Earthquake Mechanisms and Crustal Stresses in the Bolivian Central Andes

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Abstract

Crustal seismicity in the Central Andes is characterized by high activity in the sub-Andean province with predominantly reverse faulting mechanisms, and low activity in the high Andean plateau with normal and strike-slip faults. Despite having one of the largest orogenic plateaus, few crustal focal mechanisms were available for Bolivia. We determined 13 new focal mechanisms of shallow crustal earthquakes improving the characterization of the regional stresses. We used the probabilistic moment tensor inversion (Grond) combined with P-wave polarities. Reverse faulting earthquakes in the sub-Andean belt show compression perpendicular to the front of the Andean plateau. Focal mechanisms in the high plateau change to strike-slip indicating a balance between local extensional gravitational stresses in the plateau and regional compression from the Nazca plate convergence.

Introduction

Seismicity in the Andes is mostly driven by the subduction process. Near the Central Andes of Bolivia, the oceanic Nazca plate dips with about 27°-30° beneath the continental South American plate, with a convergence rate of 80 mm per year. Besides the regional compressional stresses (due to the plate convergence), large extensional stresses (due to gravitation collapse of the high plateau) combine to produce the resulting crustal stresses and deformational pattern. These processes control the formation of the seismogenic zones in the country. Six geological provinces are recognized from West to East (Fig. 1): 1) Western Cordillera (WC), a high mountain and volcanic belt, 2) Altiplano (AP), one of the largest plateaus in the world, 3) Eastern Cordillera (EC), a fold and thrust mountain chain, 4) Inter Andean Zone (IA), 5) Sub-Andes (SA), a thrust belt parallel to the Andean front, and 6) the Chaco – Beni basin (CB), in the eastern part of the South American stable platform.

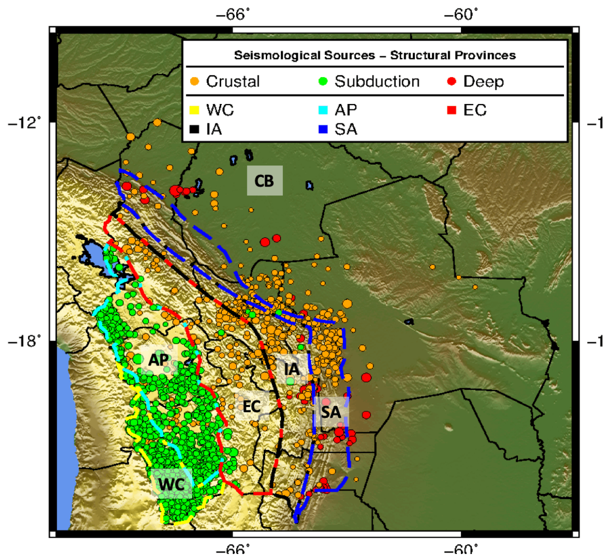

Fig. 1*. Seismicity and geomorphological provinces of Bolivia: shallow, intermediate and deep earthquakes are shown by green, orange and red dots.*

Most of the shallow earthquakes (depths from 0 to 75 km) are located in the EC, IA, and SA with the Altiplano (AP) having much lower seismicity. The intermediate earthquakes (100 to 350 km depth) occur in the Nazca slab beneath the WC and AP region and are the most frequent events. Deep earthquakes (500 to 700 km depth) occur beneath the northern part of EC, south part of EC and IA regions. Seismic hazard in Bolivia is mainly controlled by the shallow crustal earthquakes, whose magnitudes can reach M 6 or higher.

Despite the importance of the Bolivian Plateau in the Central Andes, few crustal focal mechanisms were known in this region because of a) few events larger than M 5.5 have occurred to allow reliable determination by teleseismic stations, and b) lack of more local and regional stations in Bolivia. Previous compilations of earthquake focal mechanisms in Bolivia (such as Vega & Buforn, 1991; Assumpção, 1992; Assumpção et al., 2016; Fernandez et al., 2019) produced less than 20 determinations. Here we determined 13 new focal mechanisms combining moment tensor inversions and P-wave polarities. This updated set of mechanism solutions allows a better characterization of the regional stress field in the Plateau and its borders.

Method

We used a probabilistic waveform inversion (Grond), developed by Heimann et al. (2018), assuming a regional velocity model from the CRUST2.0 database. Synthetic waveforms are pre-computed with the chosen velocity model using Wang (1999) algorithm. Grond fits observed displacement waveforms (near and far field) and their amplitude spectra, to resolve the deviatoric moment tensor (DC+CLVD). The inversion is performed simultaneously fitting amplitude spectra in the frequency domain and afterwards displacement traces in the time domain, the latter fit by cross correlation. A Bayesian optimization is used to explore the source parameters space, to estimate uncertainties and tradeoffs, testing over at least 20,000 iterations. As a result, Grond produces the best fitting solution, as well as an ensamble of good fitting solutions. Figs. 2 and 3 show examples of the results. The double-couple component of the best-fitting Grond solution was compared with the P-wave polarities, to ensure a proper match. If necessary, the moment tensor solution was updated, testing within the acceptable range, and searching for the solution which maximize the fit of clear P-wave polarities.

We used regional stations from Chile (IPOC net), Brazil (RSBR permanent net, and "3-Basins" temporary deployment), southern Perú (IGP), northern Argentina (INPRES net), as well as new stations from the San Calixto network (RS-OSC) installed since 2016.

Results

A set of 13 crustal earthquakes with Mw magnitudes from 3.2 to 4.6 were inverted for the moment tensor solutions (Fig. 4). Two events in the Altiplano showed strike-slip with normal component mechanisms. Three earthquakes in the eastern Cordillera and InterAndean showed strike-slip and reverse mechanisms. In the Sub-Andes six events were reverse faulting earthquakes and one was strike-slip. Only one mechanism, reverse faulting, was determined for the Chaco-Beni basin.

The new results depict a trend of reverse faulting earthquakes along the low topography Sub-Andean region, changing to strike-slip in the high topography Altiplano. The "SHmax" estimates from these 13 focal mechanisms (i.e., P axis orientations) were plotted in Figure 5 together with previously compiled data.

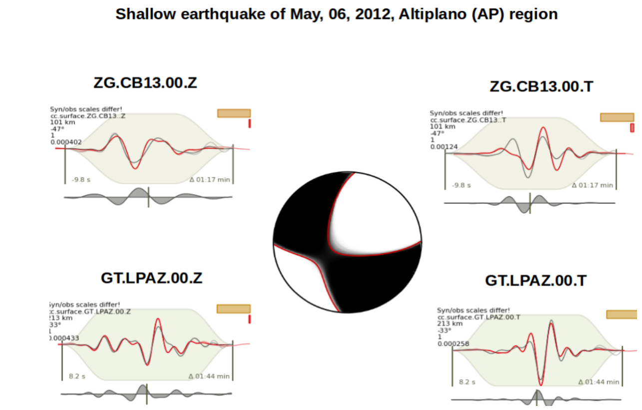

***Fig. 2**. Moment tensor solution for the Oruro earthquake of 2012-05-06, M 4.5, in the Altiplano. The beachball shows all solutions in the accepted probabilistic range;* the darkest areas indicate more stable results*. 218 stations were used (from the CAUGHT experiment). Waveform fits for two stations (temporary CB13, and LPAZ). Traces in red and gray lines are the observed and synthetic waveforms.*

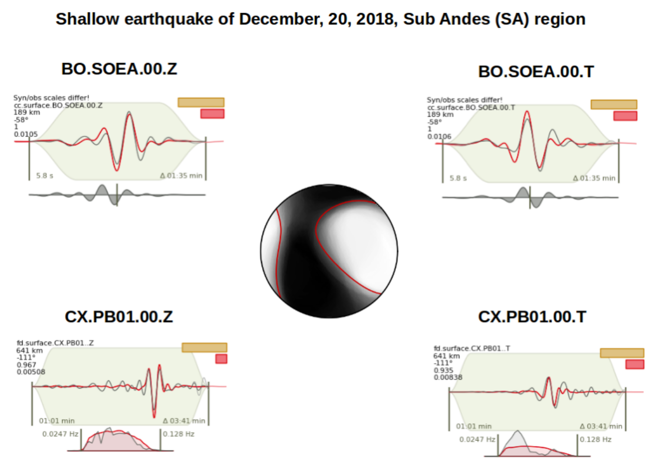

***Fig. 3a**. Moment tensor solution for the Sub-Andean earthquake of 2018-12-20, near Sucre, M 4.6. The beach-ball shows all solutions in the accepted probabilistic range, the darkest areas indicating more stable results. 31 stations were used. Waveform fits for the vertical (Z) and transverse (T) components of two stations: PB01 (Chile) and SOEA (OSC-Bolivia).*

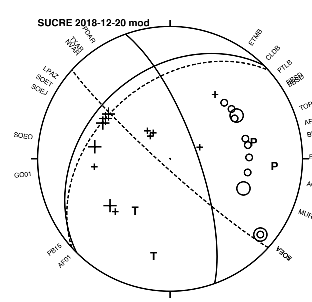

***Fig. 3b**. Double-couple solution of the GROND inversion (dashed lines) and the slightly modified solution to better fit the P-wave polarities. "+" and circles are positive and negative P-wave polarities; large symbols being clear impulsive arrivals.*

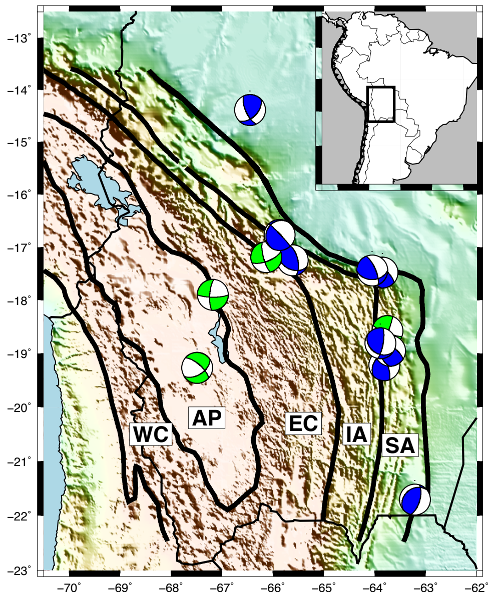

***Fig. 4**. Focal mechanisms of the 13 events determined here. Blue beachballs are reverse faulting mechanisms, green are strike-slip.*

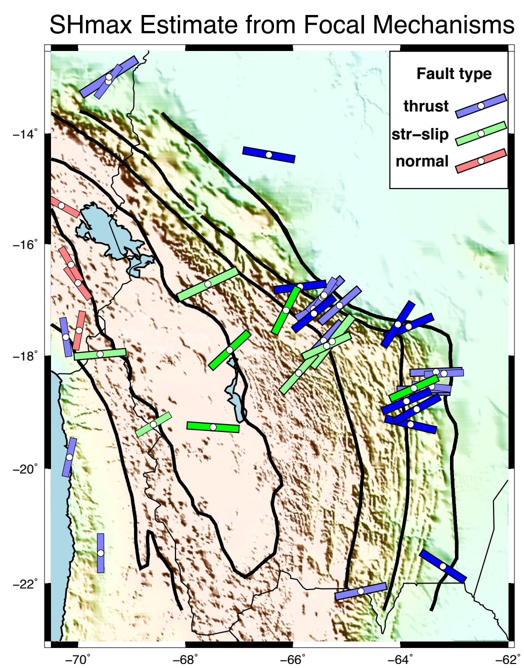

***Fig. 5**. "SHmax" estimates of the 13 events of Fig. 4, together with previously published mechanisms. Bar orientation is the direction of the P axis for reverse (blue color) and strike-slip (green) events, and the B axis for normal fault events (red). Fainter colors denote previous published data; bright colors are the 13 new data determined here.*

Discussion

The transition from compressional stresses in the Sub-Andes towards strike-slip in the elevated plateau clearly shows the effect of the gravitational spreading stresses of the elevated plateau pushing the crust of the low topography areas. North of the Bolivian orocline (north of 18ºS) the average SHmax in the Sub-Andean belt is about SW-NE, roughly perpendicular to the plateau front. South of the Orocline, the average SHmax orientation is ~E-W, also roughly perpendicular to the plateau front. This gravitational effect was already known (e.g., Fleitout & Froidevaux, 1982; Coblentz and Richardson, 1994; Assumpção & Araujo, 1993). However, the increased number of focal mechanisms allows us to determine more precisely the transition between the compressional stresses in the Sub-Andes (where the effect of the Nazca plate convergence adds to the compressional stresses from lateral spreading of the neighboring plateau) and the more extensional stresses in the high plateau. It seems this transition lies along the boundary between the Inter-Andean zone and the Eastern Cordillera.

In the high topography plateau of the Central Andes, the predominance of strike-slip events (no normal faulting mechanism was determined) suggests that compressional stresses from plate convergence are roughly balanced by gravitational extensional stresses from the plateau topography.

Conclusions

The use of 3D models in moment tensor inversions, as well as the installation of more stations in Bolivia in the last few years, have allowed a significant increase in the number of focal mechanisms for crustal earthquakes in the Central Andes.

The increased number of focal mechanism solutions for shallow earthquakes in Bolivia allowed a better characterization of the crustal stresses and the transition between compressional stresses in the Sub-Andean belt and the more extensional stresses in the high plateau. This improved pattern of regional stresses will help better understand the present geodynamic forces acting in the Central Andes. It will also help to better delineate the crustal seismic zones in future versions of the Bolivian seismic hazard map.

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