PALEOSEISMIC OBSERVATIONS OF AN ONSHORE TRANSFORM BOUNDARY: THE MAGALLANES-FAGNANO FAULT, TIERRA DEL FUEGO, ARGENTINA

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RESUMEN: *Observaciones paleosismológicas en un margen transformante en el continente: La falla Magallanes-Fagnano, Tierra del Fuego, Argentina.*
Se presenta información sobre las evidencias geomorfológicas y paleosísmicas observadas al este del lago Fagnano, relacionadas con dos terremotos de Ms 7,8, que ocurrieron en Tierra del Fuego el 17 de diciembre de 1949. Se efectuaron relevamientos en las escarpas observadas en los alrededores de Tolhuin y Estancia La Correntina-Río San Pablo. En este último sitio, se excavó una trinchera en un trazo secundario de la falla Magallanes-Fagnano con el propósito de analizar el registro paleosísmico de esta estructura. Con el apoyo de dataciones radiocarbónicas se reconoció la estratigrafía correspondiente a los últimos 9 ka, interpretándose por lo menos dos eventos sísmicos con rupturas superficiales previos al sismo de 1949 en este trazo de la falla. Se reconocieron escarpas asociadas de hasta 11 m de altura en depósitos atribuibles al Pleistoceno superior-Holoceno (?), pero la componente vertical observada o reportada de los sismos de 1949 nunca fue mayor de 1 m. Ello sugiere la participación en su génesis de varios eventos previos durante el Cuaternario. A lo largo del sector investigado, la componente horizontal de la ruptura de 1949 no ha sido mayor de 4 m y probablemente menor de 0,4 m, lo cual puede ser consistente con la localización de este sector de la estructura en una zona transtensiva, o en el extremo de una zona de ruptura trancurrente.

Palabras clave: *Falla Magallanes-Fagnano, Paleosismología, Tierra del Fuego, Terremotos 1949.*

ABSTRACT
We present preliminary information on the geomorphologic features and paleoseismic record associated with the ruptures of two Ms 7.8 earthquakes that struck Tierra del Fuego and the southernmost continental margin of South America on December 17, 1949. The fault scarp was surveyed in several places east of Lago Fagnano and a trench across a secondary fault trace of the Magallanes-Fagnano fault `was excavated at the Río San Pablo. The observed deformation in a 9 kyr-old peat bog sequence suggests evidence for two, and possibly three pre-1949 paleoearthquakes is preserved in the stratigraphy. The scarp reaches heights up to 11 m in late Pleistocene-Holocene(?) deposits, but the vertical component of the 1949 events was always less than ~1 m. This observation also argues for the occurrence of previous events during the Quaternary. Along the part of the fault we investigated east of Lago Fagnano, the horizontal component of the 1949 rupture does not exceed 4 m and is likely 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.

Keywords: *Magallanes-Fagnano fault, Paleoseismology, Tierra del Fuego, 1949 earthquakes.*

INTRODUCTION

On 17 December 1949, two Ms 7.8 earthquakes (Mercali Intensity VIII) struck the Island of Tierra del Fuego and the southern end of South America within a time span of nine hours. Damage and casualties were slight due to the sparse population and lack of urban development existing in the region at that time. Based on the surface wave magnitudes of these events, they are among the largest instrumentally recorded earthquakes with onshore surface rupture in South America. The ruptures reported in Tierra del Fuego, are located along the Magallanes-Fagnano fault. This structure represents the on-shore transform boundary between the South America and Scotia plates (Fig. 1), where sinistral-normal slip prevails, as indicated by focal mechanisms, seismic reflection data, GPS and field observations (Dalziel *et al.* 1975, Bruhn *et al.* 1976, Dalziel 1989, Pelayo and Weins 1989, Klepeis 1994, Lodolo *et al.* 2002, 2003, Smalley *et al.* 2003). Morphologies related to Holocene faulting on this fault system have also been described on the Chilean side of

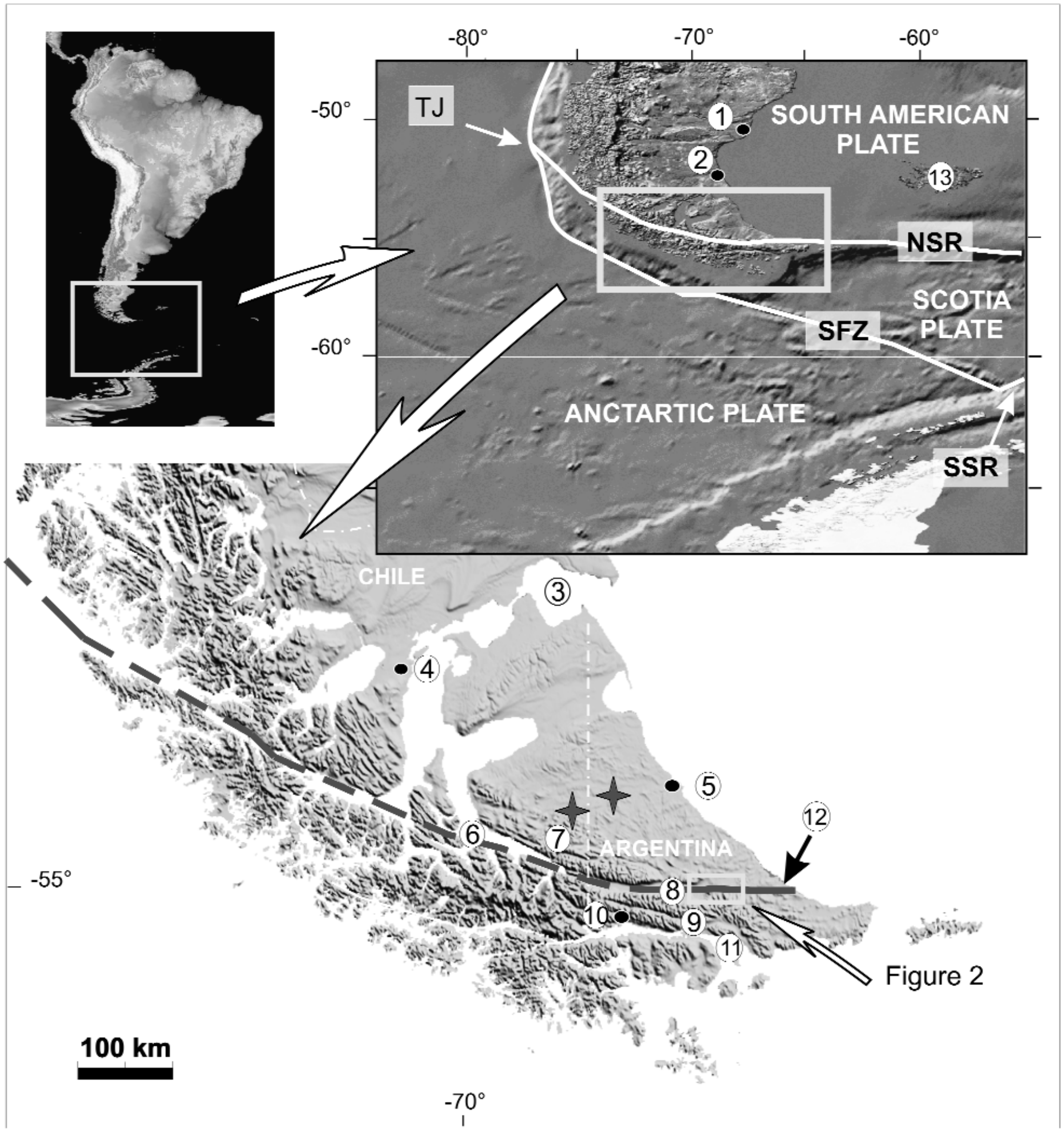


Figure 1: Regional tectonic setting of the Tierra del Fuego Island with the location of the main plates. NSR: North Scotia Ridge; SSR: South Scotia Ridge; SFZ: Schackleton Fracture Zone, TJ: Triple Junction. The red stars in the inset below point out the epicenters of the 1949 events according to Forsyth (1975), Winslow (1981) and Pelayo and Wiens (1989), whereas the Magallanes-Fagnano fault trace is indicated in red. Location index: 1. San Julián, 2. Río Gallegos, 3. Magellan Strait, 4. Punta Arenas, 5. Río Grande, 6. Seno Almirantazgo, 7. Lago Deseado, 8. Lago Fagnano, 9. Lasifashaj Valley, 10. Ushuaia, 11. Beagle Channel, 12. Río Irigoyen-Cape Leticia area, 13. Malvinas Islands.

the Island of Tierra del Fuego. (Winslow 1982, Winslow and Prieto 1991).

Although coseismic surface faulting was mentioned in many papers (Dalziel 1989, Klepeis 1994, Winslow 1982, Winslow and Prieto 1991, Lodolo *et al.* 2002) and reported by locals (J. Caibul, A. Goodall, R. Sutherland, pers. comm.) little is known on the characteristics of the faulting or the paleoseismic record of this plate-boundary fault. In this paper we report on initial field observations and results east of Lago Fagnano, where evidence of the 1949 ruptures is preserved in the morphology and Quaternary deposits.

TECTONIC AND GEOLOGIC SETTING

The study zone is located in the northern boundary of the Scotia plate (Fig 1). This plate is a principal part of the Scotia Arc, which is principally composed of young oceanic crust. The Scotia Arc formed over the past 30 myr as a response to changes in the relative motion between the South America and Antarctic plates (Barker *et al.* 1991).

The Scotia Plate is bounded by transform faults on the north and south that define the mostly submarine North Scotia Ridge (Scotia-South America plate boundary) and South Scotia Ridge (Scotia-Antarctic plate boundary) respectively (British Antarctic Survey 1985) (Fig. 1). The North and South Scotia Ridges are the sites of a small number of earthquakes with east-west oriented nodal planes and left-lateral fault-plane solutions (Forsyth 1975, Pelayo and Wiens 1989, Thomas *et al.* 2003).

The direction of the current relative motion between the South America and Antarctica plates is approximately parallel to the northern and southern boundaries of the Scotia plate. Relative plate velocity varies along the plate margins, and occurs at a rate of 20-24 $mm.yr^{-1}$ along the portion of the Antarctic-South America plate boundary where the Antarctic plate subducts beneath the western margin of the South America plate between the Chile rise (46° 30'S) and the Magellan Strait (52°S) (Chase 1978, Minster and Jordan 1978, Dalziel 1989). The South America and Antarctic plates also interact along the Schackleton Fracture Zone (SFZ), a small strike-slip interplate boundary (Fig 1).

The island of Tierra del Fuego can be divided in two structural domains (Klepeis 1994; Kraemer 2003; Ghiglione and Cristallini in press): A northern, thin-skinned domain and a southern basement-domain located in the Scotia plate side. It has been proposed that the development of the Fueguian Andes is the result from thrusting episodes from the late Cretaceous to the Oligocene (Caminos *et al.* 1981, Ghiglione *et al.* 2002, Kraemer 2003, Ghiglione and Ramos, 2005).

Lithologic boundaries and older structures produced by previous episodes of subduction-related compressional tectonics now strike parallel to the active transform plate boundary, with many of these older faults being reactivated as strike-slip faults since Oligocene times (Winslow 1981, Klepeis 1994).

THE MAGALLANES FAGNANO FAULT SYSTEM

A western continuation of the North Scotia Ridge traverses the continental crust of the island of Tierra del Fuego as the Magallanes-Fagnano fault system (Winslow 1982, Dalziel 1989, Klepeis 1994, Olivero and Malumián 1999, Olivero and Martinioni 2001, Lodolo *et al.* 2002, 2003 among many others). In addition, several major sub-parallel faults, may accommodate part of the plate motion, but amount of partitioning of motion on these faults is unknown. As the Magallanes-Fagnano fault continues westward across Tierra del Fuego it returns to a subaqueous setting in Lago Fagnano, Seno Almirantazgo and the Straits of Magellan, ending as one limb of a complex, diffuse, unstable trench-trench-transform triple junction between the Antarctic, South America and Scotia plates (Forsythe 1975, Cunningham 1993).

The Magallanes-Fagnano fault can be traced along a distance ranging from 400 to 800 km according to different sources (Winslow 1982, Dalziel 1989, Klepeis 1994, Lodolo *et al.* 2002) and many authors report evidence for left-lateral offset along its trace. Lack of piercing points has hindered estimation of strike-slip displacements and displacement rates. According to Winslow (1982) the Magallanes-Fagnano fault apparently offsets the western margin of the Patagonian batholith by 80 km Klepeis (1994), however, claims that cumulative sinistral separation in the Mount Hope area is only 2-25 km and has shown that the Cenozoic strike-slip tectonics are more distributed in nature, involving other structures such as the Deseado Fault Zone.

According to Klepeis (1994) the kinematic conditions that led to the establishment of Magallanes-Fagnano fault as a major interplate structure, started with or even before the Oligocene birth of the Scotia plate. Wrench deformation has dominated ever since, and is structurally and temporally superimposed on the older deformation (Caminos *et al.* 1981, Ghiglione *et al.* 2002, Lodolo *et al.* 2002, 2003, Galeazzi 1996). In detail however, since the plate boundary does not follow a perfect small circle, there are segments that also exhibit extensional or compressional tectonics (Lodolo *et al.*, 2003). Transpres-sional convergence has been proposed for the central eastern part of the North Scotia Ridge (Pelayo and Wiens 1989, Bry *et al.* 2004) although sidescan sonar studies south of the Malvinas Islands indicate current motion is pure strike-slip and deformation associated with current motion is superimposed on evidence for earlier convergence (Cunningham *et al.* 1998).

Lodolo *et al.* (2003), Yagupsky *et al.* (2004) and Tassone *et al.* (2005) have seismically imaged a half-graben like structure offshore Tierra del Fuego interpreting the Magallanes-Fagnano fault zone to be composed by several segments in an echelon pattern along which pull-apart depocenters have formed. On the Atlantic coast the 5 km-wide Irigoyen pull-apart basin is emplaced along the plate boundary (Ghiglione and Ramos 2005). Furthermore, Lodolo *et al.* (2002) interpret the 102 x 2-11 km Fagnano depression that hosts Lago Fagnano as a pull-apart basin. West of Lago Fagnano, the plate boundary turns northwest through Seno Almirantazgo and the Straits of Magellan in a restraining bend geometry, although geological studies have proposed both transtensional and transpressional interpretations for development of the structures in this region (Klepeis 1994).

The location of the Euler pole for the Scotia Plate is poorly constrained by spreading rates, transform azimuths and earthquake slip vectors and its magnitude is roughly determined by closure (Pelayo and Wiens 1989, Thomas *et al.* 2003). The Euler pole predicts a left-lateral slip rate across the Magallanes Fagnano fault of ~5 $mm.yr^{-1}$, which is in agreement with poorly constrained geologic estimates based on offset of geologic units (Olivero and Martinioni 2001). More recently, GPS measurements across Tierra del Fuego detect 6.6 ± 1.3 $mm.yr^{-1}$ of motion across the Magallanes-Fagnano fault (Smalley *et al.* 2003). The GPS results also suggest that the plate boundary may be a wider zone with plate motion partitioned between the Magalla-nes-Fagnano fault system and a region of distributed, but much slower, deformation to the north, similar to the San Andreas-Basin and Range distributed plate boundary in North America (Smalley *et al.* 2003).

Before and during the last glacial maximum, glaciers carved out many of the presumably weak fault zones leaving long deep valleys (Rabassa and Clapperton 1990, Rabassa *et al.* 2000). Many of these valleys are now drowned fiords, lakes or bays. Determining if the valleys contain active faults, if such faults are locked or creeping, the amount of offset, and the relative contribution to their formation of transtensional tectonics versus glacial carving is therefore difficult. Where the traces of the faults outcrop subaerially, the surface is generally covered with either very young glacial deposits or peat, further limiting geologically addressing the question of the rate of motion.

In spite of these difficulties, geomorphologic evidence of active deformation associated with earthquakes along the fault has been observed (Olivero and Malumián 1999, Schwartz *et al.* 2001, 2002, Olivero and Martinioni 2001, Lodolo *et al.* 2002, 2003) and no evidence has been reported for fault creep. Olivero *et al.* (1995) estimated that a minimum displacement of 30 km has occurred during the past 30 myr. A number of geomorphic features; such as displacement and rotation of tertiary fold axes, offset streams, truncated meanders, sag ponds, linear truncation of vegetation (Winslow 1982); fresh fault scarps, and landslides (Dalziel 1989), have been cited as evidence of neotectonic movements mainly along the fault trace in Tierra del Fuego. Winslow and Prieto (1991) also noted that the 1949 earthquakes caused major landslides, uplifting and subsidence, with drowned forests, raised beaches and scarps in the peninsula Brunswick area (Chile). These authors have indicated that Holocene raised beaches suggest uplift rates of 1-5 mm.yr^{-1}, although the rates vary abruptly across fault boundaries.

On the Argentinean side of Tierra del Fuego the Magallanes-Fagnano fault can be traced through fault-related morphologies almost continuously from Lago Fagnano eastward all the way to the Atlantic coast through the Irigoyen river valley (Ghiglione *et al.* 2002, Lodolo *et al.* 2003) (Fig 1). Although homogeneous at a regional scale, this structure is composed by several parallel-subparallel sections, particularly in its eastern half.

The geology of the Lago Fagnano area is dominated by Quaternary glacier-related deposits underlain by Mesozoic and Cenozoic rocks. The lake occupies a glacial valley, which has been recurrently invaded during the Pleistocene from the west by glaciers descending from the ice-capped Darwin Cordillera (Bujalesky *et al.* 1997, Rabassa *et al.* 2000).

THE SEISMIC EVENTS OF 17 DECEMBER 1949

The earliest report of seismic activity in Tierra del Fuego was made by Bridges (1879) who reported an earthquake, that was felt strongly in Ushuaia on 2 February 1879. Lomnitz (1970) estimated the event to have had a magnitude of Ms 7.0-7.5. A more recent earthquake of Ms 7.0 was re-corded offshore to the east on 15 June 1970 and body-wave inversion for the focal mechanism indicates left-lateral slip on a sub vertical east-west oriented plane (Pelayo and Wiens 1989). Recorded seismicity since 1930 is quite low (most events < M 3.5) and shallow as revealed by recording stations installed in the middle nineties (Vuan *et al.* 1999), with infrequent major (M > 7.0) earthquakes (Forsyth 1975, Winslow 1982, Pelayo and Wiens 1989).

The first Ms 7.8 event of 17 December 1949 ocurred at 03:58 local time as reported by the Servicio Meteorológico Nacional and the Observatorio de La Plata in Argentina and was most strongly felt in the Argentinean territory in eastern Tierra del Fuego where the collapse of a ranch building killed a policeman. In Ushuaia, the wharf collapsed and damage of varying severity was reported for many buildings. After many aftershocks, a second event of similar size ocurred at 12:12. The information reported in newspapers suggests that the second event was farther to the west as it was felt with higher intensity than the first event in Punta Arenas (VIII SMM) than in Ushuaia (see Fig. 1). In Punta Arenas, many houses collapsed, fissures and cracks were observed in most construction and three people were killed by the second event. A number of witnesses reported strong sea waves pushed many boats and small ships toward the beach. These earthquakes were also strongly felt in Rio Gallegos, 350 km to the north, and moderate intensities were reported in San Julian, almost 600 km north (see Fig. 1). A significant number of aftershocks were felt throught Tierra del Fuego for several months after the events.

The epicenters for these events are very poorly constrained with reported locations in area of the Beagle channel, or north of Lago Fagnano and depths of 10 km (Forsyth 1975, Pelayo and Wiens 1989) (Fig. 1), which although not very well controlled are reasonable for a transform boundary event.

Preliminary modeling of the focal mechanisms of these earthquakes indicate a stri-

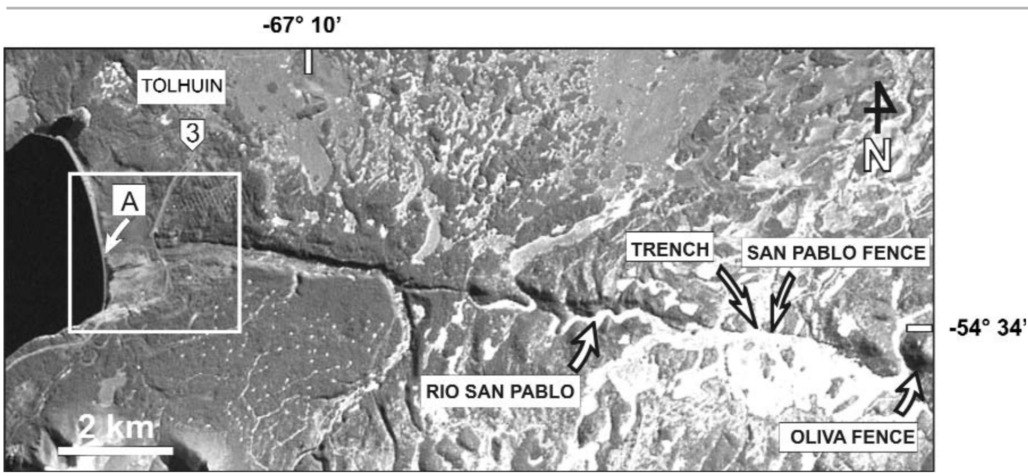


Figure 2: Landsat TM image of the area east of Fagnano Lago, showing the location of scarps at the Lago fagnano area (A), the trench site (at Río San Pablo) and fences at San Pablo and Oliva sites. The Magallanes-Fagnano main trace is highlighted by rectilinear features and scarps controlling main drainage lines. The white rectangle corresponds to the area showed in figure 3.

ke-slip regime for both of them (P. Al-varado, pers. comm.)

We interviewed a number of eyewitnesses to the earthquake who are still living in the area. Mr. Jacinto Caibul, who was in the HosterÍa Kaiken area on the eastern shoreline of Lago Fagnano, reported that the first event formed an ~1m high, east striking scarp that ruptured the road being built along the berm on the eastern shore of the Lago. Mr. Caibul cannot remember any lateral offset across the road. The formation of the scarp was followed by a large dust cloud and retreat of the Lake from the shore, with the arrival of a seiche soon afterwards. According to his testimony, the wave reached the current position of Route 3, leaving a shallow flooded area that remained flooded for several months (Figs. 2 and 3). The inundation killed ma-ny trees; most of which are still standing. The earthquake also affected the area where the Rio Turbio enters Lago Fagnano and left a permanently flooded area on the landward side of the berm.

Mr. Adrian Goodall was in Rio Grande, Argentina, area during the earthquake. He, and a number of other eyewitnesses, report that the radio station in Punta Arenas, Chile, announced a second earthquake would occur at 11 am (there is some confusion between reports about the time of the earthquakes as Argentina and Chile are in different time zones and some people living in the area used Argentine time, while others used Chilean time). He and his brother Thomas went outside just before the time predicted and waited for the second earthquake, which happened at the "predicted" time. He saw waves coming down the street and then felt the shaking. He visited Lago Fagnano soon afterwards and observed the scarp in the road along the eastern side of the Lago, which he recalled it to be about 1 m high. He also described phenomena which might account for liquefaction in the Rio Fuego between Viamonte and Rio Grande associated with the first event.

Mr. Robert Sutherland and a business partner were in Punta Maria, a hotel and general store just north of Viamonte, during the first earthquake and at a farm further inland during second. They spent the night at Punta Maria and while Sutherland was turning off the alarm clock at 4:00 am the earthquake hit. There was a rumble that grew in strength for a few seconds and then stopped. After a short time it started again, this time with a sideways movement. His partner tried to open the window during the first period of shaking but it jammed. They managed to open the window during the quiet interval between the two periods of shaking, probably the P and S surface wave arrivals. During the sideways shaking the armoire "walked" across the floor between the beds. About 500 cans fell off the shelves in the store. Noticeable aftershocks continued for about 20 minutes after the first large shock. Sutherland also reported cracks cutting a corduroy road by the Rio Fuego, and that a "blue mud" (liquefaction) came up through 15 cm wide cracks in road.

The second earthquake occurred about mid-day while Sutherland was loading logs onto a truck. The pile of logs on the truck was about 8' high when the second earthquake hit and everything fell off the truck. Sutherland managed to throw himself onto the top of the cab of the truck. He also reports that two hours before the second earthquake, there was an announcement by radio that there would be a second, weaker, earthquake in two hours. The second earthquake happened exactly at the time announced. An interesting observation is that as this was the only experience with earthquakes for many of these people, who were basically a small group of pioneers, they tell the story as if is it is perfectly normal to have announcements of upcoming earthquakes on the radio. In their only experience it is true.

Sutherland also went to visit Lago Fagnano afterwards and found the flooded area on the east side of the gravel bar (the lake shoreline gravel berm became a gravel bar with the formation of the permanently flooded area fed by the Río Turbio on the east) had subsided about 5 m during the earthquake. He also reports observing the scarp across the gravel bar.

In 1950 Sutherland was part of a search and rescue team looking for a missing airplane from the Argentine Army. They followed the fault trace from Lago Fagnano to the coast. Along the Rio Irigoyen near the coast he saw post and wire fences, that were built straight using a compass, with 6 m offsets. While crossing the Río Irigoyen one of the horses fell into a "great crack" in the bed of the river. One of the members of the search party went diving to find the bottom of the crack and it was deeper than he could dive. There were many such cracks in the river bottom. He also reports a "tremendous fault" with the peat all churned up. He only remembers horizontal displacement, no vertical displacement along this section of the fault. In the higher ground leaving the river, he saw many broken corduroy roads with horizontal offsets.

Mr Sutherland subsequently met with a german geologist, a Mr. Klausen, who worked in the area for four years performing a topographic survey for the Argentine Navy. Mr. Klausen mentioned his surveying measurements showed a 6 m horizontal displacement between the mountains Cerro Jeujepen (704 m) and Cerro Kashem-Michi (672 m) south and north of the fault respectively.

Based on the latest work on the controversial field of seismic scaling relationships (Zeng *et al.* 2005), plate boundary strike-slip earthquakes have a slip to length ration of ~.5 to ~1.7 10^{-5}. An average horizontal slip of 4-5 m would therefore be expected to occur on a fault plane extending from 250 to 1000 km in length, a very wide range although the available evidence supports a rupture length, at least subaerially, near the lower end. It is unknown if the rupture propagated further east than the coast, or further west than the eastern shore of Fagnano Lago, but the vertical only offset observed there would be consistent with it being near the western end of the rupture zone and/or on a releasing bend This means that the fault plane that ruptured, continued seaward along the North Scotia ridge at least for 300 km. Unfortunately there are no reports of offset, either by eyewitnesses or subsequent geological studies, associated with the earthquake in the sea cliffs around Río Irigoyen-Cape Leticia, where the fault is thought to go out to sea. The second earthquake was approximately the same magnitude and was reported to have been stronger in Punta Arenas, Chile, to the west. This suggests that the morning event was to the east and the noontime event was further west. Based on the lengths expected from scaling relationships at this type of crustal setting (i.e. Zeng *et al.* 2005), the two events together could have broken the complete Magallanes-Fagnano fault system from the triple junction to the Atlantic.

THE SURFACE RUPTURES

The ruptures related to the 1949 earthquakes were visited at the Lago Fagnano shoreline and east of the Río San Pablo (Fig. 2). These are the areas which provide better ground conditions and visibility to access the fault trace.

LAGO FAGNANO AREA

The fault trace here has an ESE trend and separates an uplifted block to the north from a depressed and flooded area to the south (Figs. 2 and 3). The clearest exposure of the scarp is located over the shoreline road, where a rounded step in the topography coincides with the place where the interviewed eyewitnesses pointed out the seismic rupture. The scarp cuts unconsolidated gravels of modern and paleo-shorelines of the lake. It appears quite degraded and its height ranges from 0.50 m to 1.00 m on the old section of Route N° 3. The downthrown area shows many dead threes in upright position, as a result of the seiche which inundated the area immediately after the earthquake. In aerial images the fault trace is also highlighted by a sudden change in the vegetation cover with Nothofagus woods in the up thrown side and grassy lands in the southern block (Fig. 3). The shoreline pattern also shows a noticeable change in its geometry and morphology, being more sinuous and irregular south of the fault trace, whereas slight channel entrenchment in the submerged area might account for elastic recovery after the quake. Caibul also mentioned that the old shoreline road (the original Route N° 3) had to be rectified and elevated between the fault trace and Hostería Kaiken and a bridge had to be constructed for draining the flooded area. No diagnostic evidence for strike-slip surface movements were identified here.

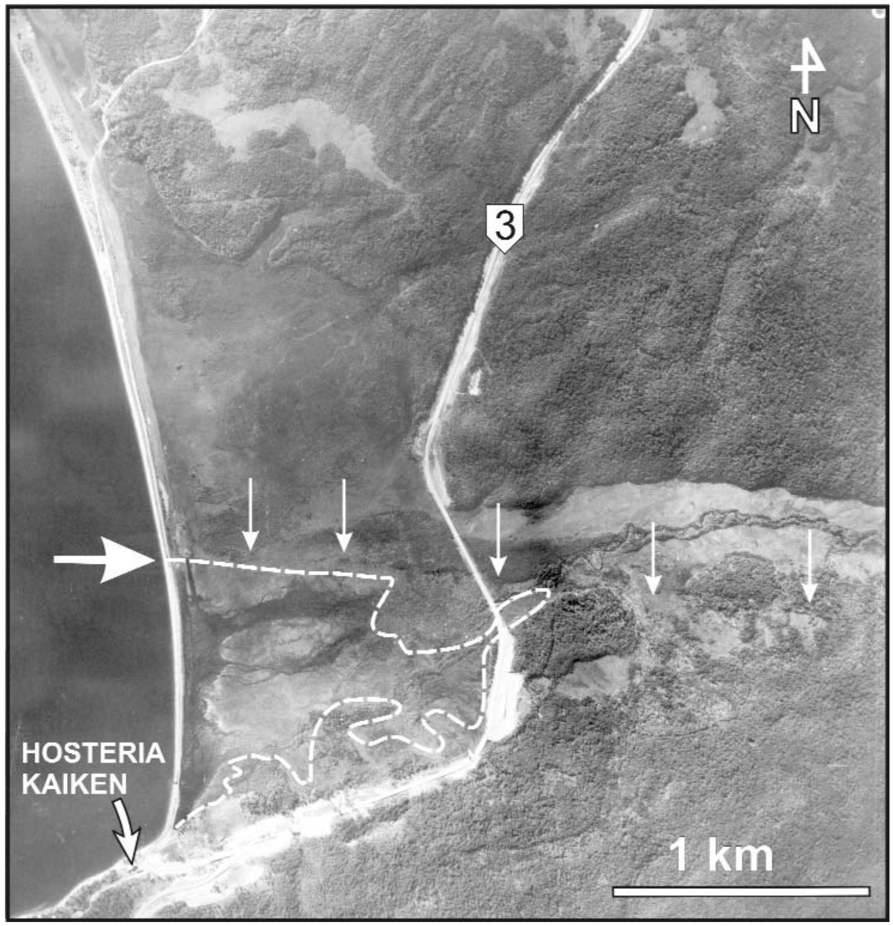


Figure 3: Aerial image of the Magallanes-Fagnano fault scarps and surface ruptures at Lago Fagnano shoreline. The vertical arrows point out the south-facing scarp and the area within dashed lines corresponds to the flooded area due to the earthquakes-related seiche, according to eyewitnesses testimonies. The road number indicates the present position of route 3, which in 1949 was located along the shoreline. The horizontal arrow indicates the surface rupture site at the shoreline. See figure 2 for location.

RÍO SAN PABLO AREA

This area is located 30 km eastwards from the village of Tolhuin, through the road to Estancia La Correntina (Fig. 2). Along this segment of the fault, observed scarp heights range from 5 to 11 m. Despite dense vegetation, the Magallanes-Fagnano fault stands out clearly on aerial images as a persistent linear trace. The northern uplifted block exposes Quaternary glaciofluvial coarse deposits. The uplift on the north side and subsequent fluvial entrenchment of the down dropped south side of the fault resulted in the development of several terraces on the north side. In a 5-10 m wide area along the ESE trending fault trace, tension gashes with an echelon arrangement, coaxial grabens, sag ponds and mole tracks have been identified (Schwartz *et al.* 2001, 2002). Many trees were uprooted and fell into these along-strike depressions during the 1949 earthquakes and their dendrochronological record is currently being investigated with the aim of recognizing pre 1949 surface faulting associated to this structure (F. Roig and J. Rabassa, pers. comm..).

The vertical slip associated with the 1949 event seems to have been 50 cm or less. As the scarp is much higher than this in general, it highlights that the scarp developed through many seismic events which ruptured or deformed the surface. Despite the general strike-slip character of this structure, diagnostic mesoscopic coseismic evidence of strike-slip offset has been quite elusive at the present reconnaissance level. The majority of surface disturbance is located within 30 m of the main fault scarp and large tension gashes (typically 2.5 m long, 0.30 m deep, 0.50 m wide) as well as discontinuous small scarps (<50 cm) exist along the main fault trace. We found two fences with offsets where they cross the fault trace. We surveyed both fences with the aim of determining the strike-slip component of slip during the 1949 rupture. There is some uncertainty, however, about the original geometry of the fences. At the San Pablo fence (Figs. 2 and 4), Mr. Pedro Oliva, the landowner, could not remember whether or not this fence was built before the earthquake and/or if it was restored after the earthquake. He guessed though, that the original geometry was not straight where it crossed the fault from the higher dry side on the north, to the submerged turba to the south, due to difficulty of working in the torn up ground of the scarp. The fence also changes from post and rail on the north to post and barbed wire to the south. The question about the original geometry adds significant uncertainty to making a trustworthy reconstruction.

As more reliable piercing points have not been found along the fault trace so far, we decided to attempt to restore the fence geometries as well as possible, considering the known problems with the aim of constraining the likely maximum and minimum slip amount for the coseismic strike-slip component. We developed three probable models, which of course do not preclude other interpretations. A left lateral component ranging from 0 to 4 m can be interpreted at the San Pablo Fence site, according to the different models displayed in figure 4, although it is difficult to determine what the correct choice might be, due to the reasons discussed above. Note that sudden bends of the fence coincide with slope breaks and with the main fault trace. In fact, if these offsest were tectonic, they are the only objective evidence that can be used to estimate the horizontal component of slip in this area.

The fence identified as "Oliva Fence" (Figs. 2 and 5) was built before the earthquake, and according to Oliva no restoration work was done after the earthquake. The fence was constructed by felling trees, stripping

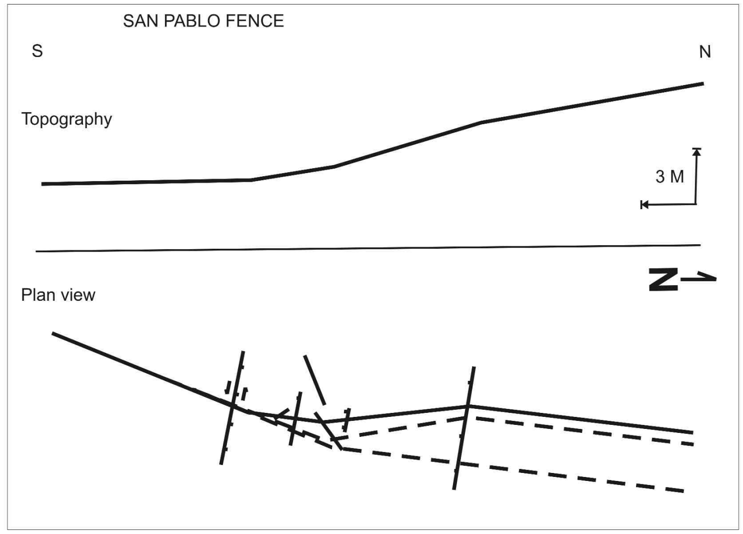


Figure 4: Topographic profile (above) and plan view of the surveyed fence at Río San Pablo. Main scarps and secondary scarplets observed at the main fault zone have been sketched. The dashed lines show possible restoration models, assuming this fence undergone deformation at the 1949 earthquakes, with a maximum left-lateral component of 4m (see scale).

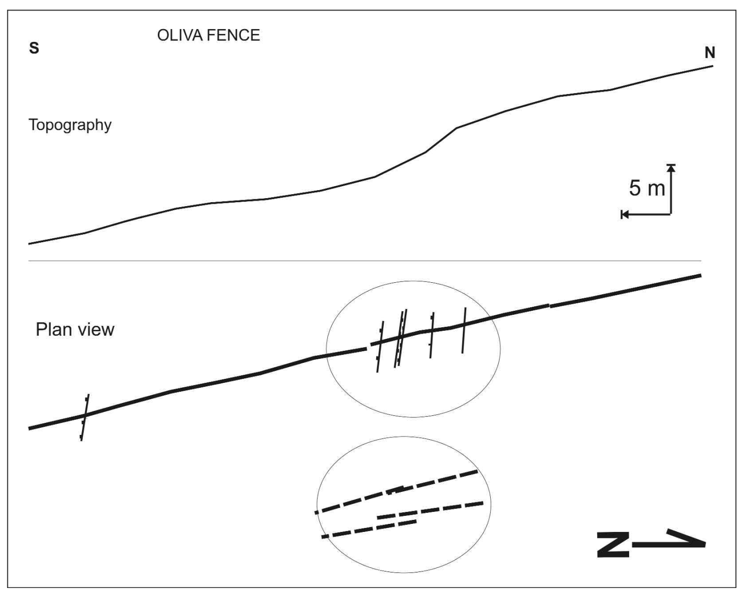


Figure 5: Topographic profile and plan view of the Oliva fence. Several subparallel scarplets are present at the main scarp slope. Possible strike-slip component of the 1949 events have been interpreted for the area within the circle.

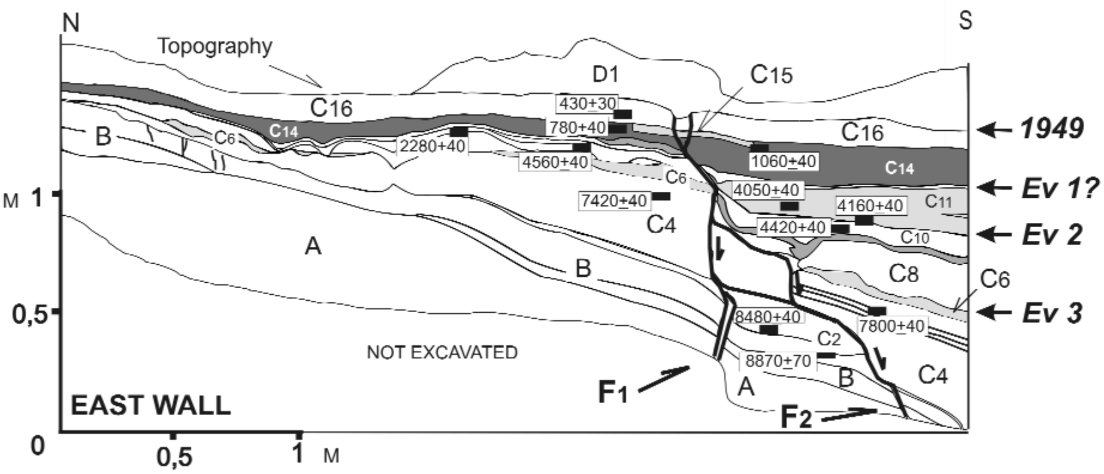
the branches and moving the trunks slightly such that the fallen trunks form the fence. The original geometry was therefore quite irregular and unknown, but Mr. Oliva pointed out one section of the fence that he reported was disrupted by the earthquake. This section looked disrupted compared to the adjoining sections and was therefore surveyed. The overall fault scarp here is higher than at fence site at Río San Pablo, and there is no evidence of significant coseismic landsliding. The fault zone is quite continuous, showing sag ponds, tension gashes, scarps and other minor related morphologies. Assuming an original linear fence across the main fault, its present geometry excludes a coseismic lateral component larger than 1m. The most conspicuous feature that might account as an evidence for sinistral strike-slip displacement is a 0.40 m step in the fence, close to a fault scarp (Fig. 5).

TRENCH INVESTIGATION AT THE RÍO SAN PABLO

Ten meters east of where the Río San Pablo crosses the Fagnano fault trace, a hand-excavated trench allowed observation of the deformation produced by the earthquake on a secondary fault trace. Surface expression of the main fault here is expressed by a 1 m scarp probably related to the 1949 seismic events. The excavated fault trace has no noticeable surface expression at the trench site. The trench stratigraphy is composed by four main units labeled A through D in figure 6. The oldest exposed unit (Unit A) corresponds to a grey glacio-fluvial gravel of unknown base and a maximum exposed thickness of 60 cm. This is partly overlain by a gray clay with slate clasts (Unit B1) and by a gray to brownish clay (Unit B2). The third unit (C) corresponds to well layered peat bog, with alternate layers of black, dark brown, reddish and orange-yellowish color. Boundaries among these beds are very well defined and fine layers such thin as 1 cm can be identified. These layers thicken to the south toward the main fault trace (not excavated) containing a variable and minor amount of silt and clay. A grey tephra layer is interbedded within the peat level. The ages of the various units have been constrained through 14C analyses and are displayed in Fig. 7. At the trench scale (Fig 6), many minor divisions within unit C can be traced, although only those relevant in terms of fault slip have been sketched. The whole sequence is capped by a present dark soil and a brownish-greenish active peat formation.

Rupture geometry is exposed on both walls of the trench and shows two main fault surfaces merging or truncating upward with different geometric patterns and significant open spaces (up to 6 cm) along them (Fig. 6). The sharp bends along fault F1 in the east wall makes it difficult to accommodate vertical slip component through conservative displacement. Many of the features on the south side of fault F1 suggest a drag along F1 with a downthrown side to the south, which is consistent with topographic relations exposed at the main fault scarp. Fault slip produced thickness changes in the stratigraphic units near the deformation zone, being some of them even stripped at one or both sides of the fault trace.

The oldest faulting event recorded in the trench is constrained by Units C6 and C7 and according to the radiocarbon ages it might have taken place between 7420 +40 BP and 4560 +40 BP. This event appears to be related to fault strand F2 since Unit C5 and C6 are not exposed on the up-thrown side (as seen at the west wall) and Unit C7 overlies it with almost no disturbance. Cumulated slip at the base of Unit C4 is 17 cm (west wall), although it is not clear if this slip is related to this event only or also to a previous event or events.



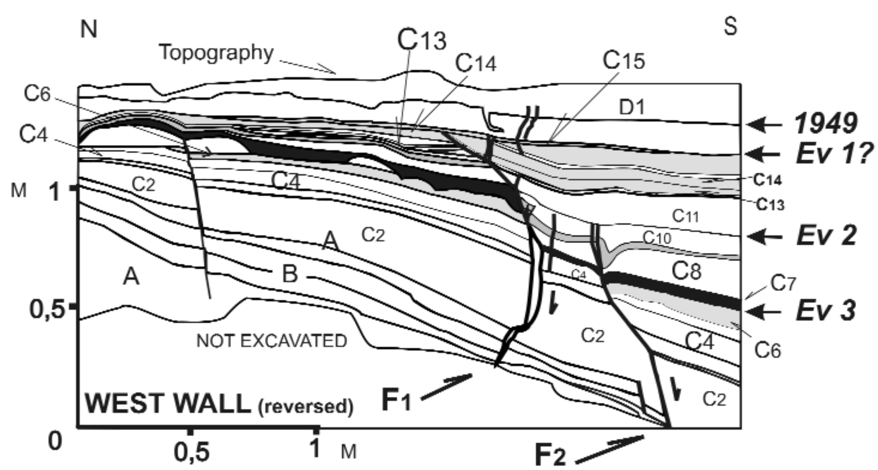


Figure 6: Logging and interpretation of both trench walls on a secondary fault trace at Río San Pablo. Black boxes indicate the sampling sites for ^{14}C dating, whose results are given in calibrated radiocarbon years. The west wall has been reversed. See text for details.

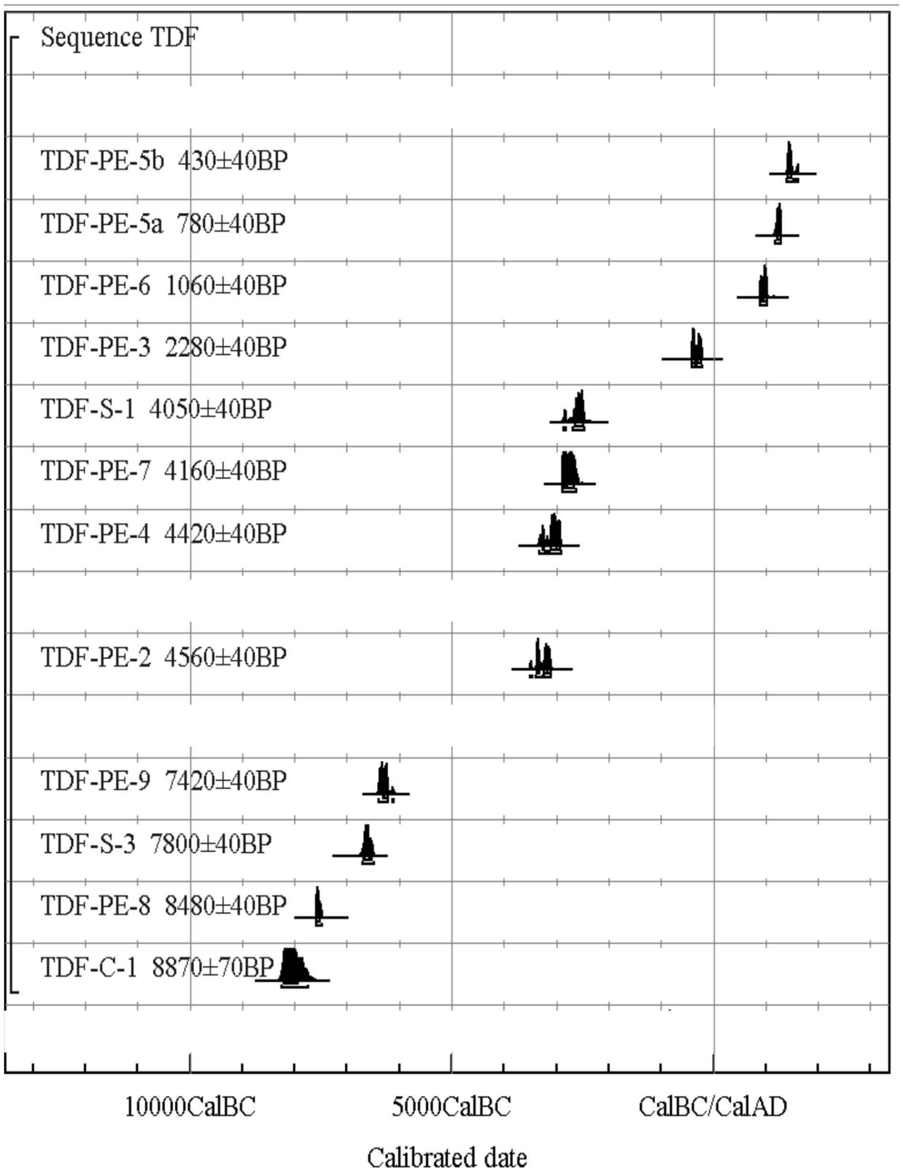


Figure 7: Calibrated ^{14}C obtained through the calibration program OxCal v3.8 (Bronk Ramsey 2002) following the atmospheric data provided by Stuiver *et al.* (1998). Dating results ordered according to laboratory number.

The next seismic event horizon identified implied slip along fault strand F1 after the deposition of Unit C10 (4420 +40 BP) and previous to Unit C11 (4160 +40 BP at its base). This is inferred based on the notable change in thickness of unit C10 across fault F2 in the west trench wall, while on the east wall this unit has been eroded. This suggests the reactivation of the south-facing scarp favoring erosion at the uplifted side. A sudden decrease in the accumulated slip after deposition of Unit C11(4050 +40 BP) is recorded at both trench walls, particularly within the Unit C14 (1060 +40 BP), where 9 cm of displacement was measured at its base (east wall) and less than 2 cm at its top (both walls), in addition to a considerable thickness change between the foot-wall and hanging-wall. A truncated layer within this unit in the foot wall (west wall) (black layer in Fig. 6) advocates for a faulting event pre-1879, followed by erosion prior to the present soil development. Thus, this event might have taken place between 780+40 BP and 430 +40 BP. It is also possible to assume aseismic creep along fault strand F1 as an alternative interpretation.

The upward graben-like culmination of the fault surface (F1) in the east wall, affects the base of current peat bog formation (Unit D1; 430 +40 BP) with 5-8 cm of vertical displacement. This slip barely reached the surface, probably as tension gashes associated to the main rupture during the 1879 or 1949 events, expressing a rather small surface rupture along this fault strand at this point.

The events recorded in this trench are certainly not complete with respect to addressing earthquake recurrence during the Holocene, because the interpreted paleoseismic record focuses only on a secondary fault plane which might not have have ruptured during all significant earthquakes along this section of the fault. Conversely, coseismic evidence at the sub-meter scale and other stratigraphic relations related to seismic event horizons could be better preserved. Evidence for three, and possibly four, seismic events, however for the last 8 ka, roughly means an estimated maximum average recurrence interval of 2 ka for events rupturing at surface at this secondary trace. Considering the limitations mentioned above, this should be regarded only as the first estimate for the maximum time span between surface rupturing earthquakes. Paleomagnitudes of the interpreted events can not be assessed as only the vertical component of slip could be determined. The magnitude threshold for producing surface rupture in this type tectonic setting is probably larger than magnitude M 6.5 (Ambraseys 1983, Wells and Coppersmith 1994).

CONCLUSIONS

Field work conducted along two sections of the Magallanes-Fagnano fault that suffered surface rupture related to one of both of the Ms 7.8 earthquakes of 17-12-1949 allow a preliminary determination of a maximum vertical component of 1 m related to the main scarp. Total length of the rupture and associated coseismic offset at the sruface still remain unknown. A significant part of the rupture could have continued into Lago Fagnano to the west and, given the short distance between Lago Fagnano and the coast, it probably also continued offshore to the east. Except for the unconfirmed reports of 4-6 m of offset further to the east by the eyewitnesses, the magnitude of the strike-slip component in the surveyed area is poorly constrained and seems to be less than the vertical offset. No typical, diagnostic strike-slip morphologies have been so far recognized along these ruptures, or in remote sensing images, whose general sense of movement is sinistral-normal. The fault parallel geologic structures, and the unconsolidated nature of the glaciar deposits and peat, combined with the heavy precipitation, conspire to obscure development of morphologic evidence of strike slip offset. The young age of the exposed surface material also limits total offset since recession of the glaciers to less than 100 m.

Reconstructing the geometry of preexisting fences yielded results for coseismic offsets with large uncertainties. Our observations, and reports of eyewitnesses of the 1949 events, indicate that along the eastern shoreline of Lago Fagnano vertical offsets ranged from 0 to 1 m with no coseismic horizontal strike-slip displacements. Paleoseismic evidence from a trench across a secondary fault trace at Rio San Pablo, suggests rupture occurred there in at least two pre-1949 events during the last 8 kyr. Apparently, the fault surfaces exposed have moved individually, and no further movement has taken place on fault F2 during the last 4160 +40 years BP. The observations indicate that the left-lateral component of fault slip during the 1949 events in the area immediately east of Lago Fagnano was most likely < 1m, and probably absent in many places, which would be compatible with either of the end member interpretations that Lago Fagnano sits in a releasing bend of the South America-Scotia transform boundary or was at the western most end of the rupture zone.

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