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Neotectonics and seismicity in southern Patagonia

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Research for evaluation of geologic hazards involving earthquakes and volcanic eruptions in southern Argentina seems to have historically received little attention. Nevertheless, the relatively small work done indicates a Neogene tectonic architecture in the area with capability of generating potential hazardous earthquakes in a growing population region. Seismicity and some morphotectonic evidences of Quaternary activity of the Magallanes–Fagnano left-lateral fault system in the transform boundary between South America and Scotia plates, are analysed in this paper. This fault system is considered to be an important seismogenic source, responsible for large earthquakes that have occurred in southern Argentina. Some examples from the South and Austral Andean Volcanic Zones are also examined in order to show recent volcanic activity which also generated crustal seismicity. Preliminary hazard estimation clearly shows the presence of both potentially active volcanic centres in southern Patagonia that may also trigger seismicity and the high probability for large crustal earthquake generation. Copyright © 2015 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The analyses of seismic and volcanic hazards carried out during the last few decades in southern Argentina have progressively been improved with the use of geologic and geophysical data. By combining these techniques it is possible to build the seismic history of active faults and the volcanic activity in the past. In southern Patagonia the historical and instrumental seismic records cover a very short time span. This precludes obtaining precise estimates of seismic activity rates and earthquake sizes over a long term period and assessing their impacts on earthquake hazards. In this paper we present an analysis of the different tectonic aspects, the principal geomorphologic features suggesting active tectonics, and the seismic and volcanic activity in the past and present around southern Patagonia.

Previous studies have pointed out the good correlation between two large neotectonic structures and seismic location distribution in Patagonia (Cembrano *et al.*, 2007; Perucca and Bastías, 2008). These regions correspond to the Liquiñe–Ofqui and the Magallanes–Fagnano fault systems (Fig. 1a). In addition, these major structures set the boundaries of volcanic environments, particularly during the Late Neogene. In fact, strike–slip structures like the Liquiñe–Ofqui fault system in western Patagonia is a N–S trending intra-arc fault that extends over hundreds of kilometres (Lavenu and Cembrano, 1999) as a dextral strike–slip duplex. The same systems runs into the Argentinean side showing extension associated with volcanics (Folguera *et al.*, 2004; Costa *et al.*, 2011).

The Magallanes–Fagnano Fault is located in Isla Grande de Tierra del Fuego, trending WNW over a distance of 600 km between the Atlantic and Pacific oceans. Along its trace, it shows evidence of active sinistral movement, with the South American continent moving slowly westward with respect to the Andean region in Tierra del Fuego (Lodolo *et al.*, 2003).

The neotectonic activity in Patagonia is still much unknown. In addition, there is a scarcity of permanent seismic stations in the region in comparison with the northern region of Argentina (Alvarado and Araujo, 2011) and the low population density of this area, cause a virtual absence of historical records. However, the presence of remarkable

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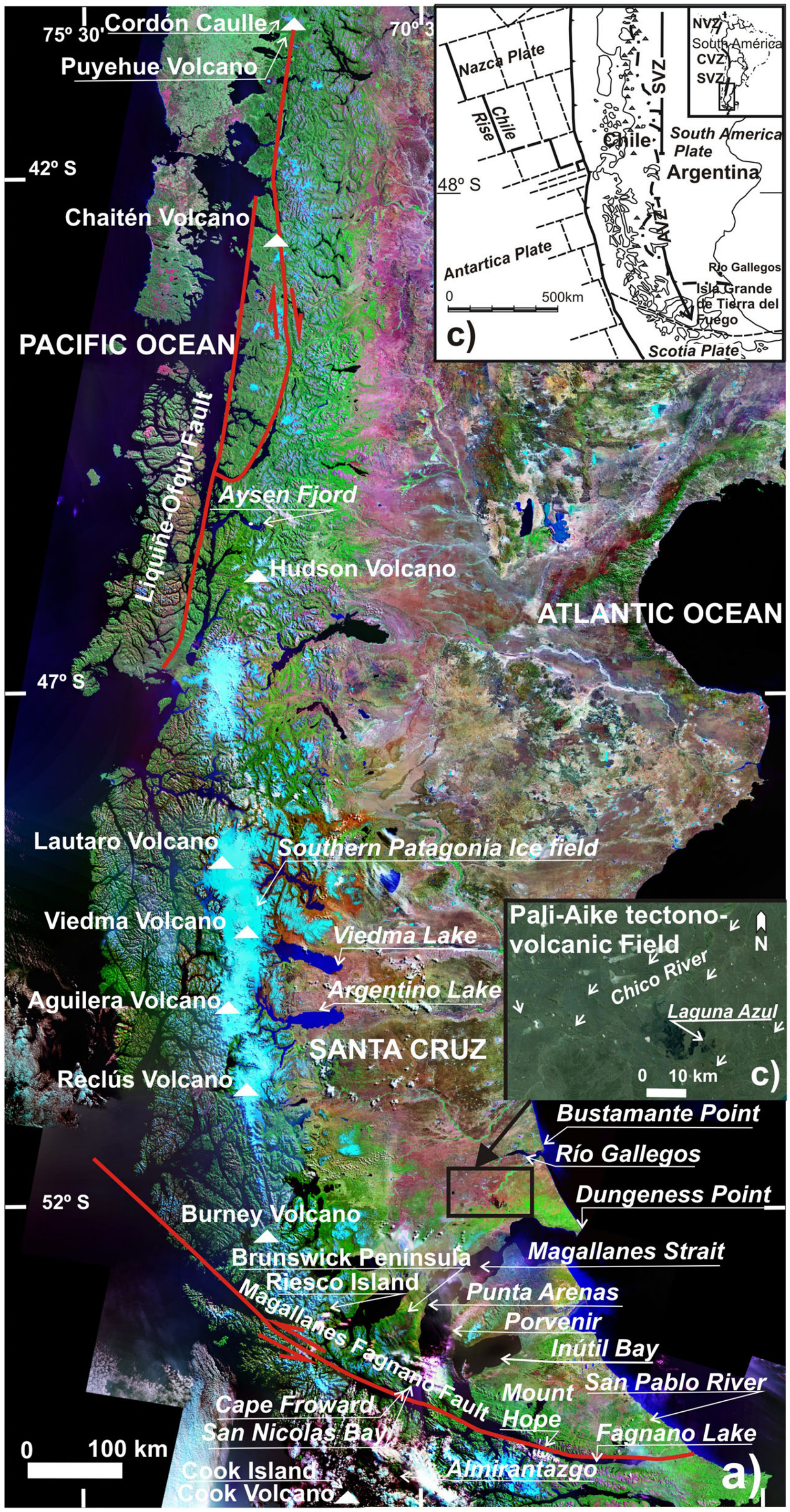

Figure 1. (a) Regional tectonic setting of South Patagonia and Tierra del Fuego Island with tectonic plate configuration, volcanoes and faults. Inset map shows plates and North Volcanic Zone (NVZ), Central Volcanic Zone (CVZ), South Volcanic Zone (SVZ) and Austral Volcanic Zone (AVZ). (b) Pali-Aike volcanic field located to the north of the Magallanes Strait. This volcanic field contains lake-filled maars (as Laguna Azul) with aligned basaltic scoria cones and fresh-looking lava flows. It is the southernmost basaltic volcanic field in Patagonia. Arrows show the main volcanic centres aligned along a northwest–southeast orientation. This figure is available in colour online at wileyonlinelibrary.com/journal/gj.

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morphotectonic features associated with active faults and the available (little) seismic information show modern tectonic activity and the potential for large earthquakes and volcanic events in this region of Patagonia.

2. SEISMOTECTONIC SETTING

2.1. Magallanes–Fagnano fault system

From a structural point of view and from south to north the region of the Tierra del Fuego Island can be roughly split into several morphostructural WNW-trending provinces (Kranck, 1932; Winslow, 1982; Dalziel and Brown, 1989; Suárez *et al*., 2000; Olivero and Martinioni, 2001; Fig. 1a). The Magallanes–Fagnano (MF) Fault corresponds to the continental segment of the transform margin between the Scotia and South America plates in the Tierra del Fuego Island, involving two structural domains: a thin-skinned domain north of the fault, and a thick-skinned domain south of the fault (Winslow, 1982). The MF fault trends N89°W and can be followed for about 200 km in length although some authors have stated 400 to 800 km for this estimation (Winslow, 1982; Dalziel and Brown, 1989; Klepeis, 1994; Lodolo *et al*., 2002a, b). The fault strikes E–W in eastern Tierra del Fuego, and bends smoothly to the NW in the western Chilean region of the island. This fault system comprises distinct tectonic lineaments arranged in '*en échelon*' geometry. The main segments exhibit near-vertical faults (Lodolo *et al*., 2003a). According to Smalley *et al*. (2003) a left-lateral dominant direction of motion at about 6.6 mm/year has been recognized along the MF fault. González Bonorino *et al*. (2012) considered that the faults have probable ages between 0.9 and 6.4 ka BP and a recurrence rate of about 1 ka for damaging earthquakes. The present deformation, measured at GPS stations located on both sides of the main faults of the South American and Scotia plates, shows a sliding rate of around 5 mm/year (Del Cogliano *et al*., 2000). Smalley *et al*. (2003) and DeMets *et al*. (2010) pointed relative motion across the MF fault system at rates between 6.6 and 9.6 mm/year.

MF is a regional alignment that can be seen mainly in the eastern branch of the Magallanes Strait, along the northern shore of Fagnano Lake and along the Atlantic coast (Winslow, 1982; Winslow and Prieto, 1991).

The MF is one of the major segments of the South America–Scotia plate boundary evidencing left-lateral offset along its trace. Thus, Winslow (1982) documented how this fault apparently offsets the western margin of the Patagonian batholith by 80 km.

Another interesting idea has been proposed by Olivero and Martinioni (2001) suggesting the MF fault is the expression of a suture between the South America and Scotia plates in the continental part. Later research by Lodolo *et al*. (2002a, b, 2003) identified the MF fault as the surface expression of the suture which separates the South American continental plate from the oceanic Scotia plate. In contrast, Rossello (2005) pointed out the similar composition of metamorphic and acid to mesosilicic intrusive rocks of the Fuegian Cordillera, which would not fit that theory. Furthermore, the regional geology in the western continuation towards the Magallanes Strait (Diraison *et al*., 1997) and its neighbouring areas near Brunswick Peninsula and Riesco Island in the Chilean side (Cunningham, 1993; Cunningham *et al*., 1995) shows no significant changes from north to south across the trace of the Magallanes–Fagnano Fault.

The MF fault system emerges on the Chilean side of Isla Grande de Tierra del Fuego, linked to Mount Hope, where the fault plane can be evidenced in the Quaternary alluvial cover by scarp alignment, truncated vegetation, deflected drainages, broom-shaped river patterns and sag ponds (e.g.., Perucca and Bastías, 2008). It consists of different segments in the transform system represented by near vertical faults, with dips that change along the fault trace. The sedimentary architecture of the asymmetric basins formed by fault slip suggests simultaneous strike–slip and extensive motion, which is a common feature among other continental transtensive systems (Klepeis, 1994). To the east of Fagnano Lake, morphological evidence of Quaternary fault activity can be found associated with the truncation of sand meanders and changes in the direction of the streams. Some of the features are very recent, such as the scarp of the 1949 earthquake related to a gravel barrier built in the eastern shore of Fagnano Lake.

Fagnano Lake is probably the surface expression of a large pull-apart basin formed by segments of the Magallanes–Fagnano fault system (Lodolo *et al*., 2003). Its length is comparable to some of the largest strike–slip basins located along transform margins (Ben-Avraham and Zoback, 1992). It is formed by at least two subparallel, disconnected and *en échelon* segments. Its western branch is outlined by a narrow depression where it lies the Río Turbio valley; its eastern branch reaches the Atlantic coast (Lodolo *et al*., 2003), (Figs. 1 and 2a).

The fault system evolution has a close relationship with the complex tectonic events responsible for the development of the oceanic bed in the West Scotia Sea during the Late Oligocene. These events caused the final separation of the Antarctic Peninsula from the South American continent (Barker and Burrell, 1977). The role played by the fault in the adjustment of the motion between the South American and Scotia plates must have been essential after the oceanic expansion stopped in the West Scotia Sea (9 Ma), though some displacement may have taken place a long time before (Cunningham *et al*., 1995). The analysis of numerous faults

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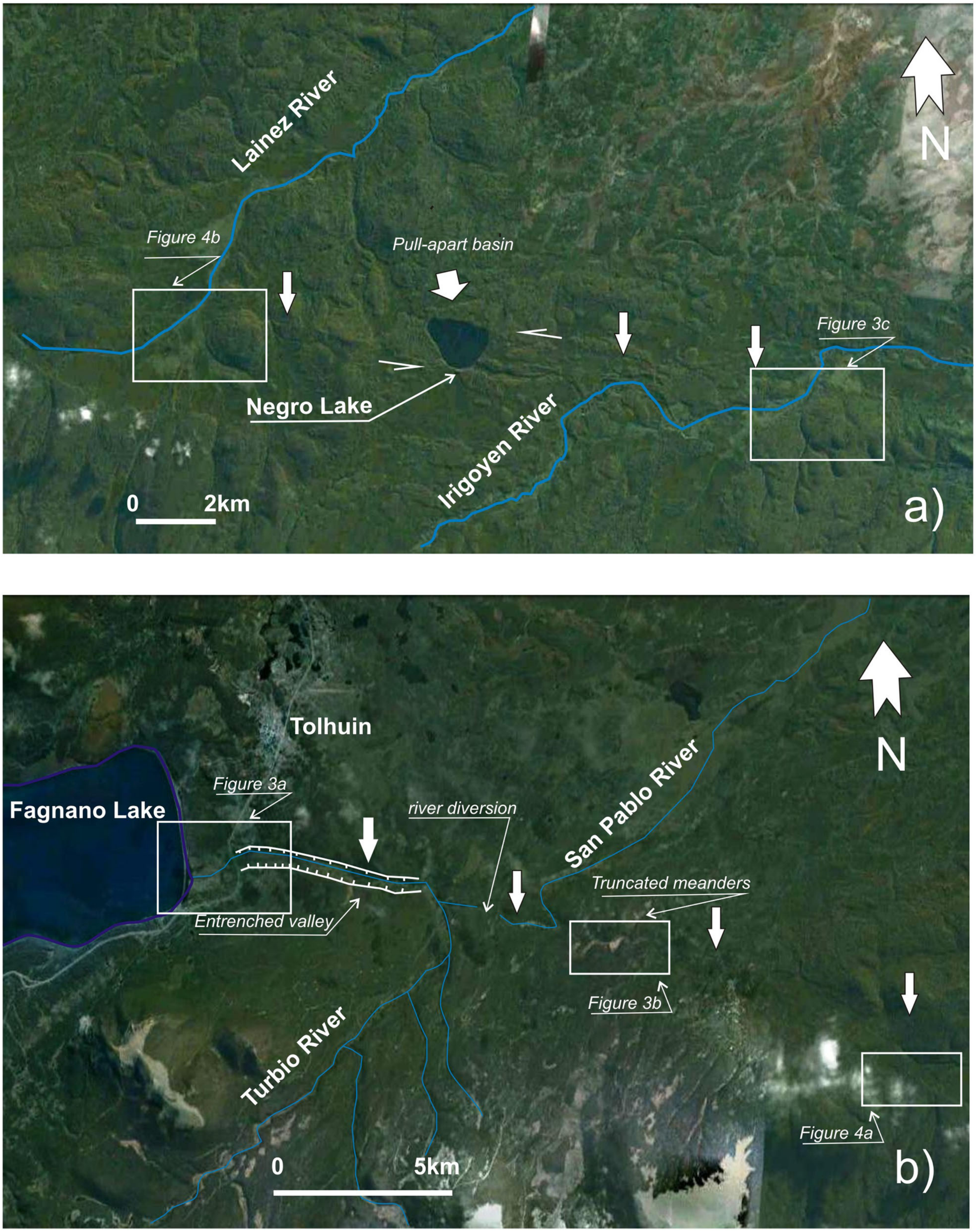

Figure 2. (a) Google Earth image of the central section of the Magallanes–Fagnano (MF) Fault. Lainez and Irigoyen rivers cross the fault scarp. Negro Lake is an example of a pull-apart basin produced by an '*en-échelon*' strike–slip motion; (b) Google Earth image of the area east of Fagnano Lake showing the location of scarps and the narrow valley of Turbio River at its mouth. This figure is available in colour online at wileyonlinelibrary.com/journal/gj.

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in the Chilean side of the Isla Grande de Tierra del Fuego (Klepeis, 1994) indicates the sinistral strike slip since the Cretaceous (Grunow *et al*., 1991). The mechanism of regional deformation has generated associated topographic alignments with offsets in the central region of the Magallanes Strait, providing evidence of Holocene activity (Winslow, 1982, 1983).

Schwartz *et al*. (2002) described two fault sections, one on the south shore of Fagnano Lake and the other in the San Pablo River. In Fagnano Lake, a quite degraded scarp has been observed, with a height varying between 0.50 and 1 m. The downfaulted block has dead trees, which are still possible to see standing in this place as the consequence of floods caused by the seiche associated with the 1949 earthquakes. In the San Pablo river, about 30 km from the locality of Tolhuin, the scarp is 5 to 11 m, with an elevated block to the north that exposes Quaternary glaciofluvial deposits and the formation of successive terrace levels (Schwartz *et al*., 2002). Schwartz *et al*. (2001) identified *en échelon* tensional cracks, coaxial grabens and sags. The fault crosses peatlands; in addition an older scarp than that one of the 1949 earthquake activity can be observed to the east of the Fagnano Lake. The stratigraphic evidence associated to a secondary fault has led to the interpretation of possible three seismic events during the last 8 ka (Schwartz *et al*., 2002) with a recurrence interval of 2–2.7 ka. Observations by Costa *et al*. (2006) are consistent, indicating a rupture that must have occurred in at least two pre-1949 events during the last 8 ka. These authors considered that, east of Fagnano Lake, the horizontal component of the 1949 rupture does not exceed 4 m and is probably lower than 0.4 m, which is consistent with the kinematics of a local releasing bend, or at the end of a strike–slip rupture zone.

2.1.1. Geomorphic evidence

Some geomorphical features along the MF fault are analysed in this study including linear valleys, offset or deflected streams, shutter ridges, sag ponds, and pressure ridges, providing a tool for the identification of Quaternary tectonic activity. We note that several drainage anomalies can be followed all the way along the fault trace, although big rivers like Lainez and Irigoyen rivers cut across the fault scarp rather easily (Fig. 2a). A narrow linear valley running to the east is well developed in the proximity of Fagnano Lake and the locality of Tolhuin, near the mouth of the Turbio River (Figs. 2b and 3a). Upstream, this river flows in a SW orientation but it is diverted to the west when merging the MF fault scarp. We consider that tectonic uplift rates must be faster than linear erosion rate by the river flow. According to Coronato *et al*. (2002), this diversion must have occurred during the late glacial period sometime after 12 ka.

The Turbio River flowed into the Atlantic Ocean before being diverted into Fagnano Lake by the MF fault scarp. Coronato *et al*. (2002) identified a tectonic activity in structures controlling the glacial carving. However, small rivers exhibit much more subtle topographic modifications than the larger ones as for example, the change of incision depth along the river course. Another feature corresponds to the change of the river pattern (from anastomosing to meandering) or in the alluvial plain width, which would indicate uplift or sagging (Audemard, 1999). A quick uplift may also disconnect a stream from its headwaters, implying that tectonic uplift rates are faster than stream power of erosion (Fig. 2b). This situation is observed along the fault trace between the Lainez River and its tributaries. Another evidence of faster tectonic uplift in the area is the presence of truncated meanders and wind gaps across the scarp fault, with abandoned fluvial valleys without a river draining to them (Fig. 3b,c).

Several rivers, that leave the foothills unit making orthogonally their traces with respect to the main river, are gathered in the footwall in a bigger single river downstream, showing a ‘broom-shaped’ pattern as defined by Audemard (1999). This pattern shows sagging close to the scarp (Fig. 4a).

In addition, some sag ponds or small and closed tectonic depressions are recognized along the subsiding bedrock and glacial plains, with a W–E trending orientation. They are developed by the strike–slip motion of the MF Fault, and are drained by subsurface seepages, since they have not inlet or outlet drainage. Also observed, are dammed channels upstream of the scarp indicating that erosion is less important than recent tectonic activity. Several peats are observed in the downthrown block and a rectilinear trace cutting the *Nothofagus* woods or with aligned trees is clearly visible, especially from aerial views (Figs. 3c and 4b).

East of Fagnano Lake is placed Negro Lake that constitutes a pull-apart basin developed between two overlapping segments of the MF fault, with an average width of over 1.5 km (Fig. 2a).

The alternating exposure of scarps to the north and south, the offset streams and ridges, sag ponds, rhombic depressions and pressure ridges are consistent geomorphological evidence for strike–slip faults.

2.2. Volcanism

The Andean volcanism in the studied area is segmented in two regions according to its relative location with respect to the triple junction between the Nazca, Antarctic and South America plates at about 48°S. The South Volcanic Zone (SVZ) is located to the north of this triple junction, and the Austral Volcanic Zone (AVZ) is located south of it (Gonzalez-Ferrán, 1995; Stern, 2004) (Fig. 1a). The eruptive centres in both segments correspond to young Pliocene, Pleistocene and Holocene (less than 2 Ma) huge

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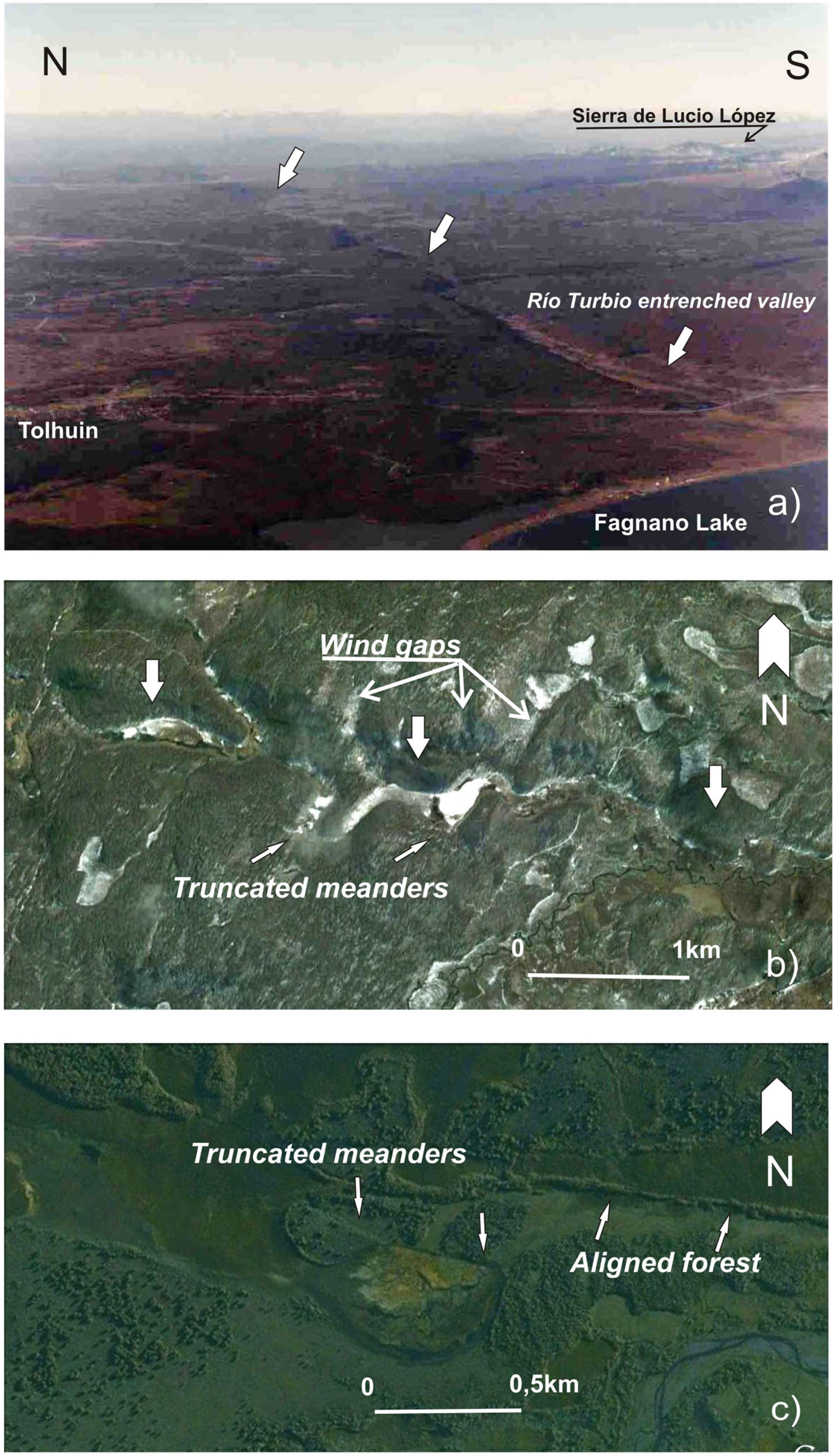

Figure 3. (a) Aerial oblique view to the fault trace (photo taken by Schiavini); (b) Google Earth image of the central portion of MF fault showing wind gaps and truncated meanders; (c) truncated alluvial plain and meander and aligned forest. This figure is available in colour online at wileyonlinelibrary.com/journal/gj.

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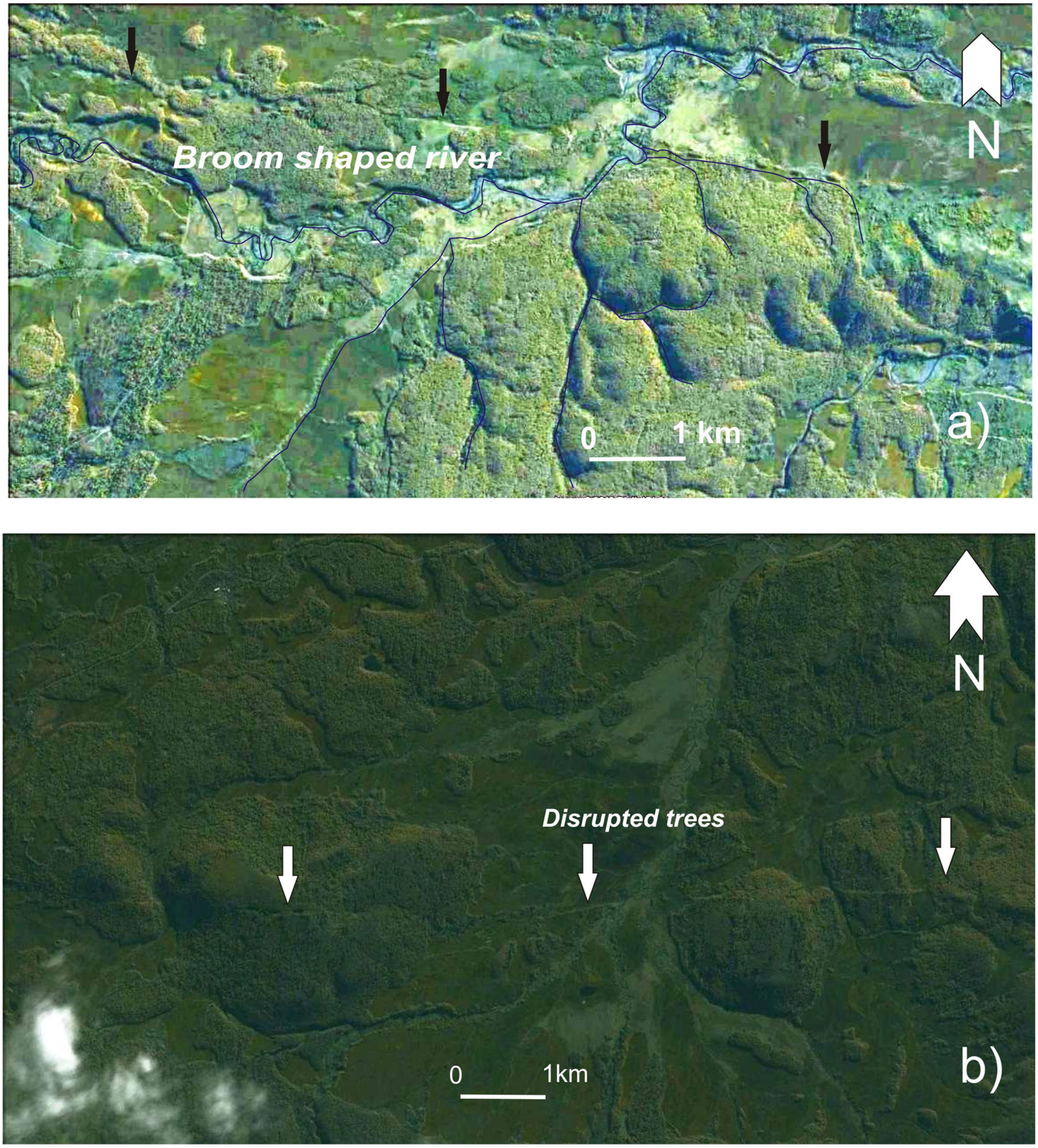

Figure 4. (a) Broom-shaped drainage in the footwall of the fault; (b) Google Earth image showing the MF fault cutting across the *Nothofagus* wood. This figure is available in colour online at wileyonlinelibrary.com/journal/gj.

strato-volcanoes, andesite–dacite calderas and basalt plateaus (Sruoga *et al*., 1993). They are related to the last great uplifting and faulting Andean events.

In the South Volcanic Zone (SVZ), which begins at 33°S and extends to the south, a Plio-Quaternary volcanism developed in two tectonic settings generated by the subduction of the Nazca Plate beneath South America: the present day volcanic arc, which is located along the Andean Cordillera and the back-arc volcanism, more to the east, outside the main Andean region. Thus, Quaternary volcanoes are not

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restricted to the Andes, but extend also, over the Andean backarc region in the Argentinean province of Santa Cruz (Fig. 1a). The southern segment between 37°S and 45°S has the highest volcanic activity records at present. Overall the volcanoes in this region are not characterized by great magnitude explosions, with the exception of the Puyehue and Hudson volcanoes, which are located in the Chilean Andean side (Sruoga and Schonwandt, 2004).

The chain of volcanoes in the AVZ comprises a length of about 700 km in the southern end of Argentina and Chile. They are characterized by adakitic composition (Ramos *et al*., 2004; Stern, 2004). The magma genesis of these adakitic volcanoes is attributed to dehydration of subducting young and hot Antarctic oceanic crust and subsequent partial melting in the mantle (Defant and Drummond, 1990). The AVZ includes a small number of stratovolcanoes and a small complex of Holocene domes and flows in Cook Island, which is the southernmost Andean volcanic centre (Stern *et al*., 1976, 1984; Puig *et al*., 1984; Suárez *et al*., 1985; Harambour, 1988; Martinic 1988; Heusser 1990; Stern and Kilian, 1996).

From the geologic hazard view point, the volcanoes in the AVZ are located far away from densely populated centres. It is worth noting that these volcanoes are not continuously monitored for activity. The historic record of the AVZ includes the eruption of the Reclús Volcano in 1908 and of the Burney Volcano in 1910. In addition, tephrochronology studies show four large explosive eruptions during the Holocene (Stern, 1990, 1992, 2002; Kilian *et al*., 2003).

2.2.1. Andean SVZ recent activity

Interferometric Synthetic Aperture Radar (InSAR) studies from Pritchard and Simons (2004) have revealed recent activity in Holocene volcanoes. These authors found unusual higher rates corresponding to surface deformation in Cerro Hudson and Cordon Caulle. They attributed the measurements to a volume change produced by injection of magmatic fluids or melting in the 5 to 8 km deep upper crust. We describe in more detail the volcanic and seismic activity observed in the last years around volcanoes Puyehue, Chaitén and Hudson (Fig. 1a).

The **Puyehue** Volcano is located in southern Chile (SVZ) at 41°S and 72°W (Fig. 1a). It consists of a volcanic complex aligned into a NW–SE trending fissure system with the oldest eruptive activity recorded 400 000 ya. In the last 100 000 year, Puyehue exhibited a preponderance of siliceous magmas, which are well correlated with the most explosive events (Sruoga *et al*., 2011). Historic eruptions in the last 500 years include the events in 1759, 1893, 1921, 1960 and 1990. In this century, a recent eruption that began on 4 June 2011 was preceded by a gradual increase in the seismic activity (60 to 230 earthquakes in an hour) up to the explosion (Sruoga *et al*., 2011).

The **Chaitén** Volcano is located in southern Chile (SVZ) at 43°S and 72° 35′W (Fig. 1a). According to Lara (2009) its background geology is poorly known. A preliminary study by Moreno (1995) is mainly based on aerial photographs. The last known main eruption occurred at *ca.* 9.4 ka BP (Naranjo and Stern, 2004), which formed a small caldera of 3 km in diameter and the ejection of pyroclastic flows and ash falls containing rhyolite pumice (Lara, 2009). On 2 May 2008 a Plinian eruption began and a dome may have occurred as observed on 10 May 2008 (Lara, 2009).

The **Hudson** Volcano is located in the southernmost SVZ of the Andean Cordillera at 45°54′S and 72°58′W at about 280 km east of the Nazca–Antarctic–South American Plate triple junction, where the Chile spreading ridge enters the Chilean trench (Gutiérrez *et al*., 2005) (Fig. 1a). This volcano lies on the boundary of a volcanic gap separating the Southern (SVZ) from the Austral Volcanic Zone (AVZ), which has been interpreted as the result of a slab window (Gutiérrez *et al*., 2005). Although its low relief of about 900 m above sea level, this stratovolcano is characterized by a volcano-tectonic depression of almost 10 km wide, set in a morphological high of the Patagonian batholith and having a circular shape (Gutiérrez *et al*., 2005).

Two major Plinian and Subplinian eruptions have been recorded in 1971 and 1991, respectively. The latter is considered one of the largest eruptions in Chile in recent times, which mainly affected Patagonia in the Argentina side. Interestingly, on 25 October 2011, the Hudson Volcano increased its activity after a seismic swarm that began at about 19 h earlier (Romero, 2012).

2.2.2. Andean AVZ

The Andean AVZ is composed of six Holocene eruptive centres from north to south: Lautaro, Viedma, Aguilera, Reclús, Burney and Cook volcanoes (Fig. 1a).

Lautaro Volcano is the northernmost volcano of the AVZ (Fig. 1a). It stands on top of 2400-m-high glacial plateau, recognized as the Southern Patagonian ice field (Orihashi *et al*., 2004). Because the volcano is covered with a thick ice layer and powerfully eroded by glacial processes, its volcanic structure is entirely unknown. Reports of several eruptions, 1897 and at least one in 1959 (Martinic, 1988, González-Ferrán, 1995) as well as the presence of tephra and ash deposits on the ice surface of Viedma and O'Higgins glaciers (Kilian, 1990; Motoki *et al*., 2003) show that Lautaro Volcano is one of the most active stratovolcanoes in the AVZ (Orihashi *et al*., 2004).

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Viedma Volcano was active during the Holocene (González-Ferrán, 1995; Stern, 2004) (Fig. 1a). It is located in the Southern Continental Patagonian Ice Field. The volcano is 1500 m high above sea level and exposes only part of its glacier edifice. Kilian (1990) described that the latest known eruption occurred from a subglacial vent in 1988. This event deposited ash and pumice on the glaciers, and the deposits were then re-mobilized and flowed into the Viedma Lake as a lahar. Characteristics of the edifice of the Viedma volcano have not been well-documented yet, due to the inaccessibility and weather conditions (Kobayashi *et al*., 2010).

Aguilera Volcano is a dacitic stratovolcano located in the Southern Continental Patagonian Ice Field, to the west of Argentino Lake (Fig. 1a). Although geological history is not well known in this area, ^{14}C ages on organic material in soil and sediment samples above and below tephra layers constrain a possible eruption at 3000 ± 100 years BP. A volume of tephra between 4 and 9 km^3 has been estimated for that eruption (Stern, 2008).

Reclús Volcano (Fig. 1a) is located in the Andean Austral Volcanic Zone, at 50° 57′ 50″S and 73° 35′ 05″W (Stern *et al*., 1976, 1984, 2007; Harambour, 1988; Stern and Kilian, 1996; Stern, 2004). It produced a large (>1 km^3) explosive eruption 12 685 ± 260 ^{14}C yr BP (Stern, 1990, 1992, 2008) during the transition between the Last Glacial Maximum (LGM) and the Holocene. Distal tephra layers resulting from this eruption are exposed at many sites along the shores of the Magallanes Strait and Inútil Bay (Stern *et al*., 2011). It has a height of 1000 m and consists of a dacitic pyroclastic cone with a crater of about 1 km in diameter. This volcano is being eroded by the Amalia Glacier, which drains the Patagonian ice field. The last known historical activity seems to have occurred in 1908. A major seismic activity has been recorded in the Reclus volcano and other seismicity in the Burney volcano, as we described below.

Mount Burney Volcano is the southernmost stratovolcano of the Southern Andean arc located in the Chilean side, about 200 km to the northwest of Punta Arenas (Fig. 1a). Its peak reaches 1758 m in height hosting permanent snow and ice. Mount Burney was built on the western edge of a 6-km-wide caldera partially filled by pyroclastic flows that were not affected by glaciation. Andesitic–dacitic flows and pyroclastic material have originated from its flank fissures. The collapse of the cone produced a large debris avalanche that travelled to the SSW. The tephra layers observed in cores indicate that Mount Burney had four small and two large Plinian eruptions during the Holocene (Kilian *et al*., 2003). The small eruptions produced tephra layers that are restricted to the Andean area just southeast of the Mt Burney Volcano. On the eastern and southeastern slopes of Mt Burney, tephra deposits are up to >5-m thick with pumices up to >5 cm in diameter at a distance of 2 to 3 km from the caldera. These tephra deposits continue towards the southeast. Kilian *et al*. (2003) suggested that these are the products of the 4254 ± 120 cal. yr BP eruption of Mt Burney Volcano. In 1910 it was reported the only known historical eruption in recent times.

Cook o Fueguino Volcano: Located on a peninsula to the southeast of the Cook Island (Fig. 1a), this volcanic group corresponds to the Scotia Plate, south of the Magallanes–Fagnano fault (Stern, 2004). It consists of andesitic lava domes that developed columnar jointing and a 150-m-high pyroclastic cone emplaced along N–S strike–slip faults. They are not affected by glacial action that eroded the underlying plutonic rocks. According to those authors, it is the southernmost Holocene volcano in the Andes. One of the cones located south of the island, has a 150-m-wide crater with a small lake inside. Reports from sailors indicated an eruption activity in 1712, with a dense ash column. A later eruption was observed with gases and incandescent emissions in 1820.

2.2.3. Extra-Andean Patagonia

2.2.3.1. Pali Aike field. Many aligned NNW trending volcanic manifestations are found along distensive fractures to the west of Río Gallegos, between 50°S and 52°S, which belong to the Pali-Aike tectono-volcanic belt. This is considered a piece of Pliocene–Holocene (3.8 to 0.01 Ma) back-arc volcanism (Corbella, 2002) and the southernmost occurrence of the Cenozoic back-arc Patagonian Plateau Lavas (D'Orazio *et al*., 2000) (Fig. 1a, b). Corbella (2002) described a volcanic field with an alignment of volcanoes throughout NW Jurassic extensional faults. Some of these faults were active during the Tertiary, ceasing activity during the Late Tertiary. These structures reactivated towards the end of the Pliocene, enabling their opening by transtensive movements and allowing extrusion of basaltic magmas. Another fracture system located to the ESE of the Laguna Azul (Fig. 1c) shows lava flow, presumably of Holocene age, diverted towards a graben bounded by two ENE parallel faults, which were activated when the eruption occurred and thus, would indicate recent movements. These two principal fracture systems play a controlling role of the emission of lavas and the close alignment of the scoria and ash cones and maars (Coronato *et al*., 2008). Holocene volcano-tectonic activity was concentrated in the SW, where most of the youngest lavas reached the surface and two parallel ENE fractures limit a 700-m wide graben. The diversion of the lava-flows towards the graben provides evidence for neotectonic activity (Coronato *et al*., 2008).

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2.3. *Crustal seismicity*

2.3.1. *Historical and contemporary seismicity in the Magallanes–Fagnano fault area*

The largest instrumentally recorded seismicity in the region of Tierra del Fuego has occurred in 1949 (Fig. 5a,b). On December 17 of that year two large earthquakes occurred the same day at 06 h 53 min 30s and 15 h 07 min 55 s GMT time. The magnitude of these events was estimated by Lomnitz (1970) from seismic intensity values as M = 7.5 and even higher according to Pasadena, USA station, which reported Ms = 7.8 for both shocks (Goodstein *et al.*, 1980). Comparatively, we observe larger P-wave amplitudes for the mainshock than for the 8-h earlier foreshock in the vertical-component seismograms recorded in Weston, Massachusetts (USA) at 9500 km epicentral distance (Fig. 5b). Thus, we provide evidence for a larger energy release during the second earthquake on 17 December 1949.

The two large earthquakes in 1949 produced several aftershocks in the following months that were felt in Cape Froward and Punta Arenas, including one large aftershock that occurred on 30 January 1950. Historical reports indicate large wave events in the localities of Porvenir and Almirantazgo. Effects of the 1949 earthquakes caused dramatic changes in the water level of Lake Fagnano and landslides in the western coast of Tierra del Fuego as well as three deaths in San Nicolás Bay (Cisternas and Vera, 2008). Evidence for strike–slip motion in 1949 in the MF

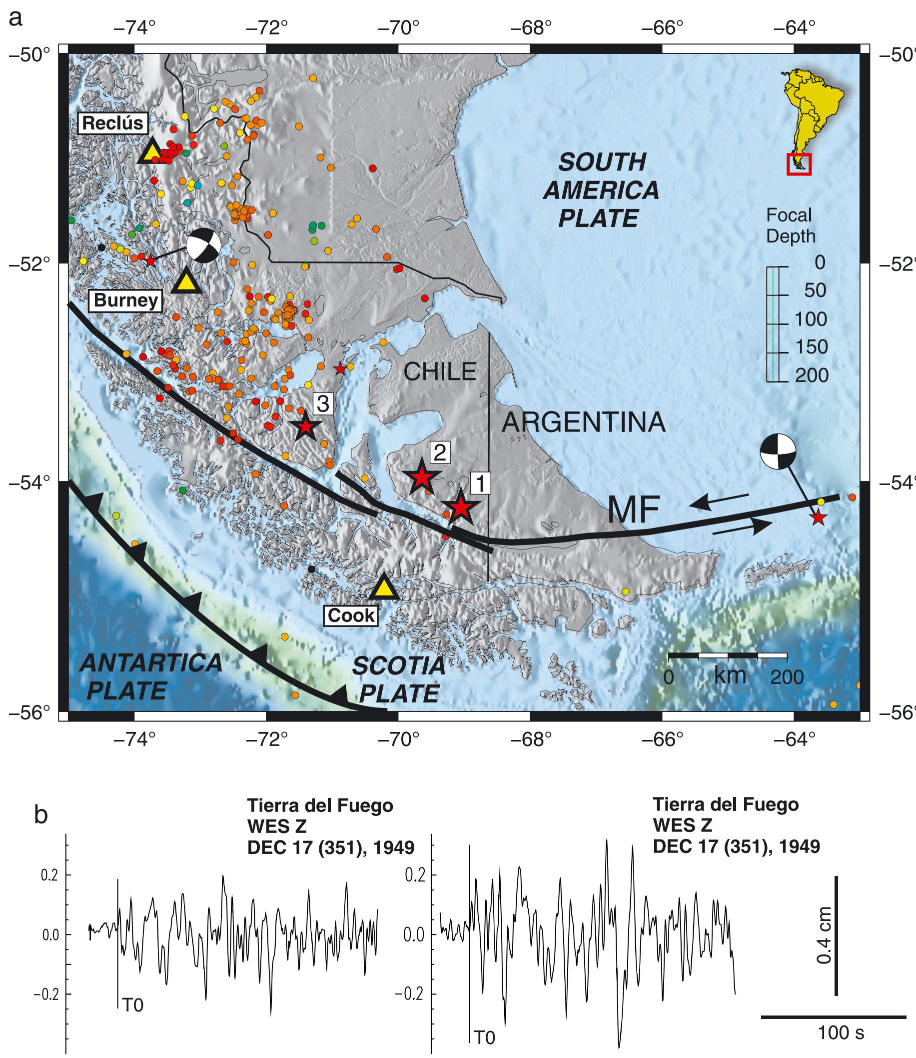

Figure 5. (a) Epicentral location of the largest instrumentally recorded earthquakes on 17 December 1949 numbered as (1) and (2) (Jaschek *et al.*, 1982). Also shown is the January 1950 (3) aftershock. Circles represent seismicity from local deployments in 1997–1998 studied by Adaros (2003) and the USGS (USA) for this region. Focal mechanisms for earthquakes in 1970 and 1972 are from Forsyth (1975) and Pelayo and Wiens (1989), respectively. (b). Digitized vertical seismograms recorded by a Benioff instrument at the seismic station Weston (Massachusetts, USA). Note that the second event (mainshock) exhibits larger P-wave amplitude than the 8-h earlier foreshock, probably because of its higher magnitude. This figure is available in colour online at wileyonlinelibrary.com/journal/gj.

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fault has been recorded in the continent in buried normal faults located at a distance larger than 300 km in Bustamante and Dungeness Points (González Bonorino *et al*., 2012—Fig. 1a).

Using seismic data from stations in Buenos Aires, Chile and Bolivia it has been possible to relatively relocate the 1949 foreshock and mainshock (González Bonorino *et al*., 2012) confirming results from Jaschek *et al*. (1982) for this sequence. These authors have determined an epicentre at 54.24°S and 69.03°W for the foreshock (in the NW of the MF fault zone) and 53.89°S and 69.67°W for the mainshock (in the SE of the MF fault zone). The largest aftershock, which occurred 45 days later on 30 January 1950 had an epicentre at 53.50°S and 71.50°W at a distance of 132 km from the 1949 mainshock and along an azimuthal direction to the NW of 293°. Taken together the epicentral locations from the main earthquake activity in December 1949–January 1950 indicate a rupture length of more than 300 km along the MF fault. This is also consistent with the seismic location and left lateral strike–slip focal mechanisms of two moderate (Mb ~5.5) earthquakes that occurred in 1970 and 1972 (Forsyth, 1975) as shown in Figure 5a,b. An association of current seismicity reported by the USGS with the active MF fault trace (Fig. 5a) is difficult, mainly because of seismic mislocations caused by the scarcity of local seismic stations in the region. We note, however, that this modern earthquake activity reported in catalogues is large-sized enough to be detected by global seismic networks.

The 1949 earthquake epicentral area might have caused previous large-sized seismicity. According to Lomnitz (1970) and Martinic (1988) one seismic event occurred on 2 February 1879 at 3 h 30 min with a magnitude of 7 to 7.5 and seismic Mercalli Modified intensities as high as VIII in Tierra del Fuego and VII in Punta Arenas. These estimations are based on the reports from Thomas Bridges (1879), an Anglican missionary, the first European settler in Tierra del Fuego. Unfortunately there are not seismic records available to study this earthquake. Also mentioned in Perucca and Moreiras (2009), it is an ancient earthquake that occurred before the European colonization according to a Yaghan (indigenous Fuegian) legend described in Bridges (2000).

Costa *et al*. (2006) identified a natural trench where the San Pablo River crosses a secondary fault trace of the main Fagnano fault. In this region, their palaeoseismologic studies evidence probably three or four seismic events in the last 8 ka. Thus, a maximum average recurrence interval of 2 ka was estimated for earthquake ruptures, which might have reached to the surface.

Other palaeoseismic studies have shown a recurrence interval of 750 years for a M = 7.8 earthquake (Smalley *et al*., 2003). Waldmann (2008) calculated a recurrence rate of 800–1000 years for slumps located in Lake Fagnano, as being due to high-intensity seismic activity on the MF fault.

One more estimation from González Bonorino *et al*. (2012) have indicated that strandplain deposits have been affected by MF faulting at least six times, with ages between 0.9 and 6.4 ka BP, giving an average recurrence rate of about 1 ka. Thus, all of these observations are consistent providing evidence for a high potential of large earthquake generation in this region.

2.3.2. *Seismicity in volcanic areas*

A relationship between seismic swarms, volcanic locations and large megathrust earthquakes has been explored in only a few cases of southern Patagonia with the main purpose to gain a better understanding of their basic interactions (Barrientos, 1994; Lara *et al*., 2004, 2006; Barrientos *et al*., 2007; Comte *et al*., 2007; Holtkamp *et al*., 2011).

In 2007, a Mw 6.2 crustal earthquake showing a strike–slip focal mechanism and thousands of aftershocks took place in the Aisén Fjord causing ten fatalities, and rock falls, rock slides and rock avalanches as a result of the sudden motion on steep fjord slopes (Barrientos *et al*., 2007; Comte *et al*., 2007; Sepúlveda and Serey, 2009). The seismicity was associated with the Liquiñe Ofqui strike–slip fault, although its possible association with a volcanic event is not clearly understood (Holtkamp *et al*., 2011). A similar episode in this region has occurred in 1991, recording a basaltic eruption of the Hudson Volcano and seismicity recorded by the global seismic network.

In 2008, seismicity around the Chaitén volcano and also along a segment located 100 km north of this volcano in the north-trending right-lateral strike–slip Liquiñe–Ofqui fault were related in time with the eruption of May of that year. The attempts to identify if the crustal seismicity was related to the eruption or a tectonic event in the transform fault were unsuccessful. Eruptions of the Chaitén Volcano are infrequent in comparison to other volcanoes in the region.

On 4 June 2011, the Puyehue Volcano in the Cordon Caulle started showing activity. Figure 6a shows seismic activity detected by the Argentinean (INPRES) permanent seismic network. The international monitoring seismic station PLCA at Flores Pass in the province of Rio Negro (Argentina) detected several earthquakes from that cluster at an epicentral distance of about 120 km. It also showed an increase in seismic occurrence after 13 h and before 20 h GMT time (see Fig. 6b). More than 100 earthquakes were recorded although only 48 have reasonable locations in the first days after the Puyehue eruptive activity. Epicentral locations are aligned along a NE–SW epicentral distribution. Some studies have postulated the relationship of this volcanic and earthquake activity to the occurrence of the large Mw 8.8 Maule, Chile megathrust 2010 earthquake. A similar phenomenon was observed in this region

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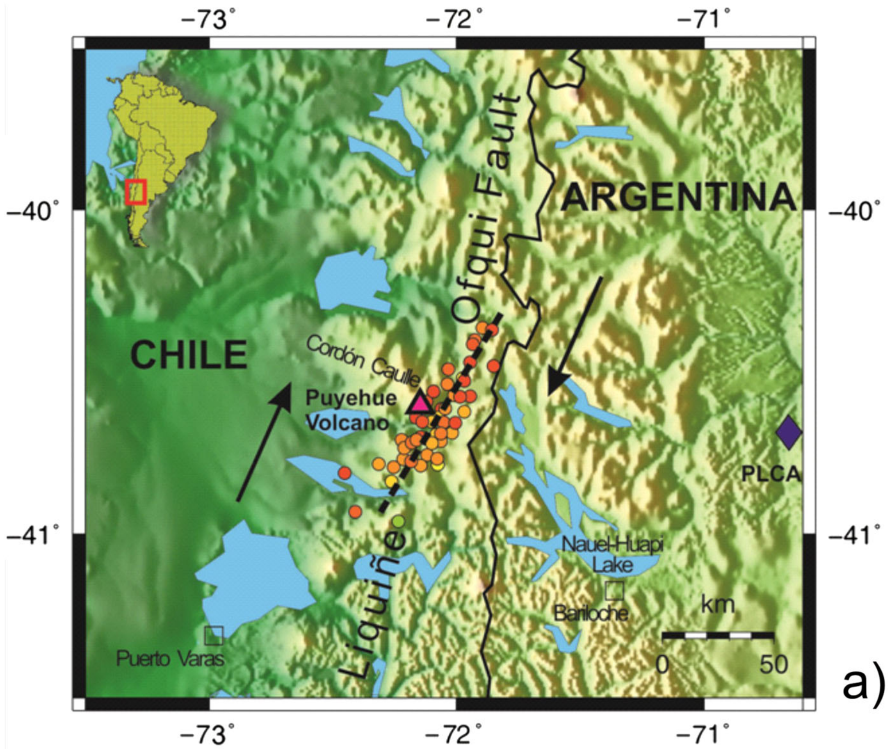

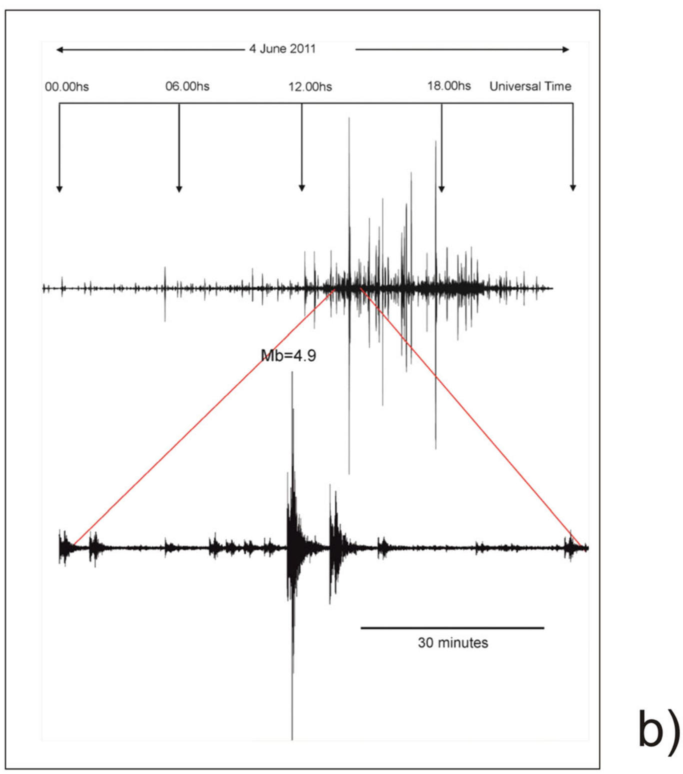

Figure 6. (a) Seismicity recorded near the Puyehue Volcano in 2011 (INPRES, 2014) and the NE–SW trending Liquiñe Ofqui dextral strike–slip fault system from Lara *et al*. (2006). (b). Example of earthquake activity detected by the vertical component of the seismic broadband seismic station PLCA (Paso Flores) from the GSN international seismic network shown in (a). Note the increased seismic activity during 4 June 2011, which is coincident with the eruptive activity of the Puyehue volcano (see the text for more details). This figure is available in colour online at wileyonlinelibrary.com/journal/gj.

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after the 22 May 1960 earthquake, known as the largest instrumentally recorded subduction earthquake on Earth (Cifuentes, 1989; Han *et al*., 2013; USGS, 2014). The 1960 swarm, however, had a preferential distribution on a NW–SE pattern and concurrent volcanic activity in the Cordon Caulle, which is located next to Puyehue Volcano.

It is worth noting that the volcanic activity in the SVZ and AVZ correlates with regions identified with an anomalous activity of higher surface deformation evidenced by InSAR data. Thus, volcanoes Hudson, Caulle and Chaitén exhibit inflation/deflation in comparison with more than 27 Holocene active volcanoes in the southern Andes (Pritchard and Simons, 2004; Holtkamp *et al*., 2011) but this deformation occur frequently without eruption and are usually short-lived. According to these authors, the earthquake and volcanic activity may be triggered by the occurrence of large megathrust events, which produce motion along regional structures like the Liquiñe–Ofqui continental fault. Although more studies on the surface deformation and evaluation of net uplift are still needed, the MF fault might pose an additional hazard on the potential volcanic activity in nearby active volcanoes.

Shallow seismicity around the AVZ has been also observed around the Reclús volcano by Adaros (2003) using broadband seismic stations in the Seismic Experiment in Patagonia and Antarctic (SEPA) during two years (Fig. 5a). InSAR surveys predict activity in this and the rest of the volcanoes in the AVZ but detailed studies linking tectonic or swarm seismicity with volcanic activity has not been explored in detail yet.

3. CONCLUDING REMARKS

Very little is known about seismic and volcanic activity in the southernmost part of South America. In this paper the main features of the Magallanes–Fagnano left lateral fault system in the transform boundary between South America and Scotia plates were discussed using geomorphologic and available earthquake and volcanic studies. Some examples from the South (SVZ) and Austral (AVZ) Andean volcanic zones were also examined showing that recent volcanic activity may be associated with crustal seismicity. In comparison with other areas, the volcanoes of AVZ do not pose an important threat to human activities, but there is substantial geological evidence pointing to the significance of volcanism in recent times. This risk probably is restricted to the damage arising from ash and the problem created for air traffic. The presence of strong winds over all of western Argentina will also facilitate the spread of fine pyroclastic material expelled by the volcanoes over wide, distant areas in a short time, as happened during the Hudson, Chaitén and Puyehue volcanoes in recent past years.

Although no historical reports exist, the active region around the MF fault system may be also capable of generating seismicity related to active volcanism besides the large crustal earthquakes. This poses an additional source for geological hazards in this region.

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