

# Tectonics

## RESEARCH ARTICLE

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### Key Point:

- The La Rinconada Fault (LRF) in San Juan, Argentina, has a late Quaternary average shortening rate of  $0.41 \pm 0.01$  mm/year

### Supporting Information:

- Supporting Information S1

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## Late Quaternary Activity of the La Rinconada Fault Zone, San Juan, Argentina

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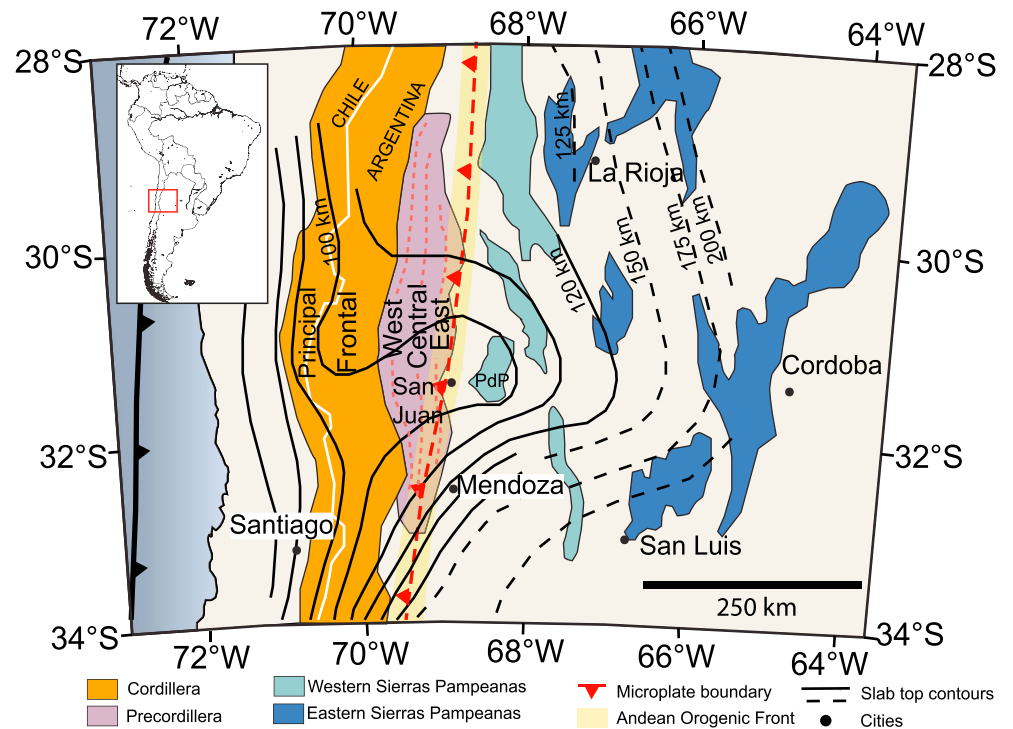
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**Abstract** Most of the permanent deformation in the Pampean Flat slab segment of the central Andes is taken up at the Andean Orogenic Front in Argentina, a narrow zone between the Eastern Precordillera and Sierras Pampeanas that comprises one of the world's most seismically active thrust zones. Active faults and folds in the region have been extensively mapped but still largely lack information on style and rates of deformation, which is essential for understanding the distribution of regional strain and estimating the seismic potential of individual faults. Structural, geomorphic, and <sup>36</sup>Cl cosmogenic radionuclide surface exposure age methods are used to focus on key sites along the 30-km-long La Rinconada Fault Zone in this region of west-central Argentina, which is ~15 km away from the highly populated (~500,000) city of San Juan, to define a late Quaternary average shortening rate of  $0.41 \pm 0.01$  mm/year. This slip rate is the same order of magnitude, but slightly lower than nearby similar east dipping Eastern Precordillera faults including the La Laja and Las Tapias Faults. Relatively low slip rates are interpreted as being a consequence of distributed deformation between the latitude of the La Rinconada Fault Zone (31 and 32°S), as compared to between latitudes 32 to 33°S where deformation appears to be focused on fewer structures, including the Las Peñas and La Cal Thrust Faults. The La Rinconada Fault Zone is capable of generating earthquakes of  $M_w$  6.6–7.2, but further investigations are required to determine timing and recurrence intervals of discrete events.

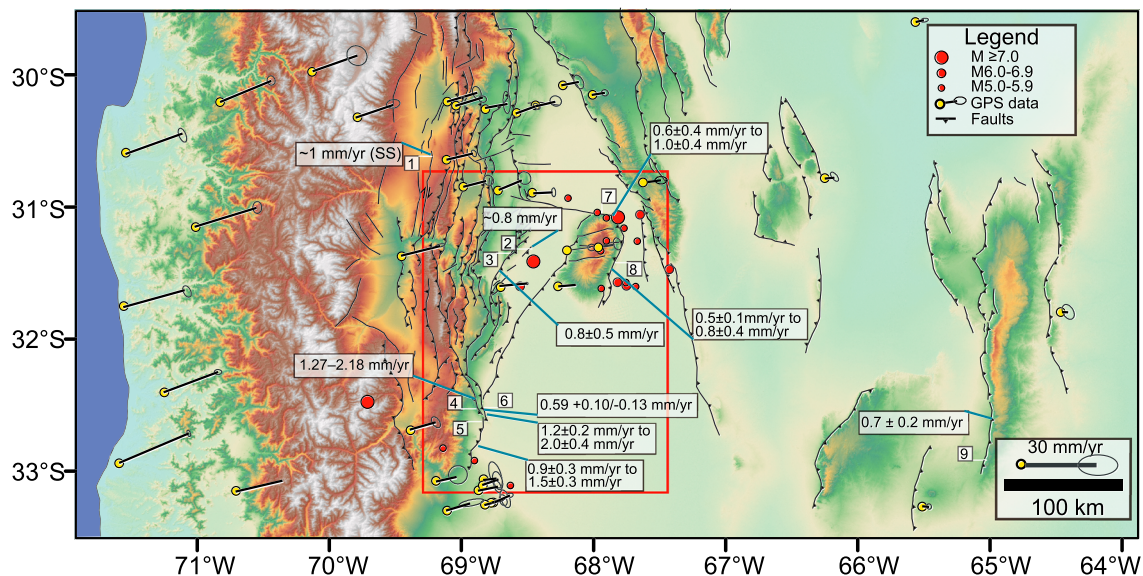
## 1. Introduction

Permanent shortening in the Pampean flat-slab segment of the South American plate has occurred mostly in doubly vergent fold-and-thrust belts (Armijo et al., 2010; Riesner et al., 2018) in the back-arc region since ~20 Ma (Baby et al., 1997; Zapata & Allmendinger, 1996), including the Argentine Precordillera (Figure 1). Some 60–75% of the total shortening between the trench and the foreland at 30°S has been accommodated within the Precordillera during the past 10–15 Ma (Allmendinger et al., 1990). Shortening has also been accommodated in the Sierras Pampeanas, a region of thick-skinned deformation directly to the east at the same time as deformation was active in the Precordillera. This partitioning of deformation has been related to the presence of flat-slab subduction from 27 to 33.5°S (Ramos, 1988; Ramos et al., 1998, 2002, 2004; Ramos & Folguera, 2009). Deformation in the Precordillera proceeded from west to east and reached the Eastern Precordillera at ~2.6 Ma. In contrast, uplift of basement rocks of the Sierras Pampeanas propagated westward, beginning ~6–5.5 Ma at its eastern extent, and reaching the Pie de Palo near its western extent ~3 Ma (Jordán, Isacks, Allmendinger, et al., 1983; Jordan, Isacks, Ramos, et al., 1983; Ramos et al., 2002; Figure 1). Presently, the oppositely verging Precordillera and Sierras Pampeanas terranes are juxtaposed between latitudes 30 and 32°S across a relatively narrow (~50 km) zone of active mountain building called the Andean Orogenic Front (Figure 1).

Evidence for highly localized back-arc deformation along the Andean Orogenic Front includes GPS gradients, the location of shallow crustal seismicity, and Quaternary offset on faults (Figure 2). Most prominent Quaternary deformation features (Figure 2) have been recorded across the Andean Orogenic Front (Cortés et al., 1999; Costa et al., 2000, 2006, and references therein). Since most of the crustal thickening in the Andes during the Neogene has been caused by tectonic shortening of the South American plate (Allmendinger et al., 1997; Isacks, 1988; Kley & Monaldi, 1998; Ramos, 1988; Ramos



**Figure 1.** Location map centered on the Pampean flat slab segment. Slab top contours are represented by thin black lines (Anderson et al., 2007) and thin black dashed lines (Mulcahy et al., 2014). ‘PdP’ stands for Pie de Palo in the western Sierras Pampeanas tectonic block.



**Figure 2.** The 30-m ASTER digital elevation model showing tectonic features (Costa et al., 2000; Siame et al., 2002), seismicity (Engdahl & Villaseñor, 2002), GPS velocity field (Brooks et al., 2003), and Quaternary slip rate data (Costa, Ahumada, Vázquez, & Kröhl, 2015; Costa, Ahumada, Gardini, et al., 2015; Costa et al., 2018; Rockwell et al., 2014; Salomon et al., 2013; Schmidt et al., 2011; Schoenbohm et al., 2013; Siame et al., 2002, 2006, 2015) in the Pampean flat slab segment. The red box shows the location of Figure 3. Numbers in white boxes indicate faults with known slip rates: 1—El Tigre Fault, 2—La Laja Fault, 3—Las Tapias segment of Villicum-Zonda-Pedral Thrust, 4—Las Higuera, 5—La Cal Thrust, 6—Las Peñas Thrust, 7—Northern Sierra Pie de Palo Fault, 8—Southern Sierra Pie de Palo Fault, and 9—Los Molinos branch of the Comechingones Fault. SS, for strike slip, denotes strike-slip rates.

et al., 1996), study of the distribution and rates of movement along active tectonic structures in this area is relevant to the understanding of ongoing mountain building, partitioning of strain, and crustal deformation related to flat-slab subduction. However, the spatiotemporal coverage and/or resolution of these data sets are limited. For instance, interpretation of GPS-derived slip rates across individual structures is currently impossible due to the sparseness of GPS stations. Further, the activity of most of the structures in the Precordillera and the Sierras Pampeanas have not been quantified since there is still a paucity of studies employing geochronological techniques to determine slip rates (Costa, Ahumada, Vázquez, et al., 2015, and references therein).

This study reports the Quaternary uplift and shortening rates of the La Rinconada Fault Zone from cosmogenic dating of recently offset landforms, which in addition to its tectonic significance, lies only 15 km south of the city of San Juan which has a population of ~100,000. In 1944 the city was shaken by a  $M_w$  7 earthquake associated with the La Laja Fault, located 15 km north of the city. This event resulted in the death of 10,000 people, 10% of its population at the time (Castellanos, 1945; Groeber, 1944; Harrington, 1948; Instituto Nacional de Prevención Sísmica (INPRES), 1977). From preliminary assessment, the La Rinconada Fault may also be capable of posing similar hazards to the city considering at least its length and proximity to the city.

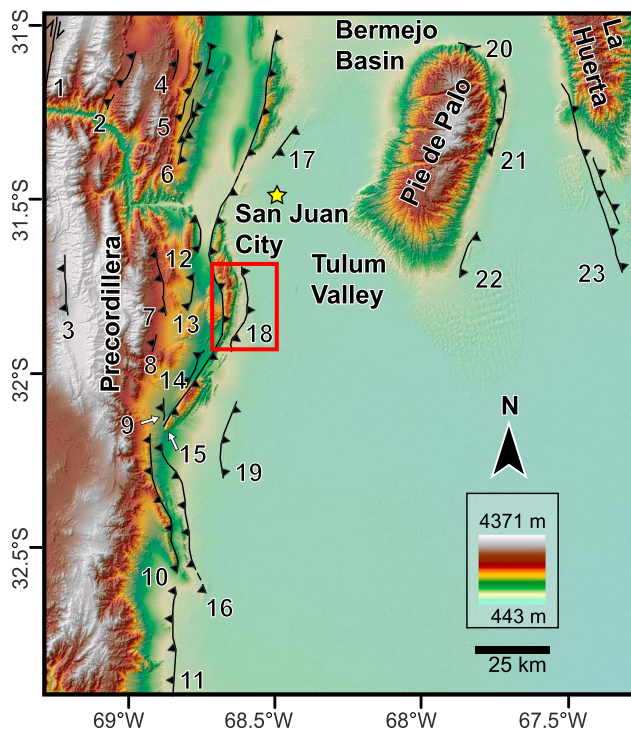
The slip rates determined in this study, together with existing slip rates for other faults, are used to interpret the role of the La Rinconada Fault in the regional tectonic context, and in particular the proportion of total shortening it accommodates in the Andean Orogenic Front of the flat slab segment from latitudes 30 to 33°S. We also estimate the potential for the La Rinconada Fault to generating  $\geq M_w$  7 earthquakes in or near the city of San Juan.

## 2. Background

### 2.1. Regional Tectonic Setting

Ongoing subduction of the Nazca plate beneath the South American plate is primarily responsible for building the Andean orogenic belt—the world's longest and highest noncollisional continental mountain range. However, the Pampean segment (27–33°S) of the central Andes subduction zone is abnormally shallow, the result of subduction of the Juan Fernandez Ridge (Pilger, 1984), with the slab extending as far as 300 km into the continental interior at a shallow depth of ~100 km (Cahill & Isacks, 1992; Engdahl et al., 1998; Gutscher et al., 2000; Jordán, Isacks, Allmendinger et al., 1983; Jordan, Isacks, Ramos et al., 1983; Ramos, 1999; Smalley et al., 1993). As a result, the Pampean segment displays a distinct tectonic style and distribution of Quaternary deformation. In particular, in addition to the development of a fold-and-thrust belt at the plate boundary, deformation has penetrated deeply into the intraplate region (Gutscher et al., 2000) either through thermal weakening of the crust due to eastward migration of arc magmatism (Ramos et al., 2002) or increased interplate coupling between the flat-slab segment and the rheologically strengthened upper lithosphere (due to cooling), resulting in a series of uplifted basement ranges known as the Sierras Pampeanas (Figure 1). The Sierras Pampeanas are a modern analogue of the Laramide Orogen in the western United States (Jordán, Isacks, Allmendinger, et al., 1983; Jordan, Isacks, Ramos et al., 1983; Jordan & Allmendinger, 1986; Smalley et al., 1993).

GPS studies indicate a convergence rate of 6.3 cm/year along the plate boundary of the flat-slab segment (Brooks et al., 2003; Kendrick et al., 2003). Deformation along the plate boundary has migrated east through time, from the Principal Cordillera, to the Frontal Cordillera, and finally to the Precordillera (Figure 1; Jordán, Isacks, Allmendinger, et al., 1983; Jordan, Isacks, Ramos et al., 1983; Jordan & Gardeweg, 1989; Ramos, 1988; Ramos et al., 2002; Zapata & Allmendinger, 1996). Between latitudes 30 and 32°10'S, the well-documented Argentine Precordillera can be further divided into western, central, and eastern structural provinces (Baldi et al., 1982; Ortiz & Zambrano, 1981), separated by basins filled with late Tertiary and Quaternary continental sediments (Jordan et al., 1993; Von Gosen, 1992). The Western and Central Argentine Precordillera are both thin-skinned. The Eastern Precordillera arguably transitions from thin-skinned to thick-skinned from west to east (Siame et al., 2015). However, convincing evidence of this transition, so far, is available only north of Pie de Palo (Allmendinger & Judge, 2014; Zapata & Allmendinger, 1996). The Eastern Precordillera formed through Pliocene-Pleistocene orogenic activity (Jordan et al., 1993; Ramos, 1988).



**Figure 3.** Quaternary faults in the provinces of San Juan and Mendoza. The red box shows the location of Figure 5. Numbers indicate the Quaternary faults: 1—El Tigre, 2—La Cantera, 3—Ansilla-Jarillal, 4—Los Gauchos, 5—Dehesa, 6—Blanquitos, 7—Maradona, 8—Las Osamentas, 9—Acequion, 10—Las Higueras, 11—La Cal, 12—Cerro Zonda, 13—Papagallos, 14—Cerro La Chilca, 15—Villicum-Zonda-Pedernal, 16—Las Peñas, 17—La Laja, 18—La Rinconada, 19—Cerro Salinas, 20—Northern Sierra Pie de Palo, 21—Ampacama, 22—Niquizanga, and 23—Las Chacras (Costa et al., 2000; Perucca & Vargas, 2014; <https://sara.openquake.org/> and <http://sigam.segemar.gov.ar/visor/>).

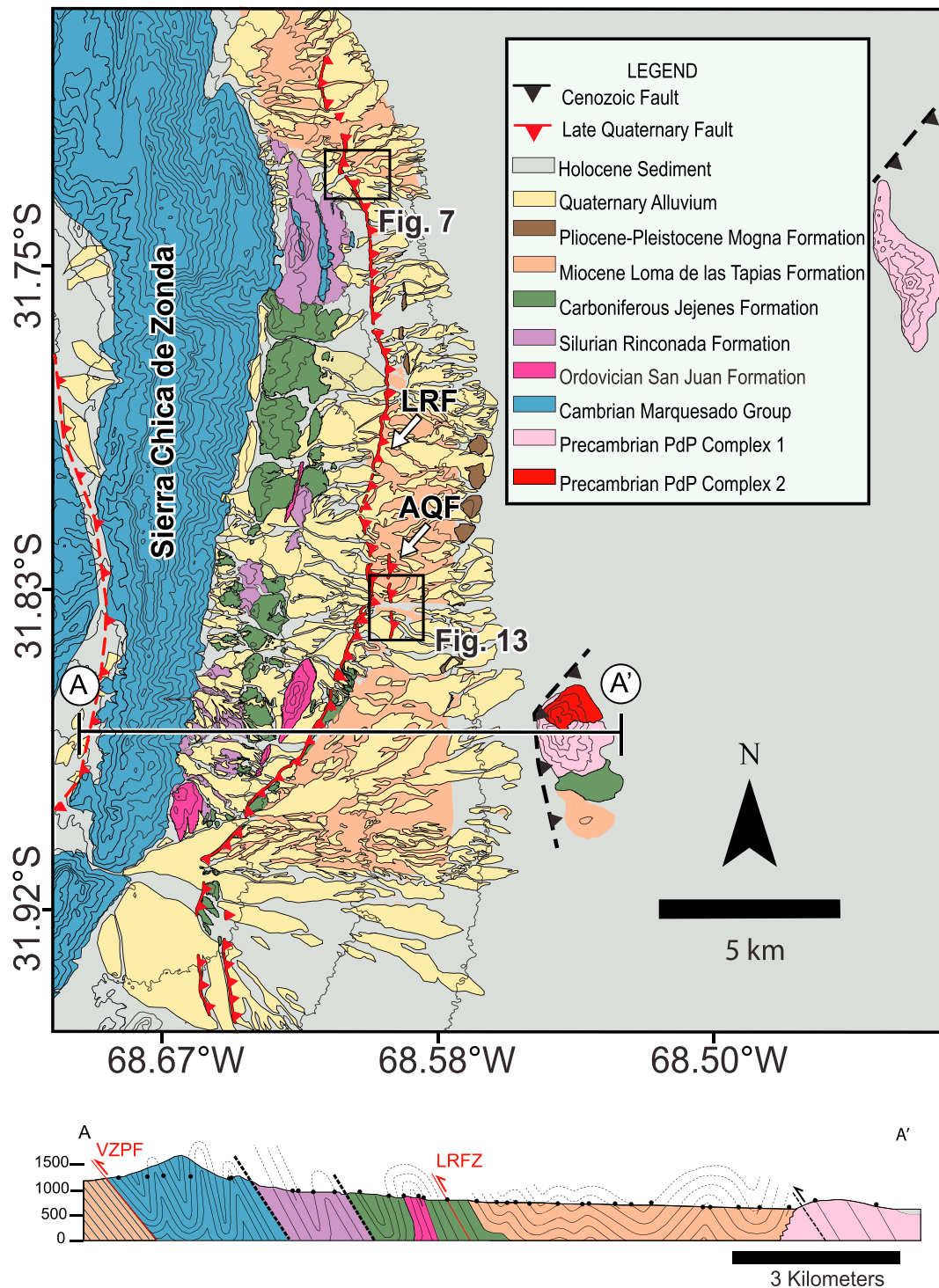
At present, the active Andean Orogenic Front is located in between the eastern foothills of the mainly east-vergent, thin-skinned Argentine Precordillera fold-and-thrust belt and the mainly west-vergent, thick-skinned Sierras Pampeanas uplifted basement blocks (Figure 1; Brooks et al., 2003; Costa, 1999; Fielding & Jordan, 1988; Groeber, 1944; Kadinsky-Cade et al., 1985; Meigs et al., 2006; Ramos et al., 1997; Siame et al., 2002, 2005, 2015; Smalley et al., 1993; Uliarte et al., 1987; Vergés et al., 2007). GPS-derived velocity fields suggest rates of back-arc deformation between the Eastern Precordillera and the Western Sierras Pampeanas range from 2 to 7 mm/year (Brooks et al., 2003; Kendrick et al., 1999, 2001, 2003; Kendrick et al., 2006). This flat subduction segment is characterized by the juxtaposition of oppositely verging thrust systems in the back-arc region that show evidence of localized Quaternary-active deformation, but with deformation concentrated at the juncture between these regions. GPS studies have proposed that strain localization is accomplished through a microplate which overthrusts both the Nazca and South American plates and deforms primarily at its boundaries rather than throughout the entire back-arc contractional wedge (Brooks et al., 2003).

Approximately 90% of the documented Quaternary deformation in Argentina is located within the Andean Orogenic Front (Costa et al., 2006). Quaternary deformation is characterized mostly by north-south oriented reverse faults and folds and, to a lesser extent, north-south oriented strike-slip faults resulting from partitioning of the oblique convergence of the Nazca and South American plates (Costa et al., 2000; Siame et al., 1997, 2005). This segment is also characterized by high levels of shallow (5–35 km) crustal seismicity (Figure 2; Smalley et al., 1993; Smalley & Isacks, 1990), with earthquake seismic moments reaching 3 to 5 times larger than in subduction segments where the slab is dipping  $\geq 30^\circ$  (Gutscher et al., 2000; Jordán, Isacks, Allmendinger, et al., 1983; Jordan, Isacks, Ramos, et al., 1983; Ramos et al., 2002; Smalley et al., 1993). The distribution of shallow earthquake hypocenters is spatially related to structures with evidence of recent deformation between the

Precordillera and the Sierras Pampeanas (Cahill & Isacks, 1992; Engdahl et al., 1998; Gutscher et al., 2000; Smalley et al., 1993). San Juan and Mendoza provinces have been the locus of large-magnitude earthquakes in the past century. Some notable examples of earthquakes which are associated with surface ruptures are the 1944  $M_w$  7.0 San Juan earthquake that was generated along the La Laja Fault (Castellanos, 1944; Groeber, 1944; Harrington, 1948) and the 1977  $M_s$  7.4 Caucete earthquake that occurred along the Ampacama-Niquizanga Fault (Bastías, 1985; Volponi et al., 1978). There are also large-magnitude earthquakes such as the 1952  $M_w$  6.8 San Juan earthquake, for which the seismogenic structure has been suspected but not been identified (Alvarado & Beck, 2006; Instituto Nacional de Prevención Sísmica (INPRES), 1977).

## 2.2. La Rinconada Fault Zone (LRFZ)

The LRFZ (Figures 3 and 5), parallel to the Villicum-Zonda-Pedernal Thrust Faults and along strike with the Cerro Salinas Fault to the south, is a north-south trending, 30-km-long, east dipping reverse fault located southwest of the city of San Juan (Bastías et al., 1990; Costa et al., 2006; Martos, 1987; Proyecto Multinacional Andino (PMA): Geociencia para las Comunidades Andinas, 2008), a city which has been hit by at least 3  $> M_w$  6.8 earthquakes in the past 100 years (Alvarado & Beck, 2006). Prominent fault scarps,  $>20$  m high, are a consequence of these earthquakes and are counterslope to the eastern flank of the Eastern Precordillera, particularly the foothills of the Sierra Chica de Zonda (Figure 4). These scarps uplift and expose the east dipping Miocene Lomas de las Tapias bedrock, which is also being uplifted along the La Laja Fault (Rockwell et al., 2014). The La Rinconada scarps, which most probably represent cumulative



**Figure 4.** Geologic map and cross sections across the La Rinconada Fault Zone (LRFZ) and the Villicum Zonda Pedernal Fault (VZPF) (Moreno, 2013; Ramos & Vujovich, 2000; Richard, 2013). Black boxes labeled “Figure 7” and “Figure 13” indicate the locations of the El Molino and Arbol Quemado sites, respectively. ‘PdP’ in the legend stands for Pie de Palo.

displacement, cut through multiple levels of well-preserved alluvial deposits, comparable to neighboring Quaternary-active faults (e.g., La Laja, Las Tapias, and Cerro Salinas Faults). The La Rinconada Fault also exhibits smaller scarps (~2 m high) which have been linked to the 1952  $M_w$  6.8 San Juan earthquake on the basis of this faults proximity to the epicentral location (Tello & Perucca, 1993; Proyecto Multinacional

Andino (PMA): Geociencia para las Comunidades Andinas, 2008; Yeats, 2015). The rate of movement of the La Rinconada Fault has not been established, nor has a relationship to the 1952 San Juan earthquake been proven. Based on its potential seismogenic history, long trace, and large, multiple-event scarps, the La Rinconada Fault is an ideal target for neotectonic studies and seismic hazard assessment that will allow us to determine its contribution to the ongoing deformation of the Andean Orogenic Front and estimate the seismic hazard it poses to the city of San Juan.

### 3. Methods

#### 3.1. Geomorphic and Geologic Mapping

High-resolution satellite images from Land Remote-Sensing Satellite (LANDSAT), Google Earth, and 30-m-resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global digital elevation models (<https://asterweb.jpl.nasa.gov/gdem.asp>) served as base for mapping structural, geologic, and geomorphic features observed in the field. The geology of the area transected by the La Rinconada Fault was mapped primarily at a scale of 1:50,000 (Figure 4). Geomorphic maps focused on two sites: the El Molino and Arbol Quemado sites, which highlight the distribution of Quaternary landforms/deposits and deformation (faulting, folding, warping) features, were mapped with at a scale of at least 1:10,000. Different cut and fill strath terraces were identified on the basis of surface morphology, stratigraphic relationships, and weathering characteristics (McFadden et al., 1989; Owen et al., 2014). We used the letter Q to indicate Quaternary, followed by a number (1, 2 ... n) from youngest to oldest, and lastly a letter to indicate the study area (e.g., m for Molino).

#### 3.2. Differential Global Positioning System Survey and Topographic Profile Construction

Fault scarp topographic profiles were surveyed with subcentimeter precision using Trimble® R3 Differential Global Positioning System survey equipment which includes a base station and two rover units.

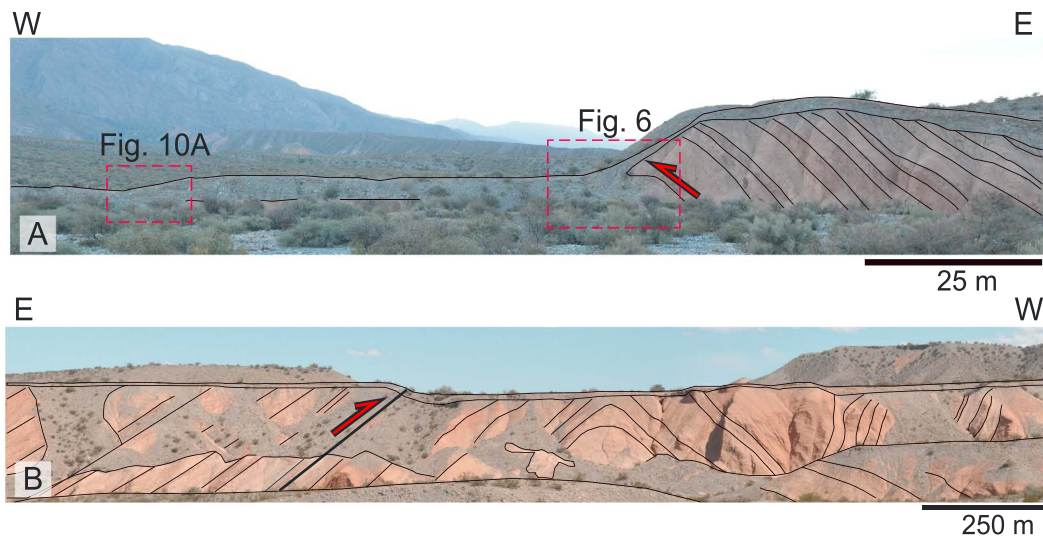
Five surfaces which are cut by the La Rinconada Fault at the El Molino Site and seven surfaces cut by the Arbol Quemado Fault were surveyed using this method. Geographic coordinates and elevation data were gathered by walking along a nearly perpendicular path across the scarps using the Differential Global Positioning System rovers which were held at constant height above the ground and set at a one-second data collection rate. For the duration of each survey, the base station received signals from satellites which provided information that allowed for postprocessing correction of data from the rovers. The surveys on both sides of the fault scarps were extended, where possible, for several tens of meters to also capture the regional slope (Figure S1) of the surface.

Postprocessing of data gathered in the field was performed using Trimble Business Centre 2. Survey points were projected on lines perpendicular to the fault trace using the point profile interactive tool on ESRI's ArcMap to adjust the minor irregularities in the traces of survey paths or variations in transit speed.

#### 3.3. Displacement Measurement

Topographic profiles across scarps in the El Molino and Arbol Quemado sites that were obtained through kinematic GPS survey were used to measure displacement. Two methods were used to explore a possible range of displacement values: (1) solving equations by Yang et al. (2015), which are based on geometric relations between the fault and the displaced surfaces, and (2) FaultFoldForward (FFF) trishear modeling.

At the El Molino site, displacement on fault scarps displaying fault-bend folding was measured using the FFF modeling software (v.7.1.1) by Allmendinger (1998) (<http://www.geo.cornell.edu/geology/facultyRWA/programs/faultfoldforward.html>; last accessed April 2017). FFF software, which is based on the trishear concept (Allmendinger, 1998; Allmendinger & Shaw, 2000; Cardozo et al., 2003; Erslev, 1991; Hardy & Ford, 1997; Hardy & McClay, 1999; Zehnder & Allmendinger, 2000), allows the creation of forward models of area-balanced cross sections with complicated fault-fold geometries using six trishear parameters first described by Erslev (1991), which include displacement, fault ramp angle, trishear apical angle (TA), propagation to slip (P/S) ratio, and the *x* and *y* positions of the tip line. The poorly consolidated, dominantly, coarse pebble-to-gravel-sized sediment which comprises the horizon that was surveyed and modeled satisfies the assumption that material must be isotropic and homogenous (Cardozo et al., 2003; Hardy & Finch, 2007; Johnson & Johnson, 2002).



**Figure 5.** Exposures of the LRFZ. (a) A fault propagation fold scarp to the west (shown in detail in Figure 10a) and the main fault scarp of the La Rinconada Fault to the east (shown in detail in Figure 6) at the El Molino site. (b) The minor Arbol Quemado Fault. Site locations are shown in Figure 4.

A series of forward models were created using different combinations of trishear parameters and were compared by visual inspection to faulted profiles that were uploaded as background in the FFF program window. Quantifiable error for displacement estimates from trishear modeling is not yet available for the current version of the FaultfoldForward (FFF) modeling software by Allmendinger (1998) (<http://www.geo.cornell.edu/geology/facultyRWA/programs/faultfoldforward.html>; last accessed December 2018). Using an iterative approach, the range of possible values of trishear parameters were narrowed to specific values that created a model which closely resembles the faulted profile in terms of height and backlimb inclination. Different scarp morphologies were also modeled to test for the effect of assumed scarp morphology on the amount of displacement. Prior to running the models, the surface was rotated to account for regional slope (Figure S1) of the terraces measured in the field.

The amount of displacement is the amount of slip associated with the model that best matches the faulted profile. However, uncertainty for the displacement measurements cannot be quantified because best fit is based on visual inspection. Several studies which use FFF modeling as one of the approaches to measure displacement on reverse fault scarps also in Argentina used this same trial-and-error and visual estimation approach for determining the model that best fits the actual faulted profile (Costa, Ahumada, Vázquez, & Kröhling, 2015; Vázquez et al., 2016). Using the fault dip value at the surface, the displacement was then resolved into components of shortening and uplift.

For the Arbol Quemado site, where the original scarp morphology is uncertain, both FFF modeling and Yang et al. (2015)'s equations were used to measure a likely range of displacement values. FFF accounted for possible involvement of varying degrees of fault-related folding while Yang et al. (2015)'s method assumed an original simple reverse fault scarp morphology. Input parameters for Yang et al. (2015)'s method were the following: slope and y-intercept values from linear regressions of hanging wall, footwall, and scarp surface survey points; fault dip; and fault-tip x-axis position. For measurement of displacement on all fault scarps, the same dip value ( $33^\circ$ ) was used and the fault tip position was placed near the base of each scarp, as was observed in the stream cut exposure of the Q9a scarp (Figure 5b).

For propagation of error associated with these parameters, a Monte Carlo simulator was used (by Brian Murphy, September 2013; <https://drive.google.com/file/d/0B3Xb1yYamd6iZUIBYUJIRU>

5rWTg/view; last accessed 15 May 2017). This required specifying the equation for displacement, and the input values, distribution types, and errors for the different variables. The fault-tip x-axis position followed a uniform distribution while all the other variables followed a normal distribution. The estimate of the true value of displacement and its associated uncertainty was then taken from the average of 10,000 realizations. For each of the calculations, a 1-sigma uncertainty of  $\pm 2^\circ$  and  $\pm 1$  m was assigned for the dip and the x-axis

position of the fault tip, respectively. The uncertainty corresponding to the slope and y-intercept values of the hanging wall, footwall, and scarp surface regression were taken from the linear regression statistics and were also input in the Monte Carlo simulations.

Trenching was also performed to expose a sectional view of the small fault-propagation fold scarp at the base of the series of cumulative scarps at the El Molino site (Figure 10a). Displacement was measured directly from the offset bedrock. Precise inverse modeling of the fault-propagation folding was not performed due to the difficulty of delineating deformed layers of the coarse alluvial material.

### 3.4. The $^{36}\text{Cl}$ Cosmogenic Radionuclide Surface Exposure Dating

Cosmogenic radionuclide dating (Gosse & Phillips, 2001; Lal, 1988, 1991; Stone et al., 1998) for surface exposure ages was combined with geomorphic analysis of fault scarps to estimate prehistoric slip rates. The ages of the carbonate-dominated strath terraces of the El Molino and Arbol Quemado sites were calculated by measuring the concentration of  $^{36}\text{Cl}$ , a spallation product of either Ca or K (Phillips et al., 1990), coupled with the production rate of  $^{36}\text{Cl}$  for the altitude and latitude of the sample site (Gosse & Phillips, 2001; Lal, 1988, 1991; Stone et al., 1998).

Since alluvial surfaces were dated, inheritance is likely (Blisniuk et al., 2012; Owen et al., 2011). To account for this, samples were collected and measured at different depths, allowing the construction of depth profiles. Production rates are usually highest at the surface and decrease exponentially with depth to zero; decay to a nonzero concentration indicates the inherited component, which can be used to correct for surface concentrations (R. S. Anderson, Repka & Dick et al., 1996; Perg et al., 2001). Approximately 2-m-deep pits were excavated on terrace T2 at the El Molino site and on terrace T9 at the Arbol Quemado site. Samples of 2 kg of coarse-sand to granule-sized sediments (2–4 mm) of mixed lithology (carbonate and metasedimentary rocks) were gathered each at depths of 25, 50, 75, 100, and 150 cm at each site.

For the remainder of offset surfaces dated in this study, ~100 pebble- to cobble-sized (4–6-cm average diameter) pure carbonate surface samples were gathered from each surface of which ~25 were selected for dating. For this type of sampling, inheritance is constrained by gathering samples from the modern channel and subtracting the inherited nuclide concentration measured from these modern channel samples (R. S. Anderson, Repka, & Dick, 1996; Repka et al., 1997). Both depth profile and surface samples were collected from the Q2m surface to assess agreement among methods.

Extraction, chemical preparation, and dissolution of samples were performed at the Cosmogenic Nuclide Laboratories in the Department of Geology at the University of Cincinnati, USA, following the procedures of Stone et al. (1996), which were modified as in Cesta and Ward (2016) to help hasten the dissolution process. The selected surface samples were amalgamated, while the depth profile samples were mixed before being crushed and sieved to obtain the <250- $\mu\text{m}$  fraction. Approximately 100 g of each of the pure carbonate surface samples and ~180 g of each of the mixed lithology depth profile samples were leached with dilute  $\text{HNO}_3$ , rinsed, and then dried. A larger amount was needed from the depth profiles to make up for the lower proportion of carbonate content. Approximately 30 g of the leached <250- $\mu\text{m}$  fraction of surface and depth profile samples was prepared for dissolution. Approximately 1 g of  $^{35}\text{Cl}$  enriched (or “spike”) carrier solution from Icon Isotopes, New Jersey was added to each sample. HF and trace metal grade  $\text{HNO}_3$  were then added for sample digestion. AgCl was precipitated and separated by adding  $\text{AgNO}_3$  solution and trace metal grade  $\text{HNO}_3$ . The crude AgCl precipitate was then dissolved with trace metal grade  $\text{NH}_4\text{OH}$  to produce a solution that was separated through anion exchange chromatography. The final AgCl product was rinsed, dried, and then loaded into Cu cathode holders packed with AgBr. These targeted samples, along with the carrier solution blanks, were sent to Purdue Rare Isotope Measurement Laboratory at Purdue University, USA, for measurement of  $^{36}\text{Cl}/\text{Cl}_T$  and  $^{35}\text{Cl}/^{37}\text{Cl}$  using accelerator mass spectrometry analysis.

Each leached sample having a mass of 13 g and selected preleached surface and depth profile samples were set aside and sent to Bureau Veritas Minerals, Vancouver, Canada, for whole rock analysis using lithium metaborate fusion. Refractory and rare Earth elements were analyzed through inductively coupled plasma-mass spectrometry. Whole rock major and minor elements were analyzed through inductively coupled plasma-emission spectrometry. Total carbon and total sulfur analysis was performed using a

LECO analyzer. Trace boron was analyzed through a sodium peroxide fusion inductively coupled plasma–mass spectrometry finish.

The topographic shielding factor was calculated using the CRONUS-Earth (Cosmic-Ray Produced Nuclide Systematics on Earth) Topographic Shielding Calculator v2.0 (<http://cronus.cosmogenicnuclides.rocks/2.0/>; last accessed 21 June 2017).

Ages of surfaces from surface clasts and depth profile samples were computed using the  $^{36}\text{Cl}$  CRONUS-Earth Web calculator v.2.0 (<http://cronus.cosmogenicnuclides.rocks/2.0/html/cl/>; last accessed in July 2017) and the MATLAB-based CRONUSCalc depth profile calculator (<https://bitbucket.org/cronusearth/cronus-calc/>; last accessed 7 September 2017), respectively, both of which are by Marrero et al. (2016). The “Lal/Stone” time-dependent scaling scheme (Lal, 1991; Stone, 2000) was used. As for erosion rate input, which can influence the surface clast age calculation, we assume a 0-mm/ka erosion rate for the calculation of surface clast ages since no direct method for measuring erosion rates was conducted at this site. We justify our assumption of zero erosion with our observation of desert varnish and large rounded clasts. Similar to previous studies in the area (e.g., Hedrick et al., 2013; Siame et al., 2015), while assuming a 0-mm/ka erosion, we also show the potential effect of assuming different erosion scenarios on the surface clast ages we calculate. For depth profiles, erosion rates are already calculated along with inheritance. Approximately 92% of in situ  $^{36}\text{Cl}$  in our surface clast samples was produced through Ca spallation. Detailed information necessary for the calculation of ages is shown in Tables 1 and 2. For naming samples (see Tables 1 and 2), we used the letter R for samples from surfaces offset by the main Rinconada Fault trace at El Molino site and Q for samples from surfaces offset by the subsidiary fault at Arbol Quemado. The letter D or S indicates whether it is a depth profile or a surface clast sample. And lastly, we used numbers to indicate different locations (1, 2, ... n) or depths in centimeters (25, 50, ... n).

## 4. Site Analysis

### 4.1. Site 1: El Molino

The counterslope, west facing scarps of the La Rinconada Fault are clearly visible, particularly where they are more continuous in its northern portion. At the El Molino site, which is ~3 km south of the northern fault terminus, the scarps of the main fault trend N30°W and reach heights of ~23 m. These displace a series of strath terraces composed of late Quaternary alluvium. A much smaller fault-propagation fold scarp (~2 m high; Figures 4a and 8) is also found <100 m west of, and parallel to, the main trace, locally forming a forward-breaking sequence. The La Rinconada Fault appears to reflect pure reverse faulting due to the lack of evidence of laterally displaced terrace risers at this site or elsewhere along the La Rinconada Fault, although a strike-slip component cannot be entirely ruled out. A sectional view of the scarp of the main fault trace is exposed in a stream cut (Figure 5a). The 40°E dipping fault dip follows the bedding orientation of the Loma de las Tapias formation. The bedding orientation of the Loma de las Tapias formation decreases toward the east; if the La Rinconada Fault continues to follow a bedding plane, it may therefore have a listric geometry. Although not unambiguous, evidence for a surface-rupturing fault scarp is that the Lomas de las Tapias bedrock is thrust over the Q2m alluvium surface, exhibiting a hanging wall-collapse scarp type (Figure 6). Distinguishing whether the LRF scarps are large cumulative fault or fold scarps is important because the measured displacement in the FFF modeling will be different for these two scenarios. This scarp could also be formed by a flat ramp-flat fault geometry, but this is unlikely because such a geometry would be reflected in much steeper backlimb inclination. Similarly, identifying the 2-m-high scarp as a fault-propagation fold, instead of a regular surface-rupturing, thrust fault scarp, changes how we measure its amount of displacement. Scarp geometry and the amount of displacement of this fault-propagation fold to the west of the cumulative scarp of the LRF is discussed in more detail in section 4.1.3.

#### 4.1.1. Geomorphic Surfaces

The El Molino site was chosen because of the presence of large cumulative-displacement fault scarps that cut through multiple levels of areally extensive, well-preserved strath and fill terraces. Three levels of displaced strath terraces (Q2m, Q3m, and Q4m) and a fill terrace (Q5m) were identified (Figure 7), the upthrown side of these surfaces standing 10 to 20 m above the stream. The relatively small difference in heights above the stream despite the large differences in the amount of displacement for each terrace is due to the general downward slope of the terrain toward the north, and the progressive cutting of younger terraces to the

**Table 1**  
The  $^{36}\text{Cl}$  Surface and Depth Profile Sample Data and Ages From Strath Terraces Offset by Cumulative Scarps of the La Rinconada Fault and Arbol Quemado Fault

Sample no.	Surface	Latitude (°S)	Longitude (°W)	Elevation (m)	Material <sup>d</sup>	Thickness (cm)	Topographic Shielding	Cl Rock (ppm)	$^{36}\text{Cl}/\text{Cl}$ ( $10^{-15}$ )	$^{36}\text{Cl}$ Concentration ( $10^6$ at $\text{g}^{-1}$ )	Normalized Concentration ( $10^{-6}$ at $\text{g}^{-1}$ ) <sup>a</sup>	Exposure Age (ka) <sup>b,c</sup>
<b>Surface samples</b>												
RS1	Q2m	31.72481	291.38925	782	L	2.5	0.9985	15.19 ± 0.31	1805.18 ± 27.44	1.7342 ± 0.0279		<b>36.9 ± 0.8</b>
RS2	Q3m	31.72393	291.39178	777	L	2.5	0.9985	21.01 ± 0.21	2371.54 ± 35.84	2.5457 ± 0.0393		<b>62.4 ± 1.3</b>
RS3	Q4m	31.72400	291.38788	788	L	2.5	0.9985	17.11 ± 0.16	2658.8 ± 35.66	2.7051 ± 0.0368		<b>67.3 ± 1.3</b>
RS4	Q5m	31.72284	291.38837	785	L	2.5	0.9985	16.33 ± 0.16	2948.1 ± 39.51	3.0105 ± 0.0409		<b>78 ± 1.5</b>
RS6	Q2m	31.72540	291.38690	787	L	2.5	0.9985	14.64 ± 0.22	1637.09 ± 24.84	1.9069 ± 0.0295		<b>41.4 ± 0.9</b>
<b>Channel samples</b>												
RS5	Q0m	31.72530	291.38770	779	L	2.5	0.9905	13.55 ± 0.39	495.07 ± 7.98	0.5109 ± 0.0089		-
<b>Depth profiles</b>												
RD25	Q2m	31.72481	291.38925	782	L&S	0.5	0.9985	30.61 ± 0.19	650.89 ± 11.94	0.8894 ± 0.0166	0.9836	<b>34.5</b> 31.4–37.5
RD50		31.72481	291.38925	782	L&S	0.5	0.9985	-	22.33 ± 1.14	-	-	
RD75		31.72481	291.38925	782	L&S	0.5	0.9985	27.39 ± 0.20	651.73 ± 10.43	0.7789 ± 0.0127	0.7273	
RD150		31.72481	291.38925	782	L&S	0.5	0.9985	35.18 ± 0.30	448.75 ± 7.98	0.5697 ± 0.0105	0.5671	
QD25	Q9a	31.83996	291.40618	742	L&S	0.5	0.9999	32.51 ± 0.24	866.93 ± 12.74	1.1202 ± 0.0169	-	<b>153.5</b> 139.8–168.1
QD50		31.83996	291.40618	742	L&S	0.5	0.9999	54.33 ± 0.39	729.6 ± 11.05	1.4974 ± 0.0234	1.3550	
QD75		31.83996	291.40618	742	L&S	0.5	0.9999	36.62 ± 0.47	670.81 ± 9.58	0.8913 ± 0.0139	0.8842	
QD100		31.83996	291.40618	742	L&S	0.5	0.9999	37.57 ± 0.38	521 ± 9.00	0.7071 ± 0.0128	0.7389	
QD150		31.83996	291.40618	742	L&S	0.5	0.9999	31.03 ± 0.51	428.56 ± 9.25	0.5209 ± 0.012	0.5666	

Note. indicates no data or not applicable.

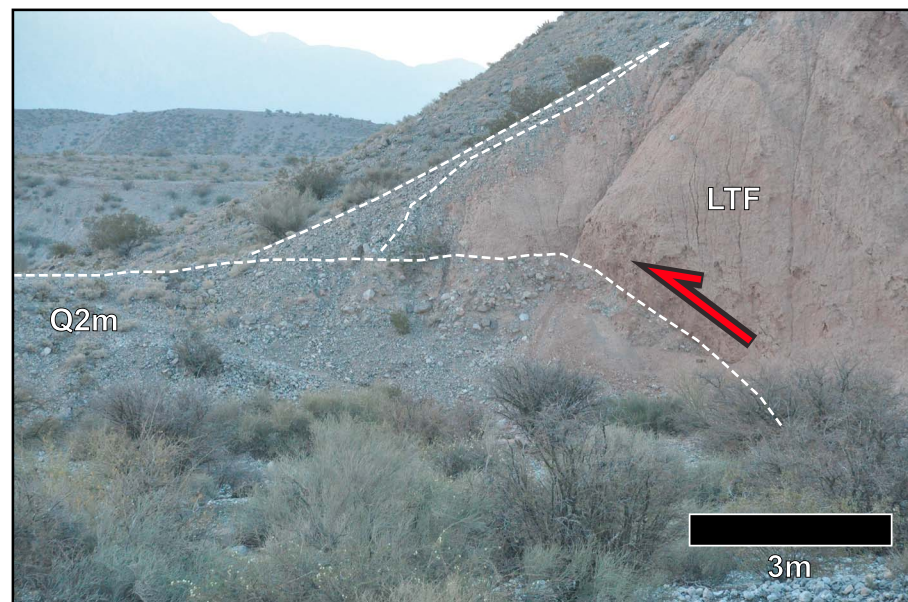
<sup>a</sup>Normalization of concentration values to average depth profile chemical composition is done for better visualization of best fit solutions. <sup>b</sup>For surface samples, inheritance correction was done by subtracting concentration of channel sample RS5 first before computing ages). <sup>c</sup>For depth profiles, Bayesian most probable solution (bold) and 95% confidence level upper and lower age range. <sup>d</sup>L = limestone, L&S = limestone and shale mix.

**Table 2**  
Geochemical and Isotopic Analytical Data for Surface and Depth Profile Samples Gathered From Both El Molino and Arbol Quemado Sites

Sample No.	SiO <sub>2</sub> (wt %)	TiO <sub>2</sub> (wt %)	Al <sub>2</sub> O <sub>3</sub> (wt %)	Fe <sub>2</sub> O <sub>3</sub> (wt %)	MnO (wt %)	MgO (wt %)	CaO (wt %)	Na <sub>2</sub> O (wt %)	K <sub>2</sub> O (wt %)	P <sub>2</sub> O <sub>5</sub> (wt %)	CO <sub>2</sub> (wt %)	H <sub>2</sub> O (wt %)	B (ppm)	Sm (ppm)	Gd (ppm)	U (ppm)	Th (ppm)	Cr (ppm)
Surface samples																		
RS1	1.11	<0.01	0.07	0.07	<0.01	1.35	53.84	<0.01	0.04	<0.01	21.70	21.70	<3	0.08	0.14	0.6	<0.2	<0.14
RS2	2.53	<0.01	0.17	0.13	<0.01	0.59	53.43	<0.01	0.06	<0.01	21.50	21.50	<3	0.28	0.31	1.3	0.3	<0.14
RS3	2.60	0.02	0.23	0.16	<0.01	0.67	53.39	<0.01	0.08	<0.01	21.40	21.40	6	0.24	0.28	0.9	0.3	<0.14
RS4	2.15	<0.01	0.18	0.12	<0.01	0.66	53.45	<0.01	0.07	<0.01	21.65	21.65	7	0.24	0.28	0.9	0.2	<0.14
RS6	2.12	0.01	0.12	0.09	<0.01	0.48	54.13	<0.01	0.05	<0.01	21.45	21.45	<3	0.18	0.19	1.1	<0.2	<0.14
Channel samples																		
RS5	1.75	<0.01	0.17	0.13	<0.01	1.7	52.87	<0.01	0.07	<0.01	21.60	21.60	10	0.21	0.24	0.9	0.2	<0.14
Depth profiles																		
RD25	41.82	0.55	10.42	4.92	0.06	2.16	18.72	1.15	2.24	0.12	8.85	8.85	37	5.2	4.59	2.8	7.9	0.62
RD50	33.18	0.43	8.1	3.81	0.06	2.07	27.31	0.87	1.77	0.09	11.10	11.10	30	3.8	3.63	2	5.9	0.75
RD75	33.69	0.45	8.52	3.94	0.05	2.16	25.59	0.90	1.86	0.09	11.30	11.30	27	3.79	3.62	2.2	6.3	0.48
RD150	37.98	0.5	9.53	4.49	0.06	2.2	21.81	1.00	2.09	0.10	10.05	10.05	33	4.46	4.22	2.3	6.8	0.55
QD25	38.67	0.29	4.84	2.86	0.05	2.61	20.36	0.83	0.81	0.07	8.55	8.55	15	2.53	2.74	2.3	3.5	0.89
QD50	46.97	0.36	6.22	3.59	0.06	2.87	20.10	0.97	1.08	0.08	8.75	8.75	21	3.32	3.51	2.3	4.2	1.03
QD75	45.53	0.35	6.14	3.6	0.06	2.84	20.60	0.95	1.09	0.08	9.30	9.30	23	3.28	3.44	2.7	4.5	1.23
QD100	47.16	0.36	6.34	3.82	0.07	2.93	18.76	0.96	1.13	0.08	9.10	9.10	22	3.58	3.58	2.2	4.5	3.35
QD150	47.61	0.36	6.42	3.56	0.07	2.72	18.77	0.98	1.13	0.09	9.05	9.05	22	3.45	3.5	2.3	4.5	2.05

Note: Uncertainties are taken to be  $\pm 0.01$  for all major oxides,  $\pm 0.10$  for all trace elements, and  $\pm 0.5$  for Boron.

<sup>a</sup>Elemental concentrations from Na<sub>2</sub>O<sub>2</sub> fusion and ICP-MS of whole sediment measured at Bureau Veritas Commodities Canada Ltd., British Columbia.



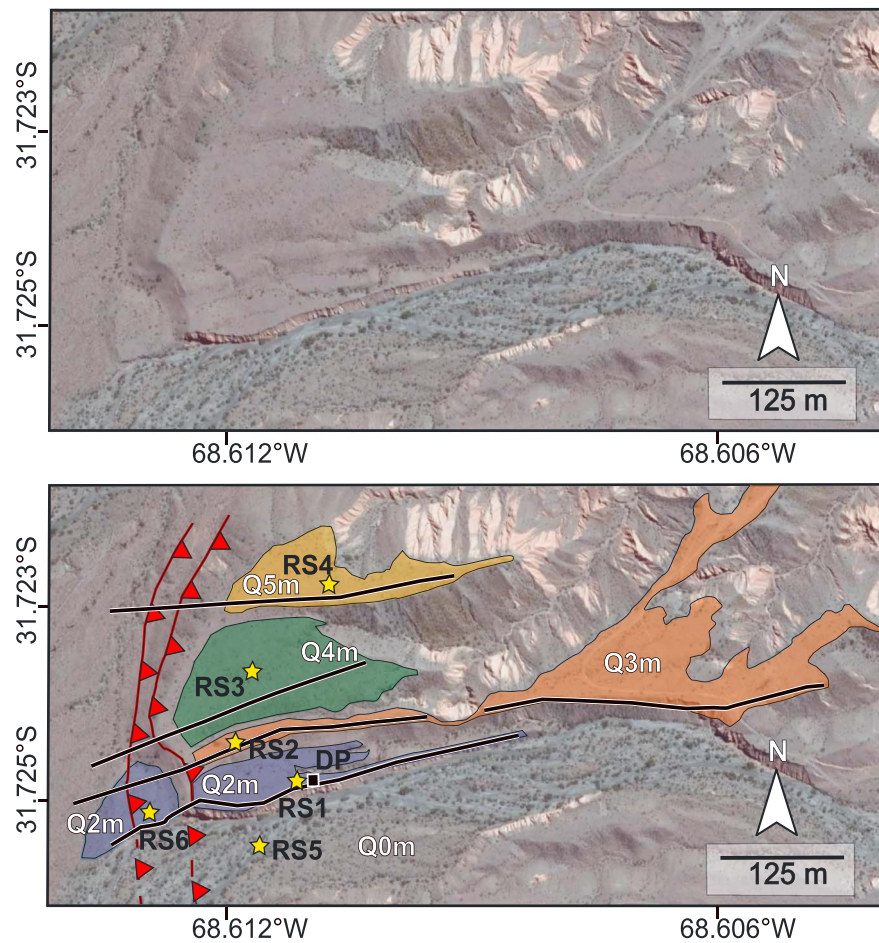
**Figure 6.** View of the natural river exposure of the LRFZ at the El Molino site of Figure 5a, showing the Lomas de las Tapias formation (LTF) thrust over the ~34.5-kyr-old Q2m surface.

north. The intersection of terrace risers and upper terrace treads on successive terrace levels serve as ideal piercing points for measurement of displacement.

The strath terrace deposits are composed of pebble- to cobble-sized polymictic clasts that include both carbonate and lithic shale lithologies and are imbricated to the east. Due to the semiarid climate of the Eastern Precordillera, the surfaces show evidence of deflation, wherein the topmost layer (up to ~5 cm) is devoid of finer sediments. The clastic sources for alluvial material are the limestones of the Cambrian Marquesado group and the shales of the Silurian Rinconada formation which are found on the eastern flank of the Sierra Chica del Zonda. Material is transported by channels flowing from west to east.

The terraces have a regional dip of around 3–4° to the east and 4–5° to the north, and unconformably overlie the Miocene Loma de las Tapias formation. The surface of the topographically lowest strath terrace (Q2m) is composed of poorly sorted, semiangular to angular sediments, which exhibit a clast-supported fabric while the highest (Q5m) strath terrace is characterized by well-sorted, consistently angular sediments, which also exhibit clast-supported fabric. Q5m has noticeably more clasts that have desert varnish compared to Q2m. The higher degree of sorting and angularity can be attributed to the more extensive in situ mechanical weathering of large clasts into smaller clasts through time and the development of desert pavement.

Except for Q2m, strath terraces are absent in the footwall to the west of the fault. One possibility is that they were formed initially but have subsequently been removed by erosion. However, there is no evidence of degraded or obscured footwall terraces or of lateral abrasion. Alternatively, incision may solely reflect hanging wall uplift, and therefore, the surface to the west of the fault may have been continuously occupied during formation of the hanging wall terraces. Finally, if the region to the west of the fault is experiencing relative subsidence (either due to subsidence or footwall aggradation) equivalent strath terraces may be buried. While there is no evidence to establish which scenario is more likely, the match in cosmogenic ages between the Q2m surfaces on either side of the main fault (see section 4.1.2 below) argue that true displacement can be calculated for at least this surface. Additionally, the thickness of the strath covering material is identical on the upthrown and downthrown side of the fault. Considering that the footwalls of the older surfaces may have been modified by subsequent alluviation, by using the present Q2m footwall elevation in our displacement calculations for all surfaces, we may be underestimating the amount of displacement for the Q3m, Q4m, and Q5m surfaces. Therefore, our displacement calculations are likely a minimum (see section 4.1.3 below). Similar offset hanging wall strath terraces without paired footwall terraces were used



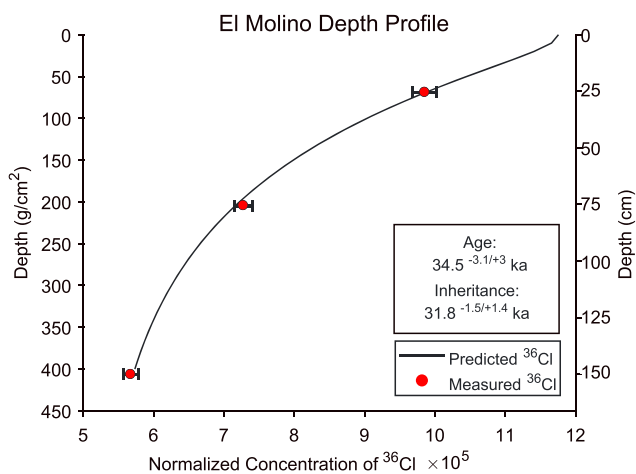
**Figure 7.** View of faulted strath and fill terraces in the El Molino site superimposed on a Google Earth image (copyright Google Earth). Black lines show location of topographic profile survey lines, stars indicate  $^{36}\text{Cl}$  surface sample locations, and black square labeled DP indicates  $^{36}\text{Cl}$  depth profile location.

along the Las Tapias Segment of the Villicum-Zonda-Pedral Thrust Fault, which is located on the western flank of the Sierra Chica del Zonda, to determine fault slip rates (Siame et al., 2002).

#### 4.1.2. Ages

In computing ages of surfaces from surface clasts, we assumed zero erosion due to the well-preserved surface as indicated by presence of desert varnish. Previous work done in nearby areas in the Eastern Precordillera and Western Sierras Pampeanas (Hedrick et al., 2013; Schmidt et al., 2011; Siame et al., 2002) also assume zero erosion. In arid environments such as this, it is more likely for computed ages of surfaces to be older due to inheritance rather than younger due to erosion.

For surface Q2m which is on the hanging wall side of the larger cumulative fault scarp (eastern trace), both surface clasts and depth profile samples to a depth of 150 cm were collected. The surface clasts yielded an age of  $36.9 \pm 0.8$  ka, and modeling of the depth profile samples (Figure 8) yielded an age of  $34.5^{+3.1}_{-3.1}$  ka, an inheritance equivalent to  $31.8^{+1.4}_{-1.5}$  ka of prior exposure, and an erosion rate of 0.11 mm/ka (which is consistent with the prevalence of desert varnish). Only three samples were modeled for the depth profile age because there were no results for the samples at 50- and 100-cm depths. The ages from both sampling methods on Q2m are in good agreement and suggest that surface



**Figure 8.** El Molino site  $^{36}\text{Cl}$  depth profile.

**Table 3***Dip-Slip Displacement, Shortening, and Uplift Calculated From the Scarps of the La Rinconada Fault at the El Molino Site*

Surface <sup>a</sup>	Ramp	Apical Angle	P/S Ratio	Tip Point Position	Cumulative <sup>b</sup>			Discrete <sup>b</sup>		
					Dip-Slip Displacement (m)	Shortening (m)	Uplift (m)	Dip-Slip Displacement (m)	Shortening (m)	Uplift (m)
Q2m (FPF)	40	15	2.5	— 5.2 m	20.76	15.90	13.34	4.2	3.22	2.7
Q2m (main)	40	50	1	Surface				16.56	12.69	10.54
Q3m	40	50	1	Surface	25.23	19.33	16.22	4.47	3.43	2.88
Q4m	40	50	1	Surface	34.48	26.41	22.16	9.25	7.08	5.94
Q5m	40	50	1	Surface	49.5	37.92	31.82	15.02	11.51	9.66

<sup>a</sup>The main scarp and the fault-propagation fold (FPF) displacements on Q2m are distinguished. <sup>b</sup>Both cumulative displacement and terrace-specific displacement values are presented for each terrace.

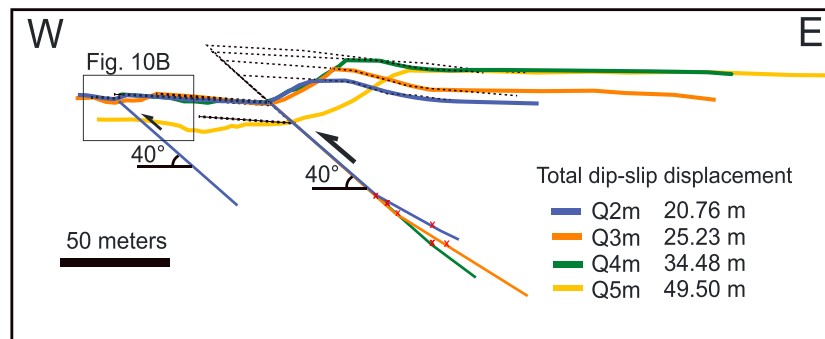
clast ages in this locality are reliable. The rest of the ages in this locality are based on dating of surface clasts. The part of surface Q2m which is on the footwall side of the larger cumulative fault scarp (eastern trace) and in the hanging wall of the smaller, probably most recent scarp (western trace) of the La Rinconada Fault, yielded an age of  $41.4 \pm 0.9$  ka. This slightly older age could be interpreted either as possibly resulting from incorporation of colluvium from the older surfaces Q3m, Q4m, and Q5m on the upthrown side of the large, cumulative fault scarps or due to the inability of surface clast dating to fully account for inheritance. Surfaces Q3m, Q4m, and Q5m yielded distinct, progressively older ages of  $62.4 \pm 1.3$ ,  $67.3 \pm 1.3$ , and  $78 \pm 1.5$  ka, respectively (Table 1).

To demonstrate the extent to which the calculation of surface clast ages is affected by assigning erosion rates, we recalculate the ages and show the percentage error between the original clast ages (0-mm/ka erosion rate) and the ages obtained by using reference erosion rates. We use both the 1-mm/ka average depth profile estimate of erosion rates in this study and the 5-mm/ka average bedrock and depth profile erosion rates also from the eastern flank of the eastern Argentine Precordillera (15 km north of our study area) measured by Hedrick et al. (2013). Both aforementioned erosion rate values are consistent with the mean  $^{10}\text{Be}$  global arid region bedrock erosion rates examined by Portenga and Bierman (2011). If we assume an erosion rate of 1 mm/ka, the ages of our Q2m and Q5m surfaces will be underestimated by up to 2% and 20% of the original ages, respectively. If we assume a higher erosion rate of 5 mm/ka, the ages of our Q2m and Q5m will be underestimated by up to 6% and 55% of the original ages, respectively. The  $^{36}\text{Cl}$  surface clast ages (Table 1) should therefore be treated as minimum ages. However, erosion rates for sediments are usually higher than for cobble-sized surface clasts in arid regions (Placzek et al., 2014); consequently, erosion rates from depth profiles likely overestimate erosion rates of surface clasts.

#### 4.1.3. Displacement

Topographic profiles of a series of cumulative scarps of the La Rinconada Fault which displace strath terraces have been utilized as markers to measure dip-slip displacement, shortening, and uplift through forward modeling of fault-fold geometries (Allmendinger, 1998). Initially, to produce simple reverse fault scarps with a gentle backlimb, the same P/S ratio, trishear apical angle, and initial fault tip position values were used and held constant throughout the model runs (see Table 3). We assume bedding plane slip that was initiated at the interface between the strath terrace and the basement rock and model the strath terrace as a line. Hence, we put the initial fault tip position at the surface. P/S ratio, which dictates the rate at which the fault tip propagates compared to slip on the fault, was set as 1.0, allowing the fault tip to propagate at the same rate that the fault is moving. Trishear apical angle was set as  $50^\circ$ . Trishear apical angle determines the distribution of strain above the fault tip; a low value results in concentration of intense strain in a narrow wedge of rock above the fault tip, while a high value results in diffuse strain (Allmendinger, 1998) in the material above the fault tip.

Fault-fold models with two hinges/inflection points which separate three ramps that become gradually shallower with depth were the best matches for the surveyed scarp profiles (Figure 9). The dip of the fault at the surface was assumed to be  $40^\circ\text{E}$  in modeling of all four profiles based on measurement directly from an outcrop (Figures 5a and 6). The dips of the two deeper ramps (Figure 9), which were determined from iteratively modeling different fault parameter combinations, decrease gradually in dip. The hinge positions modeled for



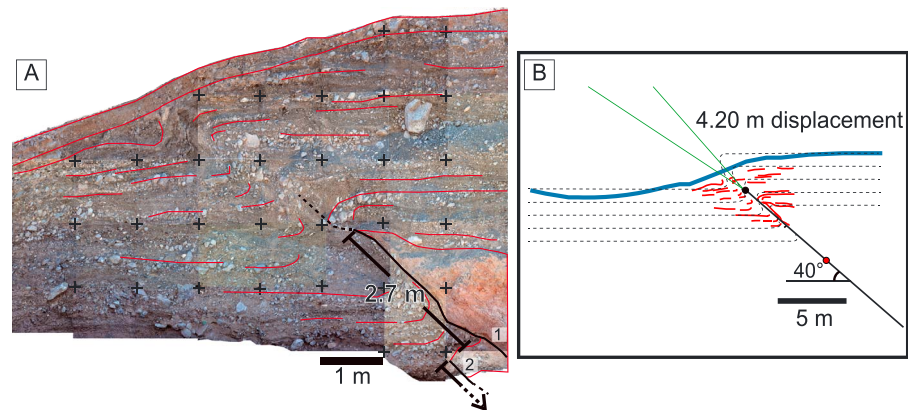
**Figure 9.** Forward models (dashed lines) and actual profiles (colored) of fault scarps with backlimb tilting used to constrain offset of the La Rinconada Fault in the El Molino site. Trishear parameters for these models are shown in Table 3. Displacement on Q2m reflects the sum of the displacement on the main scarp (i.e., 16.56 m) and the fault-propagation fold (i.e., 4.20 m). Base of Q5m scarp was aligned to Q2m-Q5m during modeling of displacement. See Figure 7 for profile locations.

the different profiles were within ~3 m of each other. On average these were found at depths of ~45 and ~60 m from the footwall datum of Q2m. The two deeper ramps had average dips of ~33 and 30°E, respectively. The modeled position of the hinges and the dip of the ramps varied slightly among the profiles probably due to both usual along-strike irregularities in the fault plane geometry and varying degree of preservation of the strath terraces being fit to the modeled profiles. In the case of profile Q5m where backlimb folding is not as evident anymore, probably due to the more erosion it has undergone compared with the three younger terraces, matching of backlimb morphology was impossible. Matching of scarp height between the actual profile and modeled scarp profile was done instead. The hinge positions, ramp dips, and other trishear parameters (except for displacement) used in modeling Q4m were used for modeling a scarp of the same height as Q5m. The gentle (~10°) backlimb inclination observed to east of the fault scarps (Figure 9) can only be explained through this gradual decreasing fault dip with depth which resembles the fault-bend fold geometry of Suppe (1983). Significantly larger differences in successive fault dips, that is, between a 40°E surface fault and a horizontal décollement, only result in steeper backlimb inclination.

Several other combinations of trishear parameters producing different scarp morphologies, exhibiting varying degrees of folding and amounts of surface rupture (see Figure S2), were used to explore the possible effect of assumed original scarp morphology on the amount of displacement measured. Original scarp morphology did not affect the modeled amount of displacement for faulted profiles at the El Molino site. This is most likely because the faulted profiles have distinct characteristics that limit the trishear parameter value combinations to those which result in the same displacement. For instance, because these scarps involve backlimb formation, and consequently require modeling fault bends, the initial fault tip point can only be modeled starting above the shallowest fault bend. The outcrop exposure showing bedrock material thrust over the Quaternary alluvium also helped in limiting possible original scarp morphologies.

Although a lateral component of displacement cannot be precluded, only evidence of vertical displacement was observed and quantified at the El Molino site. Hence, only dip-slip displacement, shortening, and uplift measurements are presented. A trend of increasing cumulative displacement was observed on scarps cutting through progressively older strath terraces (Table 3). The amount of discrete displacement on each surface was measured by subtracting the dip-slip displacement of two consecutive terraces, that is, Q3m and Q2m. Discrete displacement values were very large, with the lowest being ~9 m. The displacement modeled on the scarp cutting through Q2m is the true displacement since synchronicity of surface material on the upthrown side (Sample RS1) and downthrown surface (Sample RS6) can be argued from cosmogenic dating (Table 1). Displacement measured on surfaces Q3m, Q4m, and Q5m most likely represent minimum estimates.

The 2.7 m of bedrock displacement measured from a trench exposure of the fault-propagation fold scarp to the west of the main trace of the La Rinconada Fault (Figure 10a) is considered a minimum displacement since it only reflects offset along a single fault strand (fault strand 1; Figure 10a). The entire downthrown



**Figure 10.** El Molino fault-propagation fold. (a) A trench photomosaic (looking north) revealing the fault-propagation fold nature of the recent scarps of the La Rinconada Fault zone. Fault strands (thin black lines) are labeled “1” and “2.” Location of trench is shown on Figure 5a. (b) A forward model fitting the scarp height exhibited by the topographic profile (blue line) and deformation fabric (red lines) of the El Molino fault-propagation fold. The red and black dots correspond to the initial and final fault tip positions, respectively, and the green lines show the trishear apical angle (15°). This model exhibits 4.20 m of dip-slip displacement.

portion of the bedrock displaced by fault strand 2 (Figure 10a) was not exposed due to time constraints. 4.2 m of displacement, on the other hand, was determined by forward modeling of a fault-propagation fold (Figures 9 and 10b).

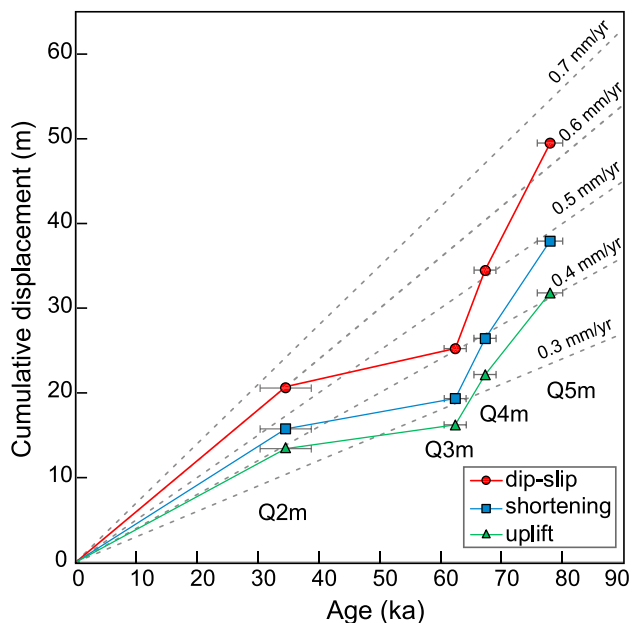
#### 4.1.4. Slip Rates

Long-term average slip rates (Table 4) were computed for each cumulatively displaced strath terrace by dividing the amount of displacement by the age of the corresponding displaced strath terrace. For Q2m, the displacements measured on the cumulative scarp and the fault-propagation fold were added and the depth profile age for Q2m was used since this more reliably accounts for inheritance (despite higher numerical uncertainty as compared to the surface sample age). The average dip-slip displacement rate, shortening rate, and uplift rate measured between surfaces Q2, Q3, Q4, and Q5 are  $0.51 \pm 0.01$ ,  $0.41 \pm 0.01$ , and  $0.34 \pm 0.01$  mm/year, respectively. Long-term average slip showed a generally similar slip rate from Q5m-present ( $78 \pm 1.5$  ka) to Q2m-present ( $34.5^{-3.1/+3.0}$  ka; Figure 11). Slip rates were also computed for the relatively shorter intervals between formation of strath terraces and showed that rates apparently increased from the intervals Q4m-Q5m ( $67.3 \pm 1.3$  to  $78 \pm 1.5$  ka) to Q3m-Q4m ( $62.4 \pm 1.3$  to  $67.3 \pm 1.3$  ka) and decreased significantly in the interval Q2m-Q3m ( $34.5^{-3.1/+3.0}$  to  $62.4 \pm 1.3$  ka; Table 4 and Figure 12). Since displacement measured on scarps cutting through Q3m, Q4m, and Q5m are minimum estimates, calculated slip rates measured represent minimum estimates as well. Furthermore, slip rate uncertainty only reflects uncertainty in the ages and not of the shortening estimation method used.

**Table 4**  
*Dip-Slip, Shortening, And Uplift Rates Calculated From the Cumulative Scarps of the La Rinconada Fault at the El Molino Site*

Time Interval	Dip-Slip Rate (mm/year)		Shortening Rate (mm/year)		Uplift Rate (mm/year)	
	Surface <sup>a</sup>	Depth Profile <sup>a,b</sup>	Surface	Depth Profile	Surface	Depth Profile
Q2m-present	$0.56 \pm 0.01$	$0.60 \pm 0.05$	$0.43 \pm 0.01$	$0.46 \pm 0.04$	$0.36 \pm 0.01$	$0.38 \pm 0.03$
Q3m-present	$0.4 \pm 0.01$	-	$0.31 \pm 0.01$	-	$0.26 \pm 0.01$	-
Q4m-present	$0.51 \pm 0.01$	-	$0.39 \pm 0.01$	-	$0.33 \pm 0.01$	-
Q5m-present	$0.63 \pm 0.01$	-	$0.49 \pm 0.01$	-	$0.41 \pm 0.01$	-
Average	$0.54 \pm 0.01$	-	$0.41 \pm 0.01$	-	$0.34 \pm 0.01$	-
Q2m-Q3m	$0.16 \pm 0.02$	-	$0.12 \pm 0.01$	-	$0.10 \pm 0.01$	-
Q3m-Q4m	$1.89 \pm 0.71$	-	$1.44 \pm 0.54$	-	$1.21 \pm 0.46$	-
Q4m-Q5m	$1.40 \pm 0.26$	-	$1.08 \pm 0.20$	-	$0.90 \pm 0.17$	-

<sup>a</sup>Slip rates computed using both surface sample and depth profile ages (see Table 1) are shown. <sup>b</sup>“Q2m-present” depth profile slip rates were used to compute average slip rates.



**Figure 11.** Plot of dip slip and shortening and uplift components of cumulative displacement against age for surfaces Q2m, Q3m, Q4m, and Q5m.

The terraces have a regional dip of around 2–3° to the east, 1–2° to the south and unconformably overlie the Miocene Loma de las Tapias formation.

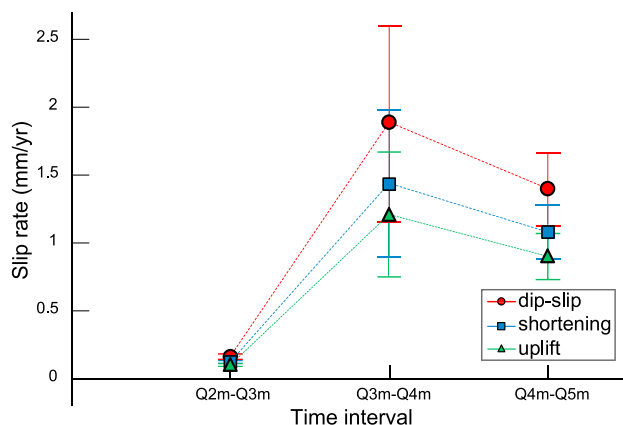
The strath terrace deposits here share the same mixed lithology and most likely have the same clastic sources as the surfaces at the El Molino site. These surfaces also exhibit evidence of deflation and clasts which are imbricated to the east due to an east flowing stream. All of the seven strath terraces are composed of semi-rounded to semi-angular clasts. While clasts are expected to be more angular on surfaces that are higher (and older) due to the formation of desert pavement, the lack of marked differences in angularity could also be due to the impact of chemical weathering. Consequently, the only features indicative of relative age are sorting and desert varnish. The topographically lowest terrace (Q3a) is poorly sorted and has minimal desert varnish while the highest terrace (Q9a) is well sorted and has a significant fraction of clasts with desert varnish.

Most terraces (Q3a, Q4a, Q5a, Q6a, Q7a, Q8a, and Q9a) can be matched across the fault scarp, and unlike in the El Molino site, there is no correlation between the heights of strath terraces above the active stream and

the amount of fault displacement on that particular terrace (see section 4.2.3 below). Both of these observations suggest that episodic downcutting, rather than abandonment due to hanging wall uplift, seems to be the main driving force of strath terrace formation in this site.

#### 4.2.2. Ages

Only the age of the topographically highest surface that was clearly displaced by the Arbol Quemado fault (Q9a) was determined for this site. Modeling of the depth profile samples in Arbol Quemado (Figure 14) yields an age of  $153.5^{+13.7}_{-13.7}$  ka, an inheritance equivalent to  $22.4^{+2.8}_{-2.8}$  ka of prior exposure, and an erosion rate of 1.74 mm/ka. The shallowest sample (QD25) was excluded in the modeling of the depth profile age because of a very low concentration (see Table 1). The low  $^{36}\text{Cl}$  concentration is likely due to error in the wet chemistry sample preparation since the composition is similar to the deeper samples and because neither bioturbation nor reworking was observed in the top layer of sediment. The chronology of the rest of the surfaces in this locality were determined from relative dating, based both on their heights above the stream and their surface texture.



**Figure 12.** Plot of dip slip and shortening and uplift components of displacement against slip rate for the intervals Q2m-Q3m, Q3m-Q4m, and Q4m-Q5m.

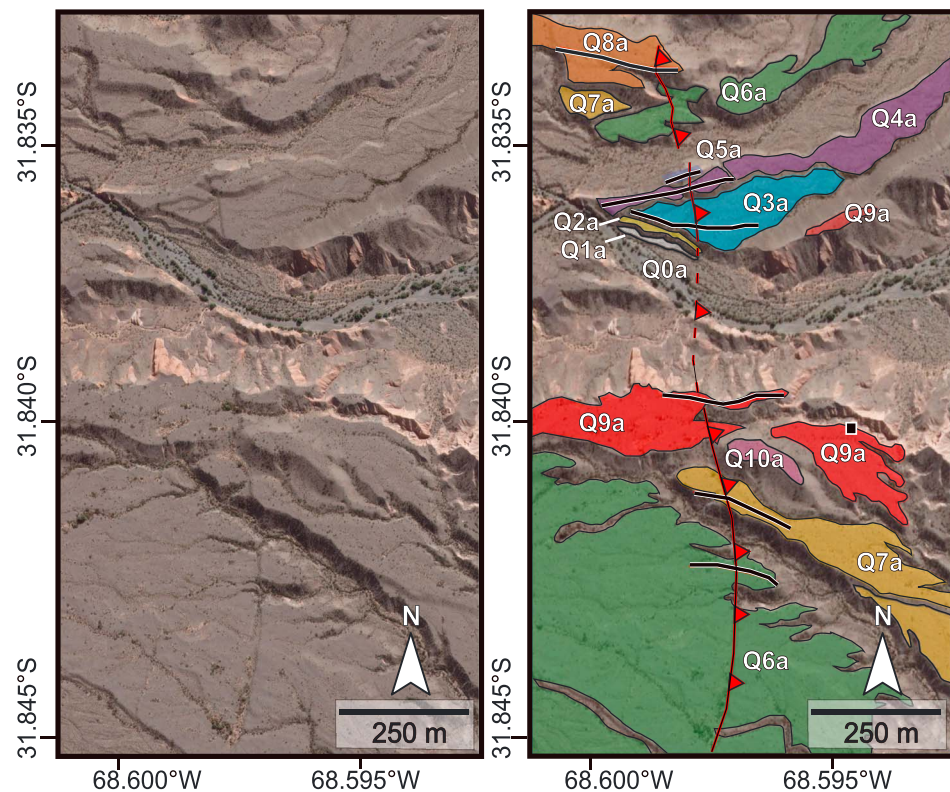
#### 4.2. Site 2: Arbol Quemado

The Arbol Quemado Fault is an ~1.5-km-long N-S trending minor fault strand ~1 km to the east of the La Rinconada Fault and exhibits west facing, counterslope reverse fault scarps. Similar to the main trace of the La Rinconada Fault, scarps are the result of bedding plane slip. The bedding plane fault, which dips 33°E, lies within the eastern limb of what now appears to be an inactive anticline (Figure 5b).

The scarps of the Arbol Quemado Fault reach as high as ~5 m. Similar to the El Molino site, the Arbol Quemado Fault displaces a series of strath terraces composed of late Quaternary alluvium and appears to reflect pure thrust faulting due to the lack of evidence of laterally displaced terrace risers. A stream-cut sectional view of the scarp shows that the 33°E dipping fault dip follows the bedding orientation of the Loma de las Tapias formation (Figure 5b).

##### 4.2.1. Geomorphic Surfaces

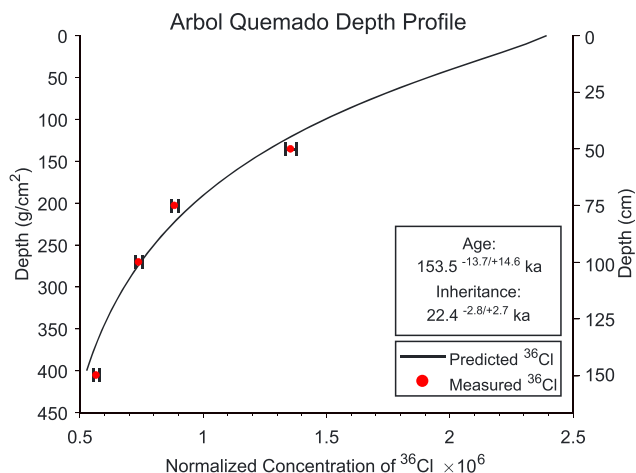
Prominent fault scarps that cut through multiple levels of extensive, well-preserved strath terraces are observed in the Arbol Quemado site. Seven levels of displaced strath terraces were identified (Q3a, Q4a, Q5a, Q6a, Q7a, Q8a, and Q9a), with the downthrown side of the strath terraces standing 12 to 19 m above the stream (Figure 13). The intersection of terrace risers and upper terrace treads between successive terrace levels also served as piercing points for measurement of displacement in this area.



**Figure 13.** Faulted strath terraces in the Arbol Quemado site superimposed on Google Earth image (copyright Google Earth). Black lines show location of topographic profile survey lines, and black square indicates  $^{36}\text{Cl}$  depth profile location.

#### 4.2.3. Displacement

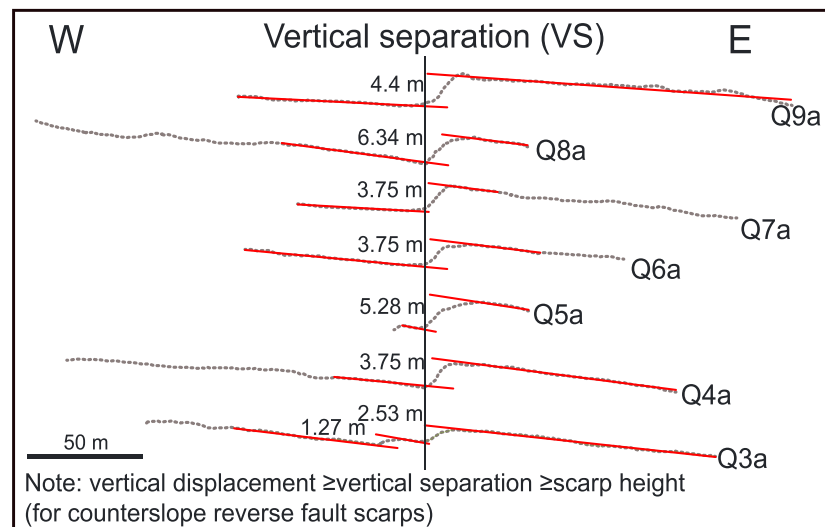
Topographic profiles of a series of fault scarps which displace strath terraces in the Arbol Quemado site have been utilized as markers to measure dip-slip displacement, shortening, and uplift using the equations presented by Yang et al. (2015) (Figure 15). The equation used in this fault displacement measurement method (Yang et al., 2015) accounts for possible difference in slopes of the hanging wall and footwall surfaces. However, this method simplifies the measurement of displacement by assuming perfectly planar surfaces on each sides of the fault (Figure 16). Dip-slip displacement, shortening, and uplift measurements are shown in Table 5.



**Figure 14.** Arbol Quemado site  $^{36}\text{Cl}$  depth profile.

The displacement measured along the scarps in Arbol Quemado are very similar for all the seven terraces, ranging from  $\sim 7$  to 11 m, with most values clustering around  $\sim 7$ –9 m. Unlike the scarps of the La Rinconada Fault in the El Molino site, the values do not show any trend of increasing displacement on older surfaces. The slight differences, including the higher displacement values for Q8a, could be due to the normal, along-strike variation in displacement along faults. The average dip-slip displacement, shortening, and uplift values on all seven surfaces are  $8.51 \pm 0.61$ ,  $7.13 \pm 0.51$ , and  $4.60 \pm 0.33$  m, respectively.

Due to the uncertainty in the original scarp morphology of the faulted profiles at the Arbol Quemado site, FFF modeling was also done to explore the possible range of displacement that can be measured from modeling several scarps with varying degrees of folding and amounts of surface rupture (see Figure S3). Variation in displacement among the different models was very limited and was still well within the range of displacement estimated from Yang et al.'s (2015) method.



**Figure 15.** Topographic profiles used to constrain offset of the Arbol Quemado Fault (vertical positions of profiles are relative and do not correspond to their actual elevation differences; with 1.5 vertical exaggeration). Geomorphic surface slopes and a field observed fault angle of  $33^\circ$  are used to reconstruct original fault geometry and calculate both uplift and shortening using equations in Yang et al. (2015). See Figure 13 for profile locations.

#### 4.2.4. Slip Rates

Displacement may have occurred any time after the formation of the Q3a surface, the youngest offset surface at the Arbol Quemado site. However, the only dated surface is Q9a, the oldest surface at the site. The age and displacement of Q9a yields a long-term average dip-slip displacement, shortening, and uplift rates of  $0.050 \pm 0.002$ ,  $0.045 \pm 0.002$ , and  $0.029 \pm 0.001$  mm/year, respectively. While the possibility of displacement occurring between Q9a and Q3a cannot be entirely ruled out, the consistency of displacement across all strath terraces strongly suggests either a single event or cumulative events which postdate formation of terrace Q3.

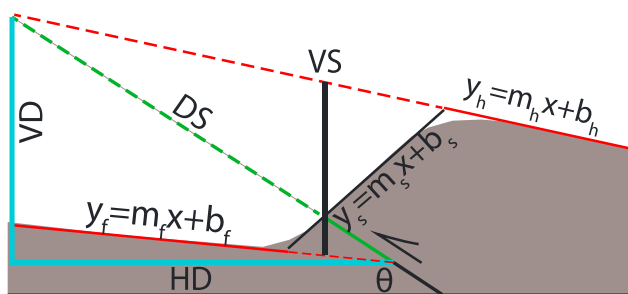
If a constant incision rate is assumed since formation of Q9a in the Arbol Quemado site, an age of  $\sim 96.9 \pm 8.8$  ka can be projected for Q3a using the Q9a height above the river (19 m) and age ( $153.5^{+13.7}_{-14.6}$  ka) and the Q3a height (12 m). The projected age and displacement of Q3a yields similarly very low long-term average dip-slip displacement, shortening, and uplift rates of  $0.08 \pm 0.016$ ,  $0.06 \pm 0.014$ , and  $0.04 \pm 0.009$  mm/year, respectively.

Although our understanding of slip rate along the Arbol Quemado Fault would benefit from additional geochronology, which is beyond the scope of this study, we can confidently constrain a relatively low slip rate of  $<0.1$  mm/year.

## 5. Discussion

### 5.1. Late Quaternary Activity of the La Rinconada Fault Zone

Several controversial, existing tectonic models have been proposed to explain surface faulting and heightened seismicity along the present-day Andean orogenic front in the region between the Precordillera and Sierras Pampeanas. These models vary in how they interpret the nature and geometry of structures at depth. Studies mainly along the southeast dipping La Laja Fault argue that the fault is the result of secondary flexural-slip or back thrusting (Costa, 1999) along an east facing monocline within Neogene deposits (Meigs et al., 2006), which result from movement along a primary, west dipping, blind thrust fault beneath the Eastern Precordillera. Meigs et al. (2006) argue that southeastward



**Figure 16.** Theoretical fault profile and linear regressions of topographic survey points on the upthrown and downthrown surfaces (solid red for actual surface and broken red line for projection) and the scarp (black solid line). Linear regression parameters ( $m$  slope and  $y$  intercept) along with dip ( $\theta$ ) of fault (green line for actual plane and broken green line for projection) were used for calculating vertical displacement (VD)/uplift and horizontal displacement (HD)/shortening (blue solid line).

**Table 5**  
*Dip-Slip Displacement, Shortening, and Uplift Calculated From Scarps of the Arbol Quemado Fault*

Surface <sup>a</sup>	Dip-Slip Displacement (m)	Shortening (m)	Uplift (m)
Q3a	$7.47 \pm 1.43$	$6.28 \pm 1.19$	$4.06 \pm 0.76$
Q4a	$9.32 \pm 3.53$	$7.76 \pm 2.92$	$5.05 \pm 1.90$
Q5a	$8.69 \pm 0.21$	$7.29 \pm 0.23$	$4.73 \pm 0.07$
Q6a	$7.98 \pm 1.58$	$6.66 \pm 1.33$	$4.34 \pm 0.85$
Q7a	$6.93 \pm 0.28$	$5.82 \pm 0.26$	$3.56 \pm 0.10$
Q8a	$11.08 \pm 0.93$	$9.29 \pm 0.78$	$6.02 \pm 0.47$
Q9a	$8.11 \pm 0.56$	$6.80 \pm 0.50$	$4.42 \pm 0.29$

<sup>a</sup>Values for Q3a reflect the sum of the upper and lower scarps.

migration of backlimb fold hinges in the hanging wall of the La Laja Fault is caused by the emergence of the west dipping blind thrust fault. Siame et al. (2002) also explain the rupture along the La Laja Fault through flexural slip, but by back-limb tightening linked to the Villicum-Pedernal Thrust on the west flank of the Eastern Precordillera. Richard et al. (2019) find no evidence from geologic mapping for a basement continuation of the LRF. Alternatively, Alvarado and Beck (2006) present seismological evidence which suggests that the La Laja Fault itself is a primary, east dipping fault, associated with listric, basement-involved thrusts of the Sierras Pampeanas rather than the Precordillera. Alvarado and Beck (2006) supported their argument with earthquake parameters such as an earthquake a focal depth of 12 km, a focal mechanism solution suggesting a fault plane with

a NE-strike, SE-dip, a right-lateral sense of slip, and of  $M_w$  7.0, all of which are consistent with the 1944 rupture being a primary fault.

Mapping of the La Rinconada Fault in this study shows that deformation is localized along the La Rinconada Fault, and to a minor degree, the Arbol Quemado Fault (Figure 4). Although slip on the La Rinconada and Arbol Quemado faults occur along bedding planes of the Miocene Las Tapias formation, there were no signs of widely distributed slip along faults within several meters or tens of meters of either, which is what one would expect to observe if the faulting were related to flexural slip. Furthermore, earthquake magnitude estimates from slip rates we measured, discussed in section 5.2, are larger than would be expected for a flexural-slip fault earthquake. The findings in this study, therefore, suggest that the La Rinconada Fault is a primary, east dipping fault that possibly continues into the basement, similar to other east dipping faults of the Sierras Pampeanas region, consistent with the findings of Alvarado and Beck (2006) for the La Laja Fault. However, further studies that will enable imaging the deeper structure of the LRFZ may help constrain the nature of this fault.

While our measurement of slip rate applies only over the last  $78 \pm 1.5$  ka, it appears that the relatively low relief across the La Rinconada Fault and lack of an associated large-scale geomorphic feature, that is, a fault-bounded mountain range, may be in part due to its slow slip rate and a relatively recent initiation of movement along this fault.

The late Quaternary shortening rates measured on the La Rinconada Fault ( $0.41 \pm 0.01$  mm/year) correspond to approximately 5–7% of the 5.5–7.7 mm/year long-term (~20 Ma) geological shortening rates estimated for the entire width of the Principal Cordillera, Frontal Cordillera, and Precordillera from latitudes 30–33°S (Ramos et al., 2002, 2004; Zapata & Allmendinger, 1996). These rates correspond to 6–10% of the 2–7 mm/year ongoing shortening of the Andean Orogenic Front at the same range of latitudes based on GPS data by Kendrick et al. (1999, 2001, 2003, 2006) and 5–12% of the  $4.5 \pm 1.7$  mm/year determined by Brooks et al. (2003).

Our slip rate results for the La Rinconada Fault are a bit lower but on the same order of magnitude as slip rates determined for nearby faults in the Eastern Precordillera. Late Quaternary shortening rates measured on the Villicum-Las Tapias (Siame et al., 2002) and the La Laja Faults (Rockwell et al., 2014) are 0.8 and 1.1 mm/year, respectively. Siame et al. (2002) argue that this relatively low slip rate compared to the overall longer-term geological slip rates for the area can be explained by distribution of shortening across several thrusts across this latitude band (31–32°S).

To the south along the Precordillera, shortening rates are generally higher. Schoenbohm et al. (2013) measured rates of  $0.59^{+0.10/-0.13}$  mm/year for the central Las Peñas thrust, and Schmidt et al. (2011) measured shortening rates of  $1.2 \pm 0.2$  to  $2.0 \pm 0.4$  mm/year in the southern portion (Figure 2). At latitude 33°S, almost half of the regional shortening is taken up by the Las Peñas and Las Higuera Faults and the rest is distributed among fold-and-fault structures, while at the latitude of the La Cal Fault, about a quarter to a third of the shortening ( $0.9 \pm 0.3$  to  $1.5 \pm 0.3$  mm/year) is taken mostly by this structure alone (Schmidt et al., 2011). The relatively lower slip rates measured on the La Rinconada Fault, and other faults in the central Andean Orogenic Front, may be due to slip distribution among a larger number of faults and folds compared to the southern end. This pattern suggests more distributed deformation in the northern Precordillera in

contrast to focusing of deformation on few structures in the southern Precordillera. We attribute this latitudinal change in strain distribution in the Precordillera to the preexisting geology. A transition from NNE to NNW trending mountain ranges and active faults between the northern and southern Precordillera reflects a change in structural control of the Southern Precordillera by the preexisting fabric and anisotropies of the Pampean crystalline basement (Ahumada & Costa, 2009; Costa, Ahumada, Gardini, et al., 2015).

## 5.2. Seismic Potential of the La Rinconada Fault Zone

### 5.2.1. La Rinconada Fault

To assess the seismic potential of the La Rinconada Fault, we must make assumptions as to whether the terrace surfaces were abandoned coseismically, and whether the faults scarps are more likely the result of single or multiple events. As we cannot definitively support either scenario, we explore both, along with non-offset-based methods to arrive at a seismic assessment of the fault.

At the El Molino site, it is uncertain whether all the terraces were consecutively coseismically uplifted. If the surfaces Q2m, Q3m, Q4m, and Q5m were uplifted by successive earthquakes, and we assume that the fault-propagation fold is attributed to the most recent 1952  $M_w$  6.8 San Juan earthquake, then this would imply the following earthquake recurrence intervals:  $34.5^{-3.1/+3.0}$  ka (1952 A.D.-Q2a),  $27.9 \pm 3.4$  (Q2a-Q3a),  $4.9 \pm 1.8$  (Q3a-Q4a), and  $11.2 \pm 2.0$  ka (Q4a-Q5a), with an average recurrence interval of  $19.6 \pm 1.3$  ka. There are unfortunately no independent constraints on timing and magnitude of past earthquakes on this fault, for instance, through paleoseismic trenching, to compare our findings with.

If the discrete displacements of each terrace (see Table 3) are taken as coseismic, earthquake magnitude can be estimated based on scaling relationships between earthquake magnitude and displacement (Wells & Coppersmith, 1994). The earthquake magnitudes estimated assuming that displacement measured can both represent either maximum displacement or average displacement ranges from  $M_w$  6.3 to 7.4. If, however, the terraces are not consecutively coseismically generated, displacement may reflect multiple events, and earthquake magnitude cannot be estimated using the methods of Wells and Coppersmith (1994).

Evidence to suggest that the terraces are not consecutively coseismically generated comes from a model by Slemmons (1982), relating recurrence interval and earthquake magnitude to slip rate. According to this model, given the slip rates we measured (i.e.,  $0.41 \pm 0.01$  mm/year) and the average age difference of terraces (the implied average recurrence interval), the discrete displacement of the terraces would have had to be generated by  $M_w$  7.5 to 8 earthquakes, which are much higher than the magnitudes estimated using discrete displacement.

Alternatively, earthquake magnitude for the La Rinconada Fault was also estimated using an equation relating magnitude to both slip rate and surface rupture length (Anderson et al., 2017; J. G. Anderson, Wesnousky, & Stirling, 1996). A slip rate of  $0.41 \pm 0.01$  mm/year and a maximum surface rupture length of 30 km yielded an estimate ranging from  $M_w$  6.9 to 7.2.

It is worth noting that if we assume that the 4.2-m displacement on the fault-propagation fold represents maximum displacement created by a single event, this yields magnitude ranging from  $M_w$  6.6 to 7.0, which overlaps with the range of slip rate-derived magnitudes. While there is no documentation as to the ground rupture associated with the 1952 earthquake, the reported magnitude for the 1952 San Juan earthquake is very close to the range of possible earthquake magnitudes estimated for the La Rinconada Fault. The epicentral location of the 1952 earthquake (31.6°S, 68.6°W; Instituto Nacional de Prevencion Sismica (INPRES), 1982) is also very close to the northern terminus of the La Rinconada Fault. These lines of evidence suggest that the La Rinconada Fault is a possible candidate for having generated the 1952 earthquake.

### 5.2.2. Arbol Quemado Fault

Similar uncertainty as to whether the Arbol Quemado Fault scarps are cumulative or single event hinder our analysis of this fault. On the basis of similarity in displacement of all seven terraces, it is likely that the displacements measured correspond to a single event that occurred after the formation of the Q3a. Multiple events could have occurred either in between Q9a and Q3a or after the formation of Q3a, given the long duration of time of time in between Q9a and Q3a ( $56.6 \pm 16.5$  ka) and Q3a-present ( $96.9 \pm 8.8$  ka). Due to this uncertainty, single-event and multiple-event scenarios are considered for the estimation of the seismogenic capability associated with the Arbol Quemado Fault.

Assuming that scarps represent single-event displacement, earthquake magnitude estimates for Arbol Quemado were computed by calculating the arithmetic mean of displacements measured from Q3a-Q9a and using the magnitude versus average displacement scaling relationship equation of Wells and Coppersmith (1994) and Stirling et al. (2013). Using this equation, an average dip-slip displacement of  $8.51 \pm 0.61$  m corresponds to earthquake of  $M_w$   $6.8 \pm 0.4$ . Due to the uncertainty of number of events, this magnitude estimate should be treated with caution. Similar to the La Rinconada Fault, slip rate and fault length were also used to calculate earthquake size (Anderson et al., 2017; J. G. Anderson, Wesnousky, & Stirling, 1996). Here we use both slip rates from Q9a-present and Q3-present, yielding  $M_w$  estimates of 6.0–6.2 and 5.9–6.3, respectively. These  $M_w$  estimates are unsurprisingly significantly lower than magnitudes calculated the same way for the main La Rinconada Fault trace of  $M_w$  6.9–7.2.

## 6. Conclusions

Average slip rates of the La Rinconada Fault Zone in Eastern Precordillera of Argentina determined from combined geomorphic, structural, and  $^{36}\text{Cl}$  cosmogenic radionuclide data show an average shortening rate for  $34.5^{-3.1/+3.0}$  to  $78 \pm 1.5$  ka of  $0.41 \pm 0.01$  mm/year. This geomorphically derived shortening rate comprises 5–7% of the million-year geological time scale shortening rates for the entire width of the Principal Cordillera, Frontal Cordillera, and Precordillera and 5–12% of the decadal scale geodetic shortening rates for the Andean Orogenic Front. This relatively low shortening rate is comparable to shortening rates of other Andean Orogenic front reverse faults at similar range of latitudes ( $31$  to  $32^\circ\text{S}$ ) and can be explained through more widely distributed strain as suggested by Siame et al. (2002) in his study of the Las Tapias Fault. The La Rinconada Fault Zone is capable of generating earthquakes with magnitudes ranging from  $M_w$  6.6 to 7.2 that may potentially be destructive for the city of San Juan. Since the sequence of strath terraces that are cumulatively offset by the La Rinconada Fault are unlikely all coseismically displaced, timing and recurrence interval of surface-rupturing events associated with this fault will have to be determined independently.

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