (Fig. 2a).
- There were no other major faults that had any coseismic rupture during the 1944 earthquake.

Our results for the 1944 earthquake show that the style of deformation is similar to that observed in the Sierras Pampeanas [13,19] where the basement blocks are mainly uplifted by east-dipping faults (Fig. 2). Although our source time function results predict the activation of one main fault (one simple source with one pulse of moment release), the 1944 earthquake may have caused coseismic deformation in the associated folding and terraces around the La Laja fault [37,49,53]. Considering the deep west-dipping active structure recognized by Smalley et al. in previous seismic studies [16] and the activation of an east-dipping thrust fault that might have reached the surface during the 1944 earthquake (Fig. 2), there is a high seismic hazard posed to San Juan from both concealed and exposed faults related to the frontal part of the eastern Precordillera.

The source characterization of the 1944 ($M_w = 7.0$) and 1952 ($M_w = 6.8$) earthquakes completes the study of the largest damaging crustal earthquakes during the last century in the vicinity of San Juan. Both events exhibit a simple source time function, a shorter duration and a shallower focal depth than the most recent 1977 ($M_w = 7.5$) multiple shock earthquake in the Sierras Pampeanas [25]. This backarc deformation is consistent with the two décollement levels proposed by [15,63,64] in the vicinity of San Juan. The crustal earthquakes in 1944 (this study) and 1977 [25] both showed predominantly thrust focal mechanisms (Fig. 2), but they differed in their focal depths and in the complexity of their coseismic ruptures. Since the occurrence of large earthquakes is sporadic, the study of historical seismograms can help in identifying active structures that are important in the mapping of the seismic hazard in this area.
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