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López, Ramiro and Magneres Ignacio: Methodology, Resources, other analysis tools

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Abstract

The Magallanes-Fagnano Fault System (MFFS) constitutes the onshore segment of the transform boundary between the Scotia and South American plates. The objective of this study is to provide a characterization of the portion of the MFFS, extending from the eastern shore of the Fagnano Lake to the Atlantic coast of Argentina, from a geometric and morphotectonic approach. Detailed morphotectonic analyses of satellite images, plane recognition, digital topographic data, and field surveys allowed us to identify thirteen discrete fault sections. These sections were differentiated according to the morphological characteristics of scarps, natural exposures and other associated morphotectonic features. The main trace fault shows opposite north- and south- facing scarps alternating along strikes being descriptively characterized by their scarps, linear rivers and valleys, drainage anomalies (e.g. diverted, deflected or offset streams), behead meanders, wind gaps, sag ponds, pull-apart basins and linear ridges, among others features. The natural exposures of glacio-fluvial sand and gravel outcrops show Quaternary vertical and strike-slip deformation. It looks unlikely that the Magallanes-Fagnano Fault System (MFFS) could rupture along the entire ∼600 km length during an earthquake. Our results show that even large strike- slip faults may be divided into several discrete fault sections with distinctive morphotectonic features that could help to an increasing understanding of MFFS as a seismogenic source. In this way we suggest different fault sections as a contribution to the recognition of potential individual surface ruptures, which should be tested with further detailed data.

Keywords: Magallanes-Fagnano fault system, fault section, neotectonics, geometric characterization, Quaternary structure.

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Introduction

Analysis of morphotectonic features and landforms along active faults provides important insights into fault evolution and present-day tectonic activity.

The Magallanes-Fagnano Fault System (MFFS) is the most important Quaternary structure in the Southern Andes, being a transform system between the Scotia and South American plates, running for >600 km from the Atlantic to the Pacífico oceans (Kepleis, 1994), and crossing Tierra del Fuego from W to E, with secondary faults with en echelon sinistral pattern (Figure 1). Costa et al (2006) and Perucca and Bastías (2008) mention that the MFFS and secondary faults affect Quaternary alluvial deposits showing characteristic morphotectonic features such as alignment of scarps and vegetation, deviated drainage, sag ponds, and anomalous drainage patterns. Several authors (e.g. Coronato et al. 2002, Lodolo et al., 2003, Costa et al., 2006; Coronato et al. 2009, Onorato et al., 2020; among others) have described truncated meanders and abrupt changes in the direction of the river channels, truncated glacifluvial fans and post-depositional structures in glacial sediments (Bujalesky et al., 1997). East of the Fagnano Lake, Schwartz et al. (2002) and Costa et al. (2006) pointed out that the fault rupture during the 1949 earthquake caused the formation of a scarp to the east of Fagnano Lake. Nowadays, the height of the rounded scarp, which shows degradation processes, ranges between 0.50 and 1 m. The footwall of the fault presents dry trees that are still standing, as a result of the block of the Turbio River delta at the Fagnano Lake shore (Figure 1) due to the seiche and berm built by the earthquake. About 30 km to the east of Tolhuin city (Figure 1), the scarp heights range between 5 and 11 m, suggesting several seismic events, with the hanging block to the north exposing fluvioglacial Quaternary deposits and several levels of river terraces. Schwartz et al. (2002) and Costa et al. (2006) identified tensional cracks with stepped design, coaxial grabens, depressions, and thrusts near the intersection between the San Pablo River and the fault trace (Figure 1). Sandoval and Di Pascale (2020) described geomorphological offsets from 110 ± 5 m to 30 ± 10 m along river channel margins. These authors considered possible post-events modification by sedimentary process and described classic strike-slip tectonic geomorphology, with sag ponds, shutter ridges, and clear sinistral offsets of landforms. Subdivision into fault segments carried out by Roy et al. (2019) is based on the images analysis of the deformation styles of each section and the coseismic ruptures quantified during the 1949 earthquake. In the present work, we divided the eastern portion of the MMFS into fault sections mainly based on the morphological evidence observed during the fieldwork. In this way, we discriminate shorter fault sections with distinctive morphological characteristics (e.g. scarps position, anomalies in the drainage patterns, among other features). In this way, a comprehensive fieldwork survey was conducted to obtain evidence that allows us to describe and analyze these fault sections improving the level of morphotectonic knowledge of the SFMF. A fault section is here conceived as a discrete km-scale part of the fault that has homogeneous structural geometries and morphological expression (Haller et al., 1993; Costa, 2000; Costa et al., 2014). The characterization of these fault sections is considered a strictly descriptive concept based on geomorphological features. We examine morphotectonic evidence along the eastern main trace of the Magallanes-Fagnano Fault System to gain insights into basic seismogenic parameters such as possible surface rupture lengths. Also, despite the large uncertainties involved in the fault sections data, we attempt to characterize and up-to-date information pertaining to seismogenic features of the onshore MFFS, to collaborate to the fault seismic hazard assessment (SHA) in Tierra del Fuego.

Seismotectonic Setting

The Magallanes-Fagnano Fault System (MFFS) constitutes the onshore segment of the transform boundary between the Scotia Plate to the south, and the South American Plate

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to the north (Figure 2) (Winslow, 1982). It extends from the western tip of the Strait of Magellan to the eastern border of the Argentinian marine shelf, north of Isla de Los Estados, and continues to the east along the North Scotia Ridge, ending next to the Georgias del Sur Islands (Figure 2) (Forsyth, 1975; Klepeis, 1994; Pelayo and Wiens, 1989).

Spreading in the Scotia Plate formed during the early Oligocene as a result of the separation between South America from Antarctica. It is a minor plate whose movement is largely controlled by this two major surrounding plates. According to Livermore et al. (2005), the Scotia Plate mainly consists of oceanic crust and small continental fragments, some of which were dragged into the Atlantic basin. Most of its surface lies beneath the ocean, except for the southern tip of South America and the South Georgia Islands (Figure 2).

The Fuegian Andes constitute the eastern segment of the Patagonian Orocline, where the Andes Cordillera changes its general trend from N-S to E-W (Figure 3) (Dalziel et al., 1973; Cunningham et al., 1991). Their main geological features developed during the Mesozoic-Cenozoic Andean orogenic cycle. It started in the Middle to Late Jurassic with a back-arc extension, crustal stretching and widespread volcanism (Menichetti et al., 2008). Compression and uplift in the Fuegian Andes began in the southeastern Tierra del Fuego during the Late Cretaceous, causing the closure and inversion of the extensional “Rocas Verdes Basin” (Figure 3) (Mpodozis and Ramos, 1989; Olivero and Martinioni, 1996; Wilson, 1991). Flexural subsidence caused by thrust-sheet loading in the orogen formed the Austral and Malvinas foreland basins (Galeazzi, 1996; Klepeis, 1994; Olivero and Martinioni, 1996). During Paleogene times, the orogenic front and the foreland basin depocenters migrated northward to their current position (Yrigoyen, 1962; Caminos, 1980; Winslow, 1982; Olivero and Malumian, 1999).

In the Darwin Cordillera (2000 m.a.s.l.), located in the southwest of the Tierra del Fuego (Figure 3), uplift began around 70-90 Ma. A second uplifting pulse occurred around 65-40 Ma (Kohn et al., 1995), contemporarily with the beginning of the uplift in the Fuegian fold and thrust belt (Figure 3). The orogenic front advanced in several pulses during the Late Cretaceous to Oligocene (Ghiglione et al., 2002). The present fold-thrust belt develops from the basement front towards the NE (Figure 3) (Ghiglione et al., 2002).

During the Neogene, compression intensified across the Tierra del Fuego (Ghiglione et al., 2002). However, due to the opening of the Drake Passage (Figure 2 and 3) and the

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formation of the Scotia Plate, the tectonic regime shifted from compressive-dominant towards strike-slip dominant (Ramos et al., 1986; Cunningham, 1993; Cunningham et al., 1995; Klepeis and Austin, 1997) resulting in the formation of the MFFS (Cunningham, 1993; Ghiglione et al., 2008).

Along the onshore segment of the MFFS (Figure 2 and 3), relative plate motion is left-lateral strike-slip on a vertical fault at 6.6 ± 1.3 mm/year based on GPS measurements, an assumed locking depth of 15 km, and crustal thickness of 28-34 km (Winslow, 1982; DeMets et al., 1990; Del Cogliano et al., 2000; Smalley et al., 2003; Lawrence and Wiens, 2004).

Roy et al (2019) dated a cumulated offset in post- glacial morphologies and estimated the long- term slip rate of the eastern trace of the MFFS, indicating a left-lateral fault rate of 6.4 ± 0.9 mm/yr. Also, Sandoval and De Pascale (2020) suggested Cenozoic slip rates along the main Magallanes-Fagnano fault of 5.4 ± 3.3 mm/yr, based on lithological displacement, and Quaternary, sinistral slip rates of 10.5 ± 1.5 mm/yr in Chile and 7.8 ± 1.3 mm/yr in Argentina.

The main fault plane has an azimuth of 80° to 100° (Cunningham, 1993) with an approximate length of 600 km (Lodolo et al., 2003).

Torres Carbonell et al. (2008) described a compressive structure which is laterally offset by the MFFS. The precise mapping of this structure and the Upper Cretaceous-Paleocene contact shows a horizontal offset of ca. 48 km along the transform system. These authors estimated the beginning of the strike-slip motion at ~7 Ma (Late Miocene). This age coincides with the formation of the divergent boundary between the Sandwich and Scotia plates. This oceanic spreading ridge has been interpreted as responsible for the beginning of the strike-slip motion between the South American and Scotia plates.

Historical Seismicity

Instrumental seismicity records in the region show a significant number of earthquakes of low to medium intensity and moment magnitude (on average Mw 2.0), with epicenters in the continental region and surrounding oceanic areas (Sabbione et al., 2007). Ammirati et al. (2020) indicated an important concentration of hypocenters distributed throughout the MFFS, while to the north they noted the events had a more diffuse distribution within the crust. The local magnitudes associated with the events range from $1.9 < ML < 5.3$, with the highest being closer to the MFFS. It is worth

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mentioning that for the present synthesis, only those seismic events of magnitude and intensity ≥ 6 on the Richter scale and VI on the modified Mercalli scale, respectively, were selected (Figure 4).

As highlighted by authors such as Vuan et al. (1999) and Febrer et al. (2000), historical and instrumental seismicity along this transform boundary has been high (Mw > 7) and shallow (< 40 km). The oldest seismic event recorded in historical times corresponds to February 2, 1879, at 5:00 a.m. (INPRES, 2015, Figure 4). Travellers who were in different locations registered and documented the moment in their diaries (Martinic, 1988). This earthquake caused the fall and breakage of bottles, jars and other glass, earthenware or ceramic items stored in cupboards and shelves. There are at least six accounts that claim to have perceived it hundreds of kilometers from the epicenter, even in sectors of the Atlantic coast of Tierra del Fuego such as San Sebastián Bay (~140 km) and Espíritu Santo Cape (~135km) (Figures 1a and 4). The earthquake had an intensity VII on the modified Mercalli scale in Punta Arenas (Figure 1a), although it did not cause significant damage to the wooden houses, and an intensity VIII in Ushuaia (Cisternas and Vera, 2008, Figure 1a) and an estimated magnitude of Ms 7.0-7.5. A testimony in Martinic (1988) indicates that “a series of very strong earthquakes were felt, making it difficult to walk and causing light objects to fall”. Based on accounts by witnesses, it is inferred that this earthquake was perceived throughout the region between San Sebastián and Bahía Inútil (53°S/70.67°W) (Figures 1a and 4, Martinic, 1988).

In the seismic catalog of Tierra del Fuego, Sabbione et al. (2007) reported an earthquake of Mw 7-7.5 dated February 2, 1879, at 3:30 a.m. (54.24°S/69.03°W, Figure 4). Both documents may refer to the same event due to the proximity of their dates; however, the location of their epicenters does not coincide.

On November 19, 1907, damages were reported in Punta Arenas because of an earthquake of intensity VI (INPRES, 2015), which was also perceived in Ushuaia (Figure 1a and 4).

In 1930, two seismic events were recorded, on June 7 of Ms 6.3, and on July 13 of Ms 6.2. These affected the Chilean region of the Tierra del Fuego, with an epicenter at 56°S/67°W and 56.67°S/69.42°W respectively (Figure 4, Sabbione et al., 2007).

On November 21, 1944, also in the Chilean region of the Tierra del Fuego (56.67°S/66.28°W, Figure 4), an earthquake of Ms 6.5 was recorded at a depth of 33 km (Sabbione et al., 2007).

Journal Pre-proof

Martinic (1988) reported an earthquake that occurred on December 17, 1949, as part of several seismic movements produced intermittently from dawn until past noon, which mainly affected Punta Arenas and some rural towns of Bahía San Nicolás and Caleta María (Figure 1a and 4). This event is also known as the “Magallanes earthquake” (Cisternas and Vera, 2008). According to Sabbione et al. (2007), two earthquakes of Ms 7.8 took place, the first at 6:53 a.m. (54.24°S/69.03°W) at a depth of 33 km and the second at 3:07 p.m. (53.89°S/69.67°W) at a depth of 13 km. These authors also mentioned two other earthquakes among those cited above, but they did not estimate their magnitude. In the INPRES report (2015), a strong earthquake of Ms 7.8 and intensity VIII was described for December 17, 1949 (54°S/68.770°W, Figure 4). After several aftershocks, a new earthquake of the same magnitude was recorded, which caused subsidence along the shore of Fagnano Lake and generated also a subsidence lagoon on its eastern bank (Schwartz et al., 2002).

Following the information in newspapers of the time, Costa et al. (2006) stated that, during the first event at 3:58 a.m., a dock collapsed and buildings in the city of Ushuaia were subjected to varying degrees of severe damage. At 12:12 p.m., after several aftershocks, a second event of similar magnitude occurred. However, these authors highlight that this second event would have occurred to the west of the previous one since it was perceived with greater intensity in Punta Arenas (VIII) than in Ushuaia. In Punta Arenas, fissures and cracks appeared in most of the buildings, some even collapsed, and three people died. A few witnesses indicated that the strong waves pushed boats and small ships towards the beach, suggesting the occurrence of a tsunami. This seismic event also affected areas far from the epicenter, such as the westernmost arm of the Strait of Magellan (Figure 1a and 4), where tsunamis were also recorded (Jaschek et al., 1982).

The USGS (2020) locates the same earthquake of December 17, 1949, at 06:53 a.m. with an epicenter at 53.923°S and 69.596°W, at a depth of 10 km, with intensity VIII and Mw 7.7. A second event is mentioned at 3:07 p.m., also 10 km deep, with Mw 7.3 and intensity VIII (53.911°S/69.753°W, Figure 4).

On January 30, 1950, at 00:56 a.m. an earthquake of Ms 7 was registered, whose epicenter was located in the Chilean region of the Tierra del Fuego (52.98°S/70.88°W) at a depth of 35 km (Sabbione et al., 2007, Figure 4).

Journal Pre-proof

On June 15, 1970, an earthquake of M 7.0 occurred in the high seas (54.3°S/63.6°W). Its focal mechanism indicates a left-lateral slip in an east-west oriented subvertical plane (Pelayo and Wiens, 1989).

Seismological data obtained from national (INPRES) and international (NEIC, IRIS) catalogs and data provided by the Estación Astronómica de Río Grande show that the earthquakes registered by these stations have Mb magnitudes between 2 and 4. Regarding their hypocentral depth, more than 50% of the recorded events are less than 10 km deep (Buffoni et al., 2009).

The records of instrumental earthquakes compiled from the available bibliography and those listed in the catalog of the International Seismological Center ISC-EHB: On-Line Bulletin, specify location and calculation of magnitude for earthquakes from 1929 to 2020. In this work, earthquakes of magnitude Mb> 4 (magnitude concerning the amplitude of the body waves) were selected, including the occurrence of at least 8 events with magnitude Mb > 5 (Figure 4).

The focal mechanisms determined in the Tierra del Fuego correspond to the main events located along the main MFFS on Tierra del Fuego (Smalley et al., 2007) and to the east of the Atlantic Ocean (Pelayo and Wiens, 1989), which indicate a pure sinistral strike-slip motion with main shortening axis consistently oriented NE–SW (Sue and Ghiglione, 2016). The focal mechanism of another Mw 4.9 earthquake that occurred on August 31, 1996 (53.43°S/73.12°W), also showed nearly pure strike-slip behavior (CMT catalog). These focal mechanism solutions are consistent with the plate movements measured with GPS (Smalley et al., 2003) and the surface geomorphological evidence described in Onorato et al. (2020) among others authors.

Also, Ammirati et al. (2020) observed earthquakes aligned along the MFFS consistent with GNSS measurements, global plate motion models, and deformation evidence indicating seismic activity during the Quaternary. They suggested that this structure is the main mechanism of crustal deformation at depths between 25 to 30 km in the southern Tierra del Fuego area.

The records of seismic events documented in seismic journals, books and catalogues, indicate the strong impact caused on the population. However, only for the 1949 events, evidence of surface rupture and fence displacements were mentioned by Costa et al. (2006), Roy et al., 2019, Sandoval and De Pascale (2020). This evidence would allow defining earthquake segments, but with a significant degree of uncertainty about their length.

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METHODOLOGY

For this study, satellite images were analyzed, together with digital elevation models (DEM) from ALOSPALSAR Global Radar Imagery with a 12.5 m resolution (https://asf.alaska.edu/data-sets/sar-data-sets/alos-palsar/). Furthermore, reconnaissance flights and field observations were performed.

Fault sections were analyzed based on a descriptive approach, considering homogeneous sections concerning their morphologies and geometries which might constitute individual surface rupture lengths. In this sense, an attempt is made to make a contribution to guide future actions to define individual Surface Rupture Lengths (Machette et al., 1992; Costa et al., 2000; McCalpin, 2009; Costa et al., 2014; Du Ross et al., 2016). The strip map was elaborated by defining geomorphological and morphotectonic heterogeneities, and favorable sites in the field to carry out future detailed studies. Fieldwork consisted of the validation of the remote mapping, the recognition, classification and description of the geology and sedimentology, beaver ponds location, and the landforms and morphostructural elements of the selected areas. It is worth mentioning that field tasks were restricted by the climatic factor, between October to April, as well as by the abundant vegetation in the region (forest and peatlands) and the river modification generated by the beavers.

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Results

The most remarkable morphological evidence corresponds to the main trace of the MFFS. Some of this evidence has already been mentioned and described in Onorato et al. (2017 and 2020), Sandoval and De Pascale (2020) and Roy et al. (2018, 2019) and includes scarps, linear valleys and rivers, whalebacks, pop-ups, sag ponds and pull-aparts, drainage control as diverted, offset or deflected streams (Figure 4). The neotectonic features of the main MFFS trace were differentiated, together with the more evident structures associated with it, such as in echelon faults and braided systems of subparallel fault traces in a narrow zone, whose geometric relationships with the main fault trace resemble Riedel-type geometries. These morphotectonic evidence loses definition and notoriety towards the east.

The morphological evidence described in this work and indicated in the strip map corresponds to linear and punctual morphotectonic features that were identified associated with the MFFS deformation zone. They were used as a descriptive basis to discretize heterogeneities throughout this structure. The Argentine onshore portion of the MFFS covered in this analysis corresponds to the surface expression of the fault trace from the eastern shore of Fagnano Lake to the Atlantic coast, it has an approximate extension of 65 km, N90°-95° trend and left-lateral displacement. However, it should be noted that the MFFS, as a transform fault system, continues westward along Fagnano Lake and Seno Almirantazgo-western Strait of Magellan towards the Pacific Ocean and eastward below the Atlantic Ocean to the Georgias del Sur Islands (Figure 1)

For descriptive purposes, the Argentine onshore portion of the MFFS has been subdivided in this work into 13 fault sections, each characterized by distinctive geomorphological features, such as free-faced scarps to the north or south and evidence of co-seismic displacements that would correspond to the last major earthquakes. In the two earthquakes that occurred on December 17, 1949, processes associated with each of the fault sections described, such as ground rupture and co-seismic displacements, were reported (Costa et al., 2006; Lodolo et al., 2003; Roy et al., 2019; Sandoval and De Pascale, 2020). Other signs of evidence are liquefaction structures (Onorato et al. 2016, 2017 and 2020) and dendrochronological studies related to such seismic events (Pedrera et al., 2014).

Journal Pre-proof

Fault Sections

Individual faults within the MFFS in eastern Tierra del Fuego are mapped and described from east to west, based on their distinctive morphotectonic characteristics.

Río Turbio fault section (FS1): it extends 6110 m from the eastern shore of Fagnano Lake to the bend of Turbio River. The most remarkable morphotectonic evidence is the scarp with a free face to the south, which develops a linear valley and diverts the Turbio River (Fig. 5 and 6). A natural exposure was observed and crossed the fault, located east of the eastern shore of Fagnano Lake, on the shoulder of National Route No. 3 (Fig. 6). Its approximate height is 5.5 m (Fig. 6b) and it is made up from base to top of glacifluvial deposits covered by till. All sedimentary levels are mainly affected by oblique-slip faults with a component of both dip-slip (normal and a few reverse) faults. Overall, these NW structures compatible with normal oblique-slip faults that are formed in the case of a left-lateral transtensional mechanism. This section is associated with the co-seismic deformations recorded by Lodolo et al. (2003) that correspond to the lagoon that developed by damming at the outlet of Turbio River and the vertical scarp (~0.5 to 1 m) in the gravel bar developed along the shore of Fagnano Lake (Costa et al., 2006).

Fault Section 2 (FS2): with a length of 3,400 m, it is located to the east of the previous fault section and it corresponds to a fault jump to the south. Pseudokarst and whaleback structures associated with this section of the fault are identified in its north block (Figure 5). A linear valley is crossed by a river that flows from west to east along this section until it merges with the Turbio River (Figure 7a). Geomorphological observations in this section allowed us to recognize the influence of the neotectonic activity of the MFFS in the development of Quaternary glacial landforms, such as the glacifluvial fan of the Turbio River. This landform began to form 26,000 + 4,500 B.P. (Onorato et al., 2020) while the watercourse drained towards the Atlantic slope as a tributary of the San Pablo River (Figure 1). At some point after the deposition of the glacifluvial deposits (during Late Pleistocene), the tectonic activity of the MFFS acted separating the apex of the fan from the rest of the landform and forcing the Turbio River runoff direction to change until it was parallel to the trend of the fault system. This led to the abandonment of the Atlantic slope to flow into the Seno del Almirantazo, a Pacificslope through the Fagnano Lake basin, resulting in how it appears nowadays.

A natural exposure approximately 20 m high, located at the western end of the section in the MFFS regional scarp (Figure 7c) shows interspersed levels of sand, gravel, and silt clay, characterized as kame terraces (Coronato et al. 2002, 2009). These glacifluvial deposits are in contact with sand and silt clay deposits (Figure 7d and e). This contact would be due to a sub-vertical normal fault that dips to the SE and trends E-W (Figure 7d). The outcrop also has a normal fault in the extreme northwest that affects some levels of the glacifluvial deposit and that inclines to the NW, the opposite trend of the previous fault (Figure 7e). It is not ruled out that this structure could be related to a gravitational process.

North of this section, in the vicinity of Estancia Don Matías (Figure 5), the ^{14}C dating by Coronato et al. (2009) at the base of the peatlands and those made by Roy et al. (2019) of 10Be concentration in glacifluvial terraces, would confirm the beginning of

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the record of tectonic deformations between ~14 ka and ~18 ± 2 ka, ages that are linked in this work (by their location) to this section of the MFFS.

De Los Castores fault section (FS3): it extends for 4,910 m in an E-W trend. Some of the most remarkable morphotectonic evidence in this section consists of: the 40 m composite scarp, the development of rounded hills resembling whalebacks and the presence of small sag ponds in the north and south block of the MFFS (Fig. 4 and 7a) (Onorato et al., 2020). A sag pond develops relative to the middle part of the composite scarp and is currently occupied by a beaver pond (Fig. 7b and c, Pt. 6 in Fig. 4). In the higher sectors of the whaleback, areas with fallen trees are also observed. These locally called "natural falling trees", with a large number of trees laying in a S-N direction, are interpreted as wind gaps. A sag pond named De Los Castores pond (of unknown depth at the moment) stands out in the south block (Fig. 4 and 7a). Further east, rounded landforms that appear to be pop-up features are distinguishable.

Throughout this fault section, Roy et al. (2019) performed displacement measurements through digital analysis of satellite images, estimating a sinistral displacement of postglacial drainage morphologies of 115 + 5m.

Towards the east of this fault section, the channel of the San Pablo River is traversed in its middle section and the composite scarp loses height. A scarp developed mainly on the east bank of the river and a structure resembling a pop up that would be associated with a fault parallel to the main system are also identified (Figure 9, Point 8 in Figure 5).

In this section, small faults in an echelon that mainly affect the north block can be seen (Figure 5 and 10a and b). Costa et al. (2006) described scarps up to 11 m high in deposits of possible Upper Pleistocene-Holocene age associated with the two Ms 7.8 earthquakes that occurred in 1949.

Fault Section 4 (FS4): it corresponds to the shortest section, only 440 m long. Although this section is markedly minor than the others, it differs from sections 3 and 5 because a scarp generated a sag pond in the north block, suggesting that this is the lower block (Figure 10c), while in sections 3 and 5, the lower block is in the south (the scarp is facing to the south). Based on the interpretation of satellite images and DEM, a fault with NW orientation is inferred, still subject to future field controls.

Journal Pre-proof

La Correntina fault section (FS5): its main feature is a well-defined rectilinear scarp, looking to the south that, despite the dense peat and forest cover, can be recognized along approximately 3,140 m, up to the Ginebra River (Figure 11a). At the eastern end of the section, a whaleback is recognized over the north block of the MFFS. The south block is lower and gives rise to sag ponds, occupied in some cases by beaver ponds. Associated with this main faulting structure, a NE fault is inferred, which generates a scarp almost 2 m high (Figure 11 b and c).

In this sector, Sandoval and De Pascale (2020) obtained average values of 110 ± 5 m to 130 ± 10 m for left-lateral horizontal displacements based on digital image analysis.

Ginebra fault section (FS6): it extends 5,780 m from the Ginebra River to the Lainez River (Figure 12a and b). A clear definition of the scarp in the forest is shown in this section. A whaleback with its greatest heights in the north block is also recognized. At least 4 sag ponds are present in the highest sectors of this landform. This morphological feature is not observed in the La Correntina fault section (FS5), which is why this section was differentiated. These sag ponds are observed as patches of open forest and some of them even have water (Figure 12 a).

Costa et al. (2006) reported a lateral displacement of fences (Figure 12a) near the Ginebra River. They estimated that the current geometry excludes a co-seismic lateral component greater than 1 m. They also pointed that the most conspicuous feature that might serve as evidence for sinistral strike-slip displacement is a 0.40 m step in the fence.

Roy et al. (2019) considered this section 6 as segment 2 “San Pablo”, and they stated a 6.2 ± 1 m sinistral offset is also visible in the foundations of an abandoned broken bridge that spanned over the fault line.

Udaeta South fault section (FS7): This fault section is 12,000 m long and is associated with other typical evidence of transform faults such as a hill that resembles a whale-back towards the west of the lake. Also, drainage inversion and offset are appreciated (Figure 5 and 13). A scarp with a free face to the north is identified and several natural exposures are recognized in the Udaeta Lake sector (Figure 13a and b). This fault section corresponds to the southern section of the pull-apart as was suggested by Onorato et al. (2019). The application of multiple geophysical methods allowed the

Journal Pre-proof

identification of a transtensional zone with two E-W main sinistral strike-slip faults with a normal component that control the North and South coasts of the lake (Onorato et al., 2019). In the latter, Onorato et al. (2016) described Holocene seismically induced soft-sediment deformation structures (Figure 13c). Besides, Pedrera et al. (2014) pointed that trees may record palaeoearthquakes directly when they grow above the fault trace and are either tilted by the fault scarp formation or sheared by the fault plane. They analysed 34 trees in the Udaeta Lake stepover, identifying asymmetric ring growth related to past earthquakes. These authors concluded that dendrochronological data suggest a rupture in the fault scarp in 1883 ± 5 and 1941 ± 10, consistent with the earthquake of February 1, 1879 (Modified Mercalli Scale, VI) and the earthquakes of December 17, 1949 (Ms 7.8). Thus, it can be unequivocally inferred that the area of the Udaeta South section has been affected by these seismic events.

Journal Pre-proof

Udaeta North fault section (FS8): it extends for 12,780 m and it corresponds to the northern fault of the Udaeta pull-apart (Onorato et al., 2019). The most characteristic morphotectonic evidence is the scarp with a free face exposed to the south (Figure 14a). In the Udaeta Lake sector, the scarp delimits the north shore and, despite the vegetation masking it, continues eastward, even affecting the peatlands (Figure 14b). Echelon faults in the north block are associated with this section and displacement scars with fallen and uprooted trees are also identified. Still standing sunken trees are observed in the lake, very close to the north shore, suggesting subsidence or lateral spreading resulting from earthquake shaking, as was mentioned by Sandoval and De Pascale (2020) along the eastern coast of Fagnano Lake.

In the Udaeta South and North sections, Onorato et al. (2019) applied multiple geophysical methods that allowed the subsoil geometry of this portion of the MFFS to be revealed. These studies suggest that the scarps of the fault sections would have been generated by transtensional strike-slip (sinistral) faulting with a minimum dip-slip (normal) component of ∼30 m for both structures, probably a releasing bend or a jump between parallel fault segments.

La Blanca fault section (FS9): it extends for 4,300 m and crosses an extensive peatland until it reaches the Irigoyen River. This section was defined La Blanca segment by Roy et al. (2019) who measured displaced fences during 1949, Mw 7.5 earthquake using GPS and obtained a sinistral displacement of 4.3 + 0.2 m.

On the south block and associated with the course of the Irigoyen River, natural exposures evidencing deposits affected by faults (Figure 15a) are observed. The faults have a general NE trend, show a normal component and are displayed in an echelon arrangement. It is inferred that they could be controlling the course of the Irigoyen River. Glacifluvial deposits composed of sands, silts and gravels (Figure 15b) are affected by one of these normal faults.

Lodolo et al. (2003) mentioned at least six short segments that constitute this part of the MFFS from Udaeta Lake to the Atlantic coast.

On the banks of the Irigoyen River, pop-up structures are also recognized (Figure 16a), which generate scarps with a displacement of more than 1.5 m (Figure 16 b and c).

<u>Fault Section 10 (FS10):</u> it extends discontinuously along 4,150 m and it is characterized by at least five faults, with a variable trend between N70° and 80° (Figure 5). The most characteristic morphotectonic evidence of this section is the small positive reliefs in the shape of pop-up structures.

<u>Fault Section 11 (FS11):</u> This section is inferred from the interpretation of the satellite images and the DEM. It extends for 5,930 m, where the alignment of the vegetation stands out as a lineament that crosses the peatland to the confluence of the Udaeta and Irigoyen rivers. Its lower block is the northern, through which the Irigoyen River flows (Figure 5). Roy et al. (2019) named this section as "Irigoyen segment". They measured a sharp sinistral offset of 5 m ± 0.5 m where the fault crossed a stream flowing southward.

<u>Irigoyen North fault section (FS12):</u> it is also inferred from the interpretation of satellite images, and it extends for 13,900 m. The structure defines the northern edge of the depression occupied by the peatlands and the river course of the Irigoyen River. It is preliminarily interpreted as the northern limit of a pull-apart type structure.

<u>Malangueña fault section (FS13):</u> It extends for 7,250 m and is the last MFFS section identified to the east onshore. The morphotectonic feature is a scarp that limits the Malangueña Hill to the north (Figure 5), with Riedel-type faults, sag ponds and associated pop-up structures. This characteristic is used as a diagnostic tool to differentiate it from section 11, in which this diagnostic evidence was not observed.

Journal Pre-proof

Roy et al. (2019) performed dating by 10Be in alluvial terraces of the Irigoyen River, indicating an exposure age of 20.2 ± 1.5 ka.

Discussion and Conclusions

Detailed geomorphological and cartographic work carried out along the eastern main fault of the MFFS, from the eastern shore of Fagnano Lake to the Atlantic coast, allowed the preliminary definition of 13 fault sections whose morphotectonic features are consistent with a main strike-slip regime. Thus, these natural heterogeneities of the geomorphological features (hills, anomalous river patterns, sag ponds, scarps) and deposits (fluvial and glacifluvial gravels, sands, silts), imply that the fault sections are not uniformly deformed. In other words, the observations allow us to infer that the ruptures were not homogeneous along the main trace of the Magallanes-Fagnano Fault System. Some of the sections could be defined more clearly, for example, those with scarps. But in those sections with indirect evidence (sag ponds or drainage anomalies), define fault sections was difficult. The evidence identified (both direct and indirect) suggests that the breakdown of this portion of the Fault System probably did not simultaneously occur in all sections. The complexity of the surface deformation is not only attributed to the heterogeneous materials of the crust as suggested by Burbank and Anderson (2011), but also to the fact that the different rupture surfaces accommodated the total displacement during the seismic events that affected the region. In the Río Turbio fault section (FS1), the structure has a marked control over the relief, mainly due to the scarp diverting the fluvial valley course and, thus, making both courses parallel to it (Figures 5 and 6). The beginning of fault section 2 is indicated by a jump to the south of the main fault trace. The link between these fault sections is interpreted as an extensional step-over geometry that has generated normal faults, pseudokarst and sag-ponds (Figures 5 and 7). The most remarkable morphotectonic evidence was identified in the fault sections 2 to 6, that is, the middle portion of the analyzed main fault trace, characterized mainly by whalebacks and composite scarps that exert drainage control (Figures 5 to 12).

Moreover, fault sections 2 to 6 are located within a local Complete Bouguer Gravity anomaly minimum of up to -49 mGal, elongated in a W-E direction (Tassone et al., 2005). Lodolo et al. (2007) applied the Second Vertical Derivative (SVD) technique to

Journal Pre-proof

the gravity anomaly, to remove the regional gravity effect and enhance local one and the obtained SVD map shows the existence of a localized, pronounced short-wavelength gravity low, which coincides with fault sections 2 to 6. Also, Lodolo et al. (2007) interpreted such gravity low as corresponding to the presence of a shallow and localized sedimentary basins. Sedimentary rocks and Quaternary glacial, glacifluvial and fluvial deposits are generally less resistant to brittle permanent deformation than igneous and metamorphic rocks, particularly if they are wet. This fact could, at least partially, explain why the most remarkable morphotectonic evidence was found along these fault sections that mainly cross these type of deposits.

To the east of the Ginebra fault section (FS6), the trace is subdivided into two sections, the Udaeta South fault section (FS7) and the Udaeta North fault section (FS8), which together form a pull-apart basin, where Udaeta Lake is emplaced (Onorato et al., 2017) (Figure 5, 13 and 14). East of fault sections 7 and 8, the MFFS continues as a single trace to Puesto La Blanca (Figure 5), where it is subdivided into fault sections 10 (FS10), 11 (FS11) to the south, and Irigoyen fault section (FS12) to the north, delimiting a second transtensional basin occupied by the Irigoyen River valley (Figure 5). The fault sections east of the Ginebra fault section (FS6), suggest a releasing bend type geometry, with the Udaeta and Irigoyen pull-apart basins and normal faults, as well as with those recognized affecting the Irigoyen River.

Further east, near the Atlantic coast, the culmination of the eastern main fault of the MFFS shows a slight change in its trend to the NE. In this sector, the Malangueña fault section (FS13) affects the northern piedmont of the hills (interpreted as a whaleback with a W-E orientation) generating rounded structures resembling pop-ups (Figure 5).

The eastern main fault trace of Fagnano Lake has previously been subdivided by Roy et al. (2018) into three segments and more recently, also by Roy et al. (2019), into eight segments. Roy et al. (2019) defined the different segments considering the 1949 surface primary ruptures and measured related sinistral slips. They pointed out that the surface rupture could be observed along 50 km, from the Lake Fagnano shore to the Atlantic coast (in their work, segment 7).

In the present work, we defined 13 fault sections. As expressed above, we use the term section with a descriptive connotation to suggest potential individual surface ruptures. We consider that the geomorphological evidence observed in the field allowed better analysis of this portion of the MFFS fault system. In this way, it was possible to define more fault sections.

Journal Pre-proof

The results of this work are based on detailed field observations carried out throughout the trace and each section of the MMFS and then contrasted with data collected from satellite images and previous research.

Also, the absolute ages available along the eastern main fault trace of the MFFS indicate that the Quaternary tectonic activity of this segment of the plate boundary has caused ruptures from at least 26 ± 4.5ka (Onorato et al., 2020) in the sector of the Turbio River alluvial fan (FS2). To the east, near the Atlantic coast, the age record for ruptures is at least 20.2 ± 1.5 ka (Roy et al., 2019).

We interpret that the surface evidence identified in this study suggests that the seismic events would have occurred mainly in the middle portion of the analyzed fault trace.

The morphotectonic evidence presented in this work for the eastern master fault of the MFFS shows that the fault system has moved at least from the Late Pleistocene to historical times almost in all fault sections (1 to 13). The eastern main fault trace of the MFFS in the Argentine territory is the one that currently has a higher density of geomorphological, geophysical and dating research that allows a better characterization compared to the rest of the MFFS. Therefore, other areas of the MFFS have scarce studies, including the fault trace near the Atlantic Ocean, where morphotectonic evidence has not yet been analyzed in detail. On the other hand, Sandoval and De Pascale (2020) described a well-defined and rectilinear master fault (~70° striking) along the north-western shore of Fagnano Lake with clear evidence of Late Quaternary surface ruptures, vegetation alignments and a 5-10 m high scarp looking to the south.

According to the field data presented in this work, when estimating the possible potential rupture unit surfaces, we suggest that sections 2, 6 and 9 have suffered the highest number of seismic events during the Quaternary, as they show the best geomorphological evidence of surface ruptures.

When using the empirical equations of Wells and Coppersmith (1994), it would be necessary an earthquake of at least Mw 6.5 to produce a rupture along each of these sections of ~ 18 km in length. However, this would not imply that in the future other sections of the fault system could rupture, such as those located to the west of Fagnano Lake or the east in the vicinity of the Atlantic coast. Also, it is not excluded that, in the case of an earthquake of Mw ≥ 7.5, the rupture occurs in several sections jointly, or in all sections at the same time, that is, a surface rupture of 600 km in length, although the latter is unlikely. Furthermore, the MFFS seems to show an irregular behavior, both in the time between ruptures and in displacement variations, which makes it difficult to

Journal Pre-proof

predict the location and magnitude of future events. However, this neotectonic analysis confirms MFFS as the main potential seismogenic source for Tierra del Fuego.

Finally, the morphostructural results presented in this work, and the results of paleoseismic analyzes collected for the eastern main fault trace of the MFFS (Costa et al., 2006; Onorato et al., 2016; Roy et al., 2019), indicate that at least the fault sections De Los Castores (FS3), Ginebra (FS6), Udaeta South (FS7) and La Blanca (FS9) generated ruptures and co-seismic displacements associated with the most recent seismic events that occurred in 1949, among other episodes. The rupture length generated by the 1949 seismic events considering the fault sections would be at least 30 km. However, it is not possible to define whether the 1949 surface rupture continued under Lake Fagnano or the Atlantic Ocean, so these values have a high degree of uncertainty since the length could have been greater. This does not imply ruling out the existence of additional co-seismic ruptures along the other fault sections identified along the MFFS, making it necessary to further morphotectonic and paleoseismic research based on detailed fieldwork throughout the system.

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Figures:

Figure 1: a: Location of the sites mentioned in the text: Isla Grande de Tierra del Fuego), the main trace of the MFFS is pointed by the red line, the eastern portion of the main trace of Magallanes-Fagnano Fault System covered in this work is indicated by the yellow line, b: Main rivers and mountains of the area of interest.

Figure 2: Tectonic setting of Tierra del Fuego (orange) modified from Smalley et al. (2003). Abbreviations: MFFS: Magallanes-Fagnano Fault System; SFZ, Shackleton Fracture Zone; PSh: Shetlands Plate; PP: Phoenix Plate; SP: Sandwich Plate.

Figure 3: Digital Globe satellite image showing the main tectonic provinces and their boundaries (modified from Klepeis, 1994; Diraison et al., 2000; Ghiglione and Ramos, 2005; and Lozano et al., 2020).

Figure 4: Seismicity of the International Seismological Centre ISC-EHB catalog: On-Line Bulletin. The star indicate the location of historical earthquakes on Tierra del Fuego: 1) February 2, 1879 (Intensity VII); 2) February 2, 1879 (Ms 7-7.5); 3) November 19, 1907 (Intensity VI); 4) June 7, 1930 (Ms 6.3); 5) July 13, 1930 (Ms 6.2); 6) November 21, 1944 (Ms 6.5); 7) December 17, 1949, (6:56 am, Ms 7.8); 8) December 17, 1949 (03:07pm, Ms 7.8); 9) December 17, 1949 (Intensity VIII); 10) January 30, 1950 (Ms 7).

Figure 5: Strip map of the fault sections of the eastern portion of the main trace of Magallanes-Fagnano Fault System. See location in Figures 1 and 4. The fault sections are indicated in black, the location of the photographs is marked with diamonds and numbers, and the morphotectonic evidence (diagnostics and non-diagnostics) mentioned in the text is marked with orange circles. Abbreviations: LV: linear valley and river, WB: whaleback, Psk: Pseudokarst, GF: glacifluvial fan, PU: pop-up structure, SP: sag pond, PA: pull-apart, DS: deflected streams, Wg: wing gap, Di: diverted drainage, PD: Paralel patron river.

Figure 6: a: Eastern shore of Fagnano Lake, a layer of gravel and sag pond at the outlet of Turbio River (Pt. 1 in Fig. 5); b: N-S oriented natural exposure in which glacifluvial deposits affected by faults can be seen (the displacement is marked with white arrows) (Pt. 2 in Fig. 5); c and e: North view of the scarp (Pt. 3 in Fig. 5), red arrows indicate the inferred fault trace; d: Southwest view of the scarp that diverts the Turbio riverbed, the inferred fault trace is indicated with red arrows (Pt. 3 in Fig. 5).

Figure 7: a: West view of fault sections 1 and 2 (Pt. 4 in Fig. 5); b: North view of the scarp of fault section 2 and sag pond (Pt. 5 in Fig. 5); c: West view of the natural outcrop affected by fault section 2 (Pt. 4 in Fig. 5); Figures d and e, corresponding to the main and secondary fault

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respectively, are indicated with a white box, with a person for scale (circled in white). Even though a gravitational origin is not ruled out for the latter, the slip plane is consistent with the MFFS trend.

Figure 8: a: North view of De Los Castores pond (Pt. 7 in Fig. 5) Red arrows point De Los Castores fault section; b and c: View of the sag ponds at the foot of scarp 2 (red arrows) (Pt. 6 in Fig. 5). Note the fallen trees on the scarp, these sectors are also interpreted as wind gaps on the summits of whalebacks.

Figure 9: a: North view of the inferred fault with NE orientation in the San Pablo River signalled by a dotted red line; b: Positive structure with a rounded shape resembling a Pop up (Pt. 8 in Fig. 5). Note the forest affected by this morphology. The fault parallel to the MFFS is indicated with red arrows.

Figure 10: a and b: Faults in echelon on the north block of fault section 3 (FS3) near Estancia La Correntina (Pt. 9 in Fig. 5), a person is indicated with a white ellipse; c: Aerial photograph to the southeast (Pt. 10 in Fig. 5). The positive and negative signs indicate the hanging wall and footwall according to the free face of the scarp and the presence of sag ponds.

Figure 11: a: Northwest oblique aerial view (Pt. 9 in Fig. 5); b: Southwest oblique aerial view of the same sector covered in the previous photograph (Pt. 11 in Fig. 5); c: South view of the scarp generated by the inferred fault and indicated in Figure b, with a person marked with a white ellipse (Pt. 12 in Fig. 5).

Figure 12: a: Northwest oblique aerial view (Pt. 14 in Fig. 5), the measurement sector of Costa et al. (2006) is indicated with a pink triangle; b: Southeast oblique aerial view (Pt. 15 in Fig. 5).

Figure 13: a: Southwest view of the scarp of the Udaeta South fault section (FS7), the profile described in Onorato et al. (2016) is marked with a white box; b and c: Photographs of the profile and detail of a part of it, respectively (Pt. 16 in Fig. 5).

Figure 14: a: Northwest view of the lakeshore, a few meters away the development of the scarp corresponding to the Udaeta North fault section (FS8) (Pt. 17 in Fig. 5) is observed; b: Photograph of the scarp, in its upper part a person is marked with a white ellipse (Pt. 17 in Fig. 5).

Figure 15: a: Echelon fault scarp (indicated with red arrows) on the Irigoyen river bank (Pt. 18 in the plan view, Fig. 5); b: The tectonic scarp in glacifluvial deposits with the free face looking east (Pt. 19 in Fig. 5).

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Figure 16: a: Inferred Pop-up like structure located on the north shore of the Irigoyen River, two faults are observed to the east; b and c: Detail of the scarps and affected glacifluvial levels (Pt. 20 in Fig. 5).

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Highlights

“Detailed morphotectonic analyses of satellite images, plane recognition, digital topographic data, and field surveys allowed us to identify thirteen discrete fault sections.”

“The sections show opposite north- and south-facing scarps alternating along strike”

“Linear rivers and valleys, drainage anomalies (e.g. diverted, deflected or offset streams), behead meanders, wind gaps, sag ponds, pull-apart basins and linear ridges, are the most common morphotectonic features.”

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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