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ORIGINAL ARTICLE

Aysén seismic swarm (January 2007) in southern Chile: analysis using Joint Hypocenter Determination

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Abstract A seismic swarm at the Aysén fjord started in January, 2007, reaching its highest activity between January and April, 2007. It was punctuated by the Mw5.3 23rd January event and the Mw6.2 21st April event which triggered a water-wave due to massive landslides; both with dextral strike slip focal mechanisms. More than 100 events were relocated with the Joint Hypocenter Determination method to study the depth distribution of the events of the swarm recorded by the Chile Ridge Subduction Project local network. The events are associated to a small area of approximately 7 × 7 km located in the Aysén fjord, on one of the main branches of the Liquiñe–Ofqui fault. Distribution in depth is located between 0 and 8 km and presents a west high dip with almost NS strike, consistent with the main trending of the Liquiñe–Ofqui fault and the published focal mechanisms. These characteristics, among others, suggest that the Liquiñe–Ofqui fault is active in this region and thus seismic risk has to be re-determined.

Keywords Seismic swarm · Aysén Fjord · JHD · Southern Chile · Liquiñe–Ofqui fault

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1 Introduction

The Aysén fjord is located on one of the two main branches of the Liquiñe–Ofqui fault, near Puerto Chacabuco and Puerto Aysén, formed as a weakness zone from the Chile Triple Junction and the buttressed system formed as the Nazca plate subducts obliquely under the South American plate. This zone is known for its poor seismicity, and only a few teleseismic events related to Lonquimay and Hudson activity have been recorded, along with some shallow seismic activity obtained from teleseismic and other temporary local networks (Lange et al. 2008 and references therein), for which the 2007 seismic swarm stated a precedent in the activity register.

A *swarm* refers to a series of seismic events that occur concentrated in time and space (Mogi 1963), with its magnitude and number of events increasing in time to wane after a certain period. Unlike a typical seismic cycle, which has a main event considerably larger than its aftershocks and/or foreshocks, a seismic swarm shows a few peak events with magnitudes that stand out from the other events in the swarm (Ibs-von Seht et al. 2008). Although a swarm can precede a main-shock, its temporal evolution does not follow any known law, as the potential law for foreshocks, or Omori's Law for aftershocks. It is known that the temporal behaviour of a swarm follows a fractal distribution (Hainzl 2003), but its interaction with energy release is not known.

The Aysén swarm started with several events at the end of January, 2007, and had its highest activity between January and April, waning through August and showing very few events on the consecutive months. The last event, according to the National Seismological Center (SSN 2009), was in May, 2008. Two of the larger events that punctuated this swarm were the Mw5.2 and Mw6.2 (USGS) occurred on January 23rd and April 21st, respectively. The first one practically started the activity, and the second one caused several damages on the fjord coasts due to tsunami waves triggered by massive landslides.

This work presents results based on unpublished data recorded between January 1st and 27th, 2007, previous to and after the Mw5.2 January 23rd seismic event, recorded by the Chile Ridge Subduction Project (CRSP) temporary network. This offers the possibility to study the crustal seismicity of the zone, its relationship with the main faults and to identify seismic risk areas. The study of temporary evolution of the events and its correlation with geological features will allow us to determine a possible tectonic, volcanic or mixed origin for this activity.

2 Geotectonic setting

The Liquiñe–Ofqui Fault Zone (LOFZ) is located in southern Chile, comprising ca. 1,000 km long between 38°S and 48°S (Fig. 1). It is separated into two main lineaments that run parallel to the trench, one between 39° and 44°S and another between 44° and 47°S, connected by NE trending *echélon* lineaments and at least three lineaments of tens kilometers concave to the SW (Cembrano et al. 1996).

The LOFZ crosses the North Patagonian Batholit, the ancient volcanic arc, and the Austral Andes Volcanic Zone, the actual volcanic arc, where volcanoes are distributed along the western NS main fault and in the NE lineaments.

The southern end of the LOFZ starts near the Chile Triple Junction, location where the Chile Rise intersects the Peru-Chile Trench. North of the Triple Junction, the Nazca plate is subducting below the South American plate at 66 mm/year (Angermann et al. 1999), whereas to the south, the Antarctic plate is subducting below the South American plate at about 22 mm/year (De Mets et al. 1994). For the last 15 m.y. the directions of plate motions between the South American, Nazca, and Antarctic plates have remained relatively constant (Cande 1983). As a result, the Triple Junction migrated northward to its actual position north of Peninsula de Taitao and Golfo de Penas (46°S), and the successive Chile Rise segments collisions acted as indent and main force in the regional tectonism (Thomson 2002) which, in addition to difference in subduction velocities, causes stress partition along the trench between 38° and 42°S (Rosenau et al. 2006), and vertical axis rotations of the blocks to the east and west of the fault as in a buttressed system (Beck et al. 2000).

Seismicity along the LOFZ has been scarcely studied, mainly for the lack of constant local networks. Some teleseismic events previous to 2007 are related to Hudson volcano (1965) and Lonquimay volcano (1989) activity (Lange et al. 2008). Only a few regional studies had been carried out, mostly on the northern and central part of the LOFZ, focusing on crustal and subduction related seismicity. Studies from Bohm et al. (2002) and Haberland et al. (2006) concentrated on the northern part of the LOFZ, around the Arauco Peninsula (37°S), and found several clusters associated with thrust and intermediate subduction zones, and others aligned with NW deep-reaching crustal faults. Further south, Lange et al. (2007, 2008) focused on the Chiloe Island zone (41°–43°S), where seismicity is following the Benioff zone between 12 and 70 km depth, and some

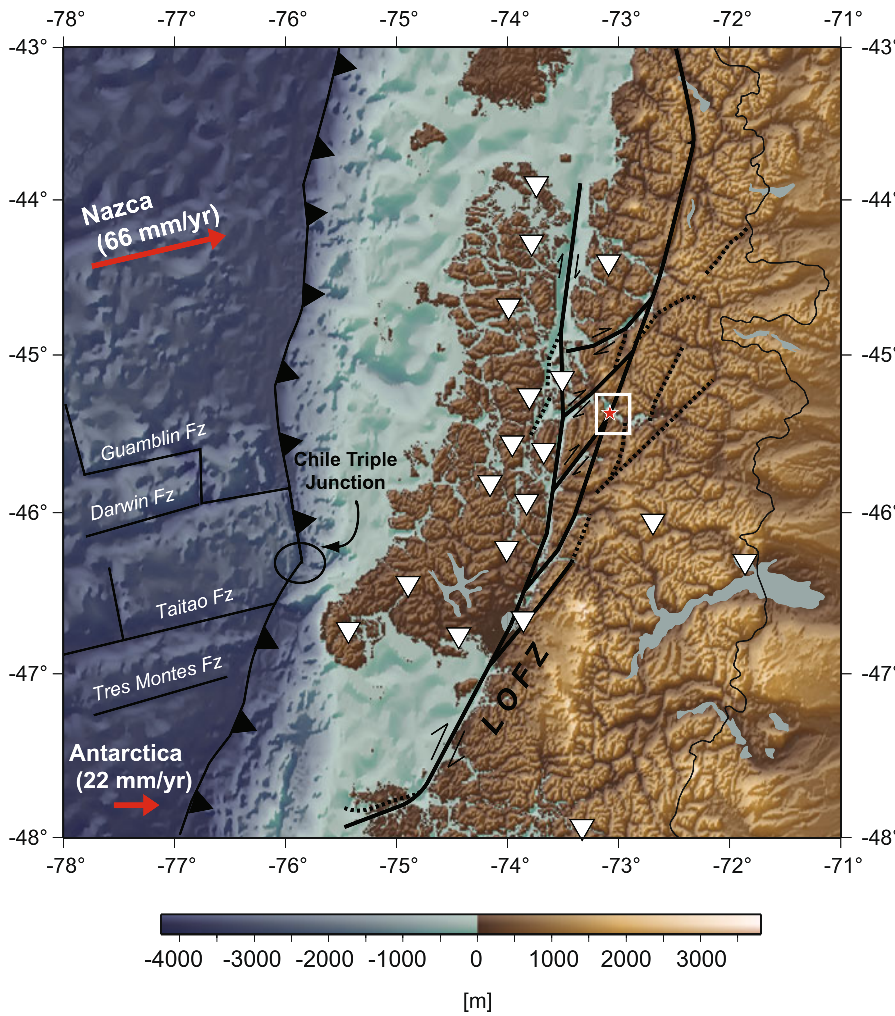


Fig. 1 Geotectonic setting for the LOFZ (*black thick and dashed lines*) modified from Cembrano and Lara (2009) and SERNAGEOMIN (2003), actual path for fracture zones and active ridge spreading (*thin black lines*) and typical convergence angles and velocity for Nazca and Antarctic plate (*red arrows*) presented. Active stations from CRSP temporal network for this study shown as *white inverted triangles*. *White box* shows boundaries for Fig. 3. *Red star* denotes Aysén swarm location

shallow clusters spatially related with volcanoes, like Corcovado, Chaitén, Hornopirén and Michimahuida. The closest study performed in the proximities of the Aysén fjord region is the one from Murdie et al. (1993) which presented, using both local network and teleseismic events, seismicity associated to subducted fracture zones and crustal weakness due to slab windows location. Subsequently, no regional seismicity related to the fault has been recorded because no local network had been deployed near the fault zone previous to the Mw6.2 earthquake in April 2007 in the Aysén fjord.

3 Chile Ridge Subduction Project temporary network and data acquisition

The Chile Ridge Subduction Project (CRSP), a joint project between Universidad de Chile and University of Florida, deployed a temporary broadband network between 43°–48°S and 71°–76°W, comprising 54 seismometers and four "fat" stations (a broadband STS-2 Streckeisen station accompanied by closely spaced short period seismometers) displayed inland and in islands during Dec. 2004–Jan. 2007. From January 1st to 27th, 2007, only 19 stations were active (Fig. 1), most of them located between 73°–74°W and 44°–47°S, and were deinstalled after January 28th. These stations captured more than 300 events near Aysén Fjord, the majority of these events occurred between January 23rd and 27th, 2007.

Preliminary, 353 hypocenters were located picking P-wave and S-wave arrivals visually from the continuous record, and using the velocity model from Robertson et al. (2003). Whenever possible, coda was also determined by inspection. On the first week (January 1st to 7th), no events were found on the Aysén fjord, while on the next three weeks, January 8th to 14th, 15th to 22th, 23th to 27th; four, 12 and more than 300 events occurred, respectively (Fig. 2). On January 23rd, a Mw5.3 strike slip earthquake announced the beginning of the seismic swarm, that had its major activity between January and April, 2007, which later decreased towards August of the same year. Last event reported, according to the National Seismological Center (SSN) was in May 11th, 2008.

As 90% of the events occurred between January 23rd and 27th, these five days were chosen as five groups for relocation with Joint Hypocenter Determination (JHD) method. We selected 132 events, including the master event, with clear P wave arrival in more than 14 stations and error rms < 0.2, and used the calculated hypocenter for the Mw5.2 January 23rd event as master event.

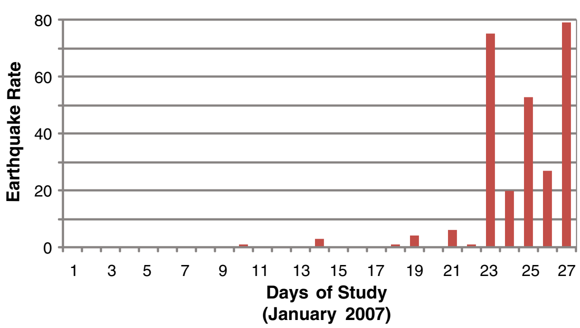


Fig. 2 Number of events versus time plot for the events on this study, between January 1st and 27th

4 Joint hypocenter determination of swarm event location and results

The Joint Hypocenter Determination method (JHD, Douglas 1967; Dewey 1972) is used to determine the position and origin time of a group of events simultaneously, and the station travel time corrections. The method assumes that travel time anomalies of P waves in a group of events are identical to all common stations, thus the difference in arrival times is due only to differences in the hypocenter. These travel time anomalies are caused by horizontal bias not considered in the 1D velocity model.

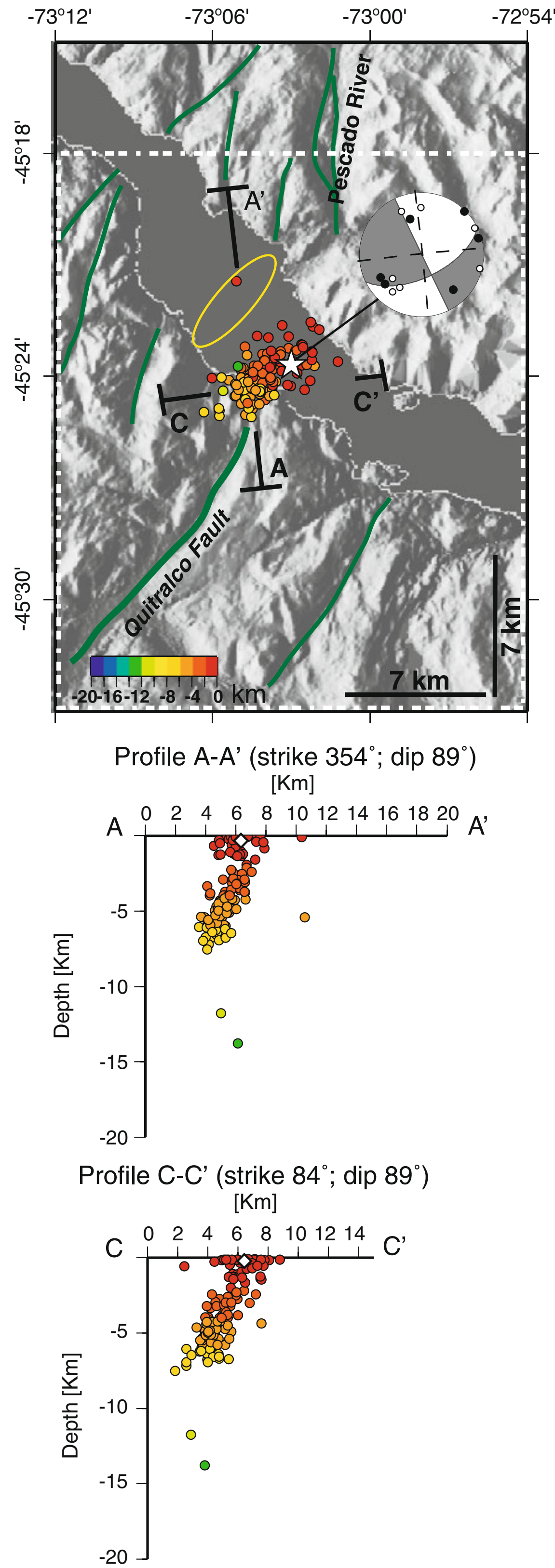
A main event is used to relocate the group of events relative to it. Its parameters are assumed to be known, accurate and fixed. Latitude, longitude, depth and origin time differences relative to this main event are calculated iteratively for each event, using a decreasing linear variation of velocity, giving a better constraint to the fault geometry. In addition, station corrections are calculated to mend the bias produced by high and low velocity zones.

This method is useful in areas where the 1D velocity model is poorly known or there is a complex 3D velocity structure (Ratchkovsky et al. 1998), as is the case of southern Chile, considering the LOFZ, the Chile Rise and its active spreading before and after subduction.

After the relocation process, these 132 events presented significant rising from a distribution between 0 to 15 km, to final depths between 0 and 8 km, with 90% of the events presenting errors lower than 1.4 km. The studied events are confined to an area of 7.8 km in longitude and 7.4 km in latitude, with 90% of the events presenting errors below 1.8 km. Events for which magnitude was calculated, which was done whenever possible, presented values between 3 and 5.3.

To analyse structure in depth, along-strike profiles were performed following strike directions from the plane solution given by USGS (354°) and the N10°E hanging valley north of Aysén fjord, which possibly is the surface expression of a previous weakness zone in depth that has been exhumed and/or the continuation of the

Fig. 3 *Top*: Plan view of the seismic swarm activity in the ▶ Aysén fjord (*coloured dots*). Quitralco fault shown as a *green thick line*, other faults found in the topography shown as *green thin lines*. Calculated focal mechanism for the mainshock event in *gray*, and planes solutions from USGS shown as *dashed lines* inside the sphere for comparison. *Yellow ellipse* denotes bathymetric anomaly position presented in Lara (2008). *White dashed box* shows boundaries for Fig. 4. *Centre*: Profile view (*A–A'*) along strike (354°) and dip (89°) given in the focal mechanism solution by USGS for the January 23rd event. *Bottom*: Profile view (*C–C'*) along perpendicular direction of previous profile, following strike (84°) and dip (89°) given the focal mechanism solution by USGS. January 23rd mainshock, used as master event, shown as a *white star* on plain view and as *white diamonds* on profiles



observable Quitralco fault on the south shore of the fjord (Fig. 3). All profiles were performed following an 89° dip angle, according to USGS focal mechanism solution. Both directions (N354°E and N10°E) are consistent and show similar distribution, considering the small separation between both strikes, and present the distribution of events in depth as a south trending structure with west high angle dipping, with depths decreasing northward.

5 Focal mechanisms and stress tensor

From the JHD events selection, 25 focal mechanisms were calculated based on P-wave arrival polarity using FocMec (Snoke et al. 1984; Snoke 2003) in SEISAN, considering those with two or less polarity mismatches and with 14 or more stations read. The results (Fig. 4) show clear dextral movement in a strike slip fault segment, with a strike near N-S. These characteristics are consistent with the main trending of the Liquiñe–Ofqui fault and with the geological features found in the surroundings of the fjord. These characteristics are also in agreement with the solution presented by USGS and Harvard CMT for the January 23rd and April 21st, 2007 events. Although stations used for this study are located mainly to the west of Aysén fjord, the focal mechanisms calculated

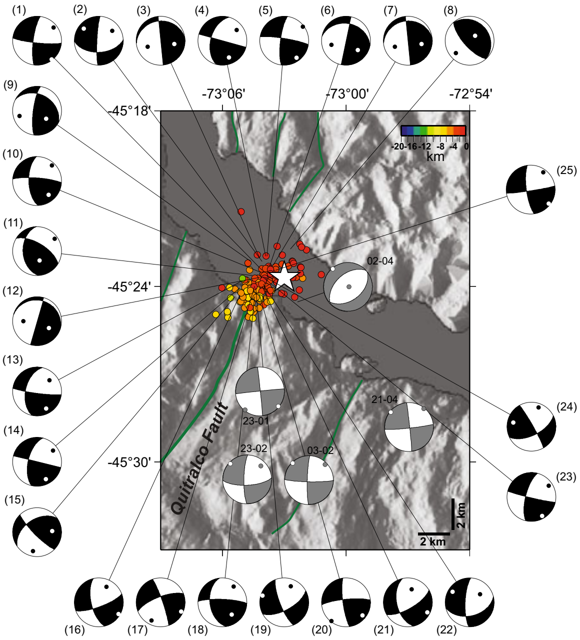


Fig. 4 Calculated focal mechanisms of 25 events in the JHD selection (black mechanisms) and solutions, added for graphical comparison, presented by Harvard CMT for medium magnitude events during the swarm (gray mechanisms). *White star* shows the January 23rd mainshock. *Green lines* follow fault trace from topography

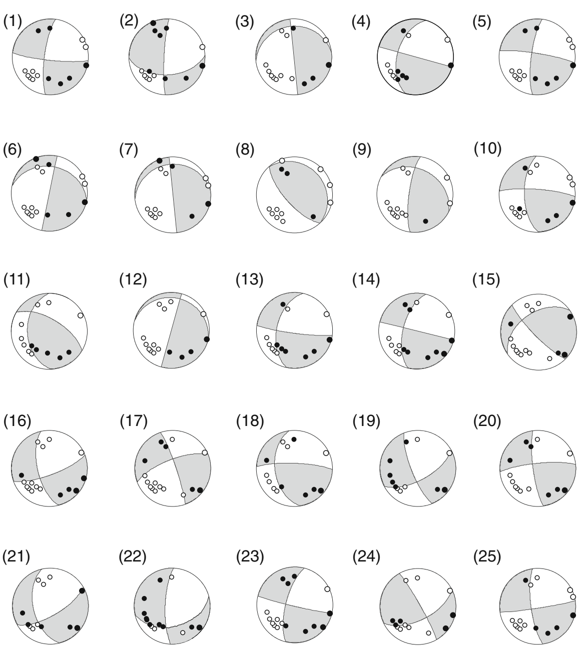


Fig. 5 Azimuth coverage for focal mechanisms presented in Fig. 5. P-wave polarities shown in black for compression, and white for dilation

show good azimuth coverage, as can be seen in Fig. 5.

The obtained focal mechanisms were used as input for the Rivera and Cisternas (1990) method to obtain the local stress tensor and its shape factor *R*. The method calculates the stress tensor (ϕ, θ, ψ) from the solution space by Montecarlo's method, and calculates the average of the dot products between the estimated slip vector from the obtained stress tensor and the slip vectors

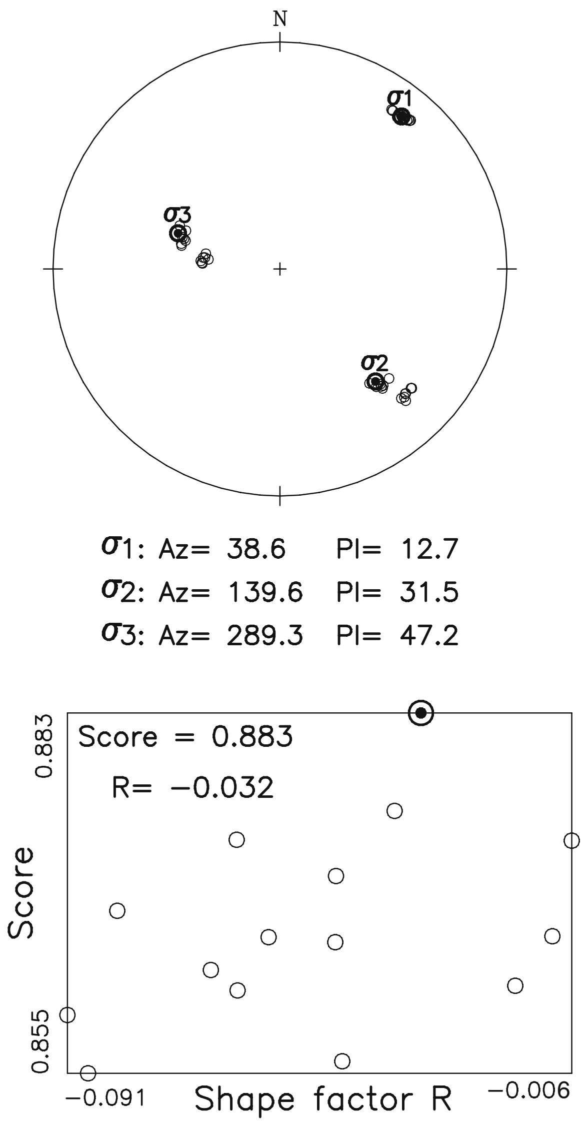


Fig. 6 Stress tensor solution obtained from Rivera and Cisternas (1990) method using the 25 focal mechanisms from Fig. 5

from the input focal mechanisms. This value represents the accuracy of the stress tensor found. Also, the Rivera and Cisternas (1990) method calculates the shape factor $R = \frac{\sigma_z - \sigma_x}{\sigma_y - \sigma_x}$, with $\sigma_y > \sigma_x$, which indicates if the tensor corresponds to compression ($R < 0$), transpression ($R > 1$) or strike-slip ($0 < R < 1$).

The obtained solution (Fig. 6) corresponds to a transpressional stress ($R = -0.032$) predominant in the studied region, with σ_1 in N38°E direction and subhorizontal (plunge 13°), and σ_3 in N289°E direction and plunge 47°. These directions are in agreement with average directions obtained by Lavenu and Cembrano (1999) for the Quaternary event (1.6 Ma) of σ_1 between N–S to NE–SW ($N42° \pm 20°$).

6 Discussion

The south part of Chile has a considerably low seismicity rate in comparison to the northern and central parts. In particular, the Liquiñe–Ofqui Fault Zone has not presented this type of seismic activity, or any, except the expounded by previous works (Murdie et al. 1993; Bohm et al. 2002; Haberland et al. 2006; Lange et al. 2007, 2008) along the LOFZ. These studies point out different zones along the LOFZ where the stress accumulation and stress release is more efficient. Considering that pore fluid pressure decreases the effective stress when it is added to the system, then the water mass induces the fracture of the structures beneath the Aysén fjord. Given the geometry of the Liquiñe–Ofqui fault, it is very likely that weakness zones and fault intersections are generated between the main trend and duplex structures, with concomitant faults and/or with concave faults due to the buttressed system. The seismicity may also be generated in between horsetails structures or in the reactivation of a fault segment. Possible geological features for horsetail structures are the intersection under the fjord between Pescado river valley (Fig. 3), and Quitralco fault segments north and south of the fjord.

Apart from the lack of known base seismicity, the seismic activity of the Aysén fjord increased suddenly from no more than 5 events per day to more than 300 events in less than a week. Including in the months of highest activity, 4 events with magnitudes $5.2 \leq Mw \leq 5.7$ were reported in January and February, and 2 events of Mw6.1 and Mw6.2 were reported in April 2nd and April 21st, respectively (Harvard CMT 2009).

The studied focal mechanisms solutions and those obtained from the USGS agency for events of moderate magnitude between January and April, 2007, coincide with a high-angle dextral strike-slip fault solution, even though the epicenters for the USGS events are displaced from the epicentral zone for this study. The double couple component from the focal mechanism associated to moderate magnitude events presented by Harvard CMT, is in agreement with the focal mechanisms obtained in this study, even when the Harvard CMT solutions have high non-double couple component.

Nazca plate at Aysén latitude is relatively young (~ 8–10Ma, considering Jarrard 1986 and Herron and Hayes 1969), which allows the asthenosphere wedge to be closer to the thin crust (35 km thick at 46°S, Tassara and Yañez 2003). This can be correlated with magma fluid movements underneath the crust and, considering the LOFZ as a crustal depth structure (Beck et al. 1993; Cembrano et al. 1996; Lavenu and Cembrano 1999), this may cause induced abnormal stress in the crust that could be released as seismicity. There is no solid evidence that could relate this seismic swarm with volcanic activity. Although to the NW of the epicentral area a bathymetric anomaly (yellow ellipse in Fig. 3) has been described as a Holocene volcano, it has not shown any recent activity (Lara 2008). Moreover, it is interesting to note that the nearest volcanoes (Maca, Cay and Hudson) did not show any activity during the swarm period of activity.

However, under a mixed scenario, the studied region is located at a very complex area where the Triple Junction is a main constraint, and is clearly related to the formation and existence of the Liquiñe–Ofqui fault and the high volcanic activity present along this feature. Therefore, considering the use of a seismological database, earthquakes observed under this study present a tectonic origin.

7 Conclusion

The Aysén seismic swarm is related to a transpressional stress due to the oblique subduction of the Nazca plate and the thermal weakness of the volcanic arc. The liberation of the accumulated slip into several NS strike-slip events, allows the intra-arc region to absorb the deformation.

The events may be associated to an intersection of fault segments as a horsetail structure or between one of the main trend segments and a concomitant fault under the fjord, following structures as the northern and southern part of Quitralco fault, giving the swarm a tectonic origin.

The evidence of seismicity in this region demonstrates that the fault itself is seismically active in this zone, and considering the association of these events with the fault and the water-wave generated by massive landslides induced by the April 21st earthquake in the same location, it is clear that seismic hazard estimations in the Aysén region must be reestimated.

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