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# Seismically-induced soft-sediment deformation structures associated with the Magallanes–Fagnano Fault System (Isla Grande de Tierra del Fuego, Argentina)

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ABSTRACT

In this paper, evidence of paleoearthquake-induced soft-sediment deformation structures associated with the Magallanes–Fagnano Fault System in the Isla Grande de Tierra del Fuego, southern Argentina, has been identified. Well-preserved soft-sediment deformation structures were found in a Holocene sequence of the Udaeta pond. These structures were analyzed in terms of their geometrical characteristics, deformation mechanism, driving force system and possible trigger agent. They were also grouped in different morphological types: sand dykes, convolute lamination, load structures and faulted soft-sediment deformation features. Udaeta, a small pond in Argentina Tierra del Fuego, is considered a Quaternary pull-apart basin related to the Magallanes–Fagnano Fault System. The recognition of these seismically-induced features is an essential tool for paleoseismic studies. Since the three main urban centers in the Tierra del Fuego province of Argentina (Ushuaia, Río Grande and Tolhuin) have undergone an explosive growth in recent years, the results of this study will hopefully contribute to future analyses of the seismic risk of the region.



## 1. Introduction

Soft-sediment deformation structures (SSDS) are the result of liquefaction or fluidization in water-saturated unconsolidated sediments that may be caused by various natural processes (Owen, 1987). They occur during or after deposition, when the sediment is still unconsolidated (Maltman, 1994), providing valuable information about the syn- or post-depositional physical processes that have taken place in the sedimentary environment, as well as changes in the hydrodynamic conditions and the paleo-seismic characteristics (Van Loon and Brodzikowski, 1987; Van Loon, 1992). The SSDSs result from the combination of a deformation mechanism, which allows sediment to behave temporarily as a fluid (i.e. liquidization, Allen, 1977), and a driving force, which is latent in the sediment under normal conditions and manifests itself when liquidization occurs (Owen, 1987, 1996, 2003; Suter et al., 2011). The trigger agents that generate these structures may be related to different processes during deposition or to external pressure fluctuations associated with storm waves, turbulent flow (Eyles and Clark, 1986; Molina et al., 1998; Alfaro et al., 2002), tides (Greb and Archer, 2007), rapid sedimentation (Lowe and LoPiccolo, 1974; Lowe, 1975; Postma, 1983), overloading (Moretti et al., 2001; Moretti and Sabato, 2007; Owen and Moretti, 2008), gravity sliding (Owen and Moretti, 2008) or earthquakes (Audemard and De Santis, 1991; Obermeier, 1996a, 1996b; Pope et al., 1997; Alfaro et al., 1999; Moretti et al., 1999; Rossetti, 1999; Moretti, 2000; Tuttle et al., 2002; Wheeler, 2002; Audemard et al., 2005; Neuwerth et al., 2006; Moretti and Sabato, 2007; Suter et al., 2011).

The term seismites is used to describe all geologic structures and sediments genetically related to earthquakes (Vittori et al., 1991). The study of seismites is important for the reconstruction of the palaeoseismic history of a region; such study can be carried out by determining the seismic nature of the different seismogenic features, as well as by establishing the magnitude and date of the pre-historical earthquakes (Michetti et al., 2005). Most intense and abundant soft-sediment deformation features are related to a nearby seismic area, as is indicated by the spatial distribution of clastic dykes and the size of associated structures (Obermeier, 1994, 1998). Magnitudes of paleo-earthquakes can been estimated by noting the regional extent and size of liquefaction features and comparing these data to known earthquakes in similar settings (Obermeier, 1998). This information is important to arrive at estimates of earth-quakes strengths.

The island of Tierra del Fuego is crossed by the Magallanes–Fagnano Fault System (MFFS), which corresponds to the continental segment of the transform margin between the Scotia and South American plates (Fig. 1).

The SSDS presented in this paper were recognized in the sedimentary deposits located in the southern coast of a small pond of Tierra del Fuego,

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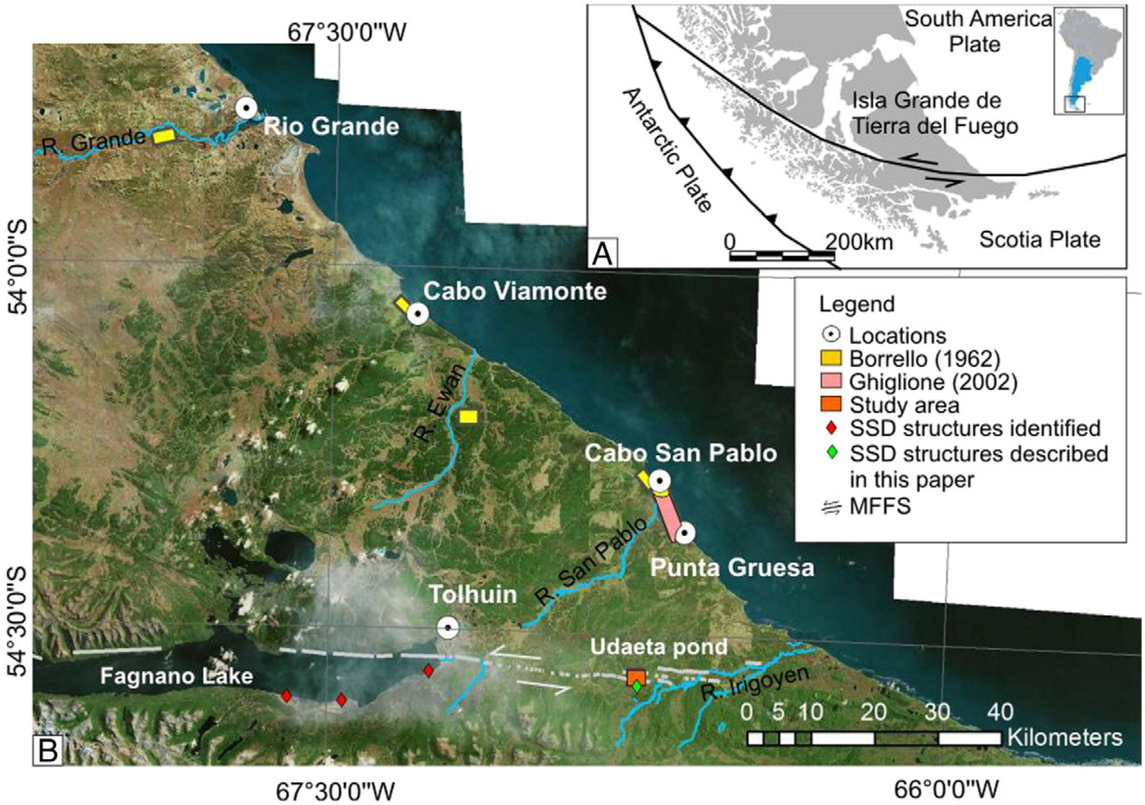


**Fig. 1.** A) The Isla Grande de Tierra del Fuego in the southern tip of South America, B) places mentioned in the text.

named as Negra pond (Torres-Carbonell et al., 2008; Pedrera et al., 2014; Perucca et al., 2015) or Udaeta pond (Onorato et al., 2015). It occupies a segment of the main axis of the MFFS and it is located about 30 km east of the headwall of Fagnano Lake, in the central-eastern portion of the Isla Grande de Tierra del Fuego. The study area is located at: 54°32′29.42″–54°34′42.59″ S and 66°48′0.6″–66°41′47.88″ W being Udaeta pond at the center of this area (Fig. 2).

There are few records of seismites in the Holocene deposits associated to the MFFS: In the southern cliffs of Fagnano Lake and in the coastal outcrops of Udaeta pond (Fig. 1). These sedimentary sequences include glaciofluvial, till, and interspersed paleolake deposits, and contain clastic dykes of variable dimensions and liquefaction structures which have already been interpreted to be of seismic origin (Onorato et al., 2014, 2015).

The SSDS features in the Isla Grande de Tierra del Fuego were first described by Borrello (1962), who identified them in a Late Cretaceous and Cenozoic sedimentary succession located between the Grande and San Pablo rivers, along the Atlantic Ocean coast of the island. They were also described as epigenetic dykes by Ghiglione (2002, 2003), who measured the trends of these clastic dykes in the localities of Cabo San Pablo and Cabo Viamonte and proposed that they were generated by a two diachronous, transpressive seismic events that affected the Austral Basin during the Early Miocene (Fig. 1) (Ghiglione, 2003).

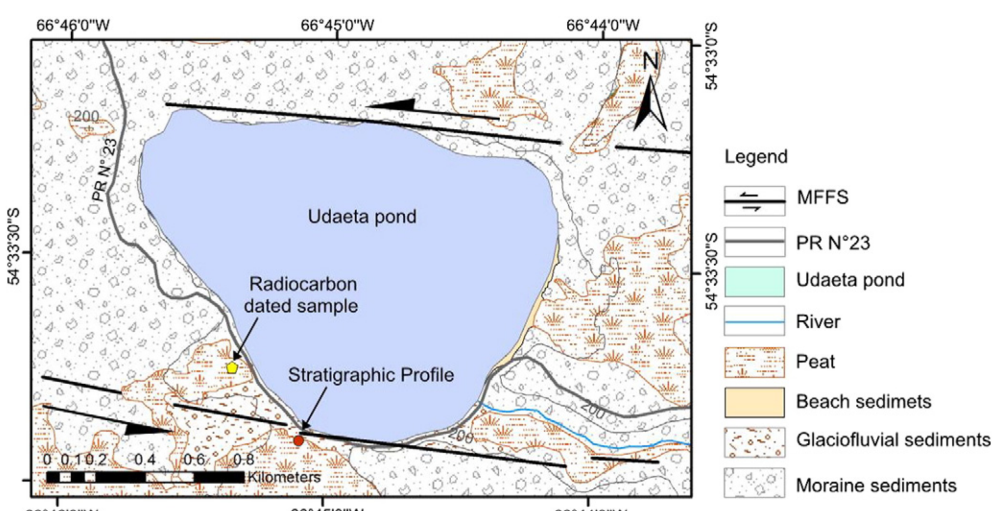


**Fig. 2.** Study area, location of the studied section and dates.

In this paper, we describe several SSDS involving Holocene lacustrine deposits outcropping in the Udaeta pond area. The study and recognition of paleo-liquefaction structures are a very useful tool in regions such as the Isla Grande de Tierra del Fuego, for which there is a lack of historical seismic data. The main objective of this study is to determine their relationship to tectonic activity and possible paleo-seismic events.

## 2. Geological setting

From south to north, the Isla Grande de Tierra del Fuego can be roughly split into several morphostructural WNW trending provinces (Kranck, 1932; Winslow, 1982; Dalziel and Brown, 1989; Olivero and Martinioni, 2001). The Magallanes–Fagnano Fault System corresponds to the continental segment of the transform margin, involving two structural domains: a thin-skinned domain north of the fault, and a thick-skinned domain south of the fault (Winslow, 1982). The MFFS trends N 89°W and its length is about 200 km, although some authors suggest a total length of about 400 to 800 km (Winslow, 1982; Dalziel and Brown, 1989; Klepeis, 1994; Lodolo et al., 2002). The MFFS strikes NW in the western Chilean region of the Isla Grande de Tierra del Fuego changing its orientation to E-W in Argentina. It comprises distinct tectonic alignments arranged "*en échelon*" with the main segments exhibiting near-vertical faults (Lodolo et al., 2003).

Torres-Carbonell et al. (2008) noted that the compressive regional structure that forms part of the Fuegian thrust-fold belt has a horizontal lateral offset of ca. 48 km along the MFFS. These authors reported a maximum age of ~7 Ma for the beginning of the strike-slip regime in this sector and they determined that this Late Miocene age coincides with the creation of the divergent plate boundary between the Sandwich and Scotia plates, proposed as the mechanism responsible for the beginning of the strike-slip activity between South America and Scotia Plates.

Along the entire MFFS trace there is evidence of active sinistral movement (Lodolo et al., 2003). For instance, east of Fagnano Lake, the morphological evidence for Quaternary tectonic activity is associated with truncated meanders and abrupt changes in stream channel orientation, truncating of glaciofluvial fans (Coronato et al., 2002, 2009) and post-depositional structures in glacial sediments (Bujalesky et al., 1997). Perucca et al. (2015) briefly described some morphotectonic features along the MFFS, including linear valleys, offset or deflected streams, broom-shaped rivers, wind gaps across the scarp fault, abandoned fluvial valleys, shutter ridges, sag ponds, pressure ridges, truncation of sand meanders and changes in the direction of the streams providing a tool for the identification of Quaternary tectonic activity. These authors also observed several dammed channels upstream of the scarp indicating that erosion is less significant than recent tectonic activity. The Udaeta pond is a pull-apart basin (average width of over 1.5 km) developed between two overlapping segments of the MFFS (Perucca et al., 2015; Onorato et al., 2015) (Fig. 2).

The most important geological units recognized in the area belong to the Fuegian fold and thrust belt (Ghiglione, 2003). Torres-Carbonell et al. (2008) distinguished two major stratigraphic units: Late Cretaceous and Paleocene, each involving unique lithostratigraphic units. According to these authors, structural evolution of the area includes two major tectonic events, linked to the regional, geological evolution of Isla Grande de Tierra del Fuego. The first event is part of the development of the Fuegian fold and thrust belt and the second one, includes the MFFS, trending transverse to and cutting previous compressive structures.

## 3. Historical seismicity

According to Lomnitz (1970) and Martinic (1988) the first historical earthquake recorded in the study area occurred on February 2nd, 1879, with a magnitude of 7 to 7.5. However, Perucca and Moreiras (2009) mentioned a previous event based upon a Yaghan (aboriginal inhabitants of Tierra del Fuego) legend when, at least one ancient seismic earthquake took place before the European colonization (Bridges, 2000).

The largest instrumentally recorded event in the region of Isla Grande de Tierra del Fuego occurred on December 17th, 1949. Lomnitz (1970) estimated a magnitude of Ms. = 7.5 while the Pasadena seismic station (U.S.A.) reported an Ms. = 7.8 for two large events (Goodstein et al., 1980).

Smalley et al. (2003) calculated an earthquake recurrence interval of 750 years for this MFFS earthquake of M = 7.8 and Costa et al. (2006) recognized evidence of three major seismic events during the last 8000 years. These authors estimated a maximum average recurrence interval of 2000 years for the formation of surface ruptures.

Cisternas and Vera (2008) reported that these two large earthquakes caused numerous secondary effects, such as landslides in the western coast of the Isla Grande de Tierra del Fuego, and substantial changes in the water level of Fagnano Lake.

Waldmann (2008) obtained a recurrence rate of 800–1000 years for slumps located within Fagnano Lake, which he associated to high-intensity seismic activities. González Bonorino et al. (2012) indicated that strand plain deposits have been impacted by MFFS movements at least six times between 0.9 and 6.4 ka BP, providing an average recurrence rate of about 1000 years.

Along the southern shore of Udaeta pond, and a short distance from the outcrops described here, dendrochronological research was carried out by Pedrera et al. (2014). They identified deformation structures within trees which grew between 1883 ± 5 and 1941 ± 10 in the rupture zone of the MFFS escarpment, and related these to seismic events which occurred in 1879 and 1949 in Tierra del Fuego.

## 4. Methods

A natural exposure of 5 m long and 2.80 m high, located in the southern shore of Udaeta pond was described in order to analyze deformation structures. Many soft-sediment deformation features such as sand dykes, convolutions, load structures and small faults were analyzed, and their distribution was established. Sediment textures were obtained by sieving, using N°1/4 (6.3 mm), N°10(2.0 mm) and N°18(1.0 mm) sieves, as well as a Malvern MASTERSIZER 2000 sedi-graph.

Near the study area, a radiocarbon age was obtained for peat associated with a tephra unit (Fig. 2). Radiocarbon ages were calibrated using the Shcal13.14c Calib Radiocarbon Calibration Program, of Stuiver and Reimer (1993) and Hogg et al. (2013).

## 5. Results and analyses

### *5.1. Lithologic, environmental and timing constraints of the SSDS occurrence*

The Udaeta pond is located in the central-eastern portion of the island of Tierra del Fuego, approximately 30 km east of the town of Tolhuin at the head of Fagnano Lake (Fig. 1). SSDS structures within interbedded glaciofluvial and glaciolacustrine deposits were exposed during construction of Provincial Route N°23, near the southern shore of Udaeta pond.

The stratigraphic section is 2.80 m high (Fig. 3) and is composed of detrital sedimentary deposits (silt and sand, with a smaller amount of clay), which were deposited in a glaciolacustrine environment.

Eleven units numbered LU-1 to LU11 from the base to top of the section, were recognized in the stratigraphic section. The unit LU-1 comprises boulders, cobbles, pebbles and very coarse sand. The unit LU-2 is composed of cobbles, pebbles and a higher percentage of sand. Both units are highly oxidized, with no internal structure, and irregular bodies of sands. Unit LU-3 is composed of finer materials, with 80% silts in the lower beds and 90% well-sorted sands near the top of the unit. Color also varies vertically, from light brown to dark brown. Unit LU-3 is a silt-clay, lens-shaped unit with irregular upper and lower contacts.

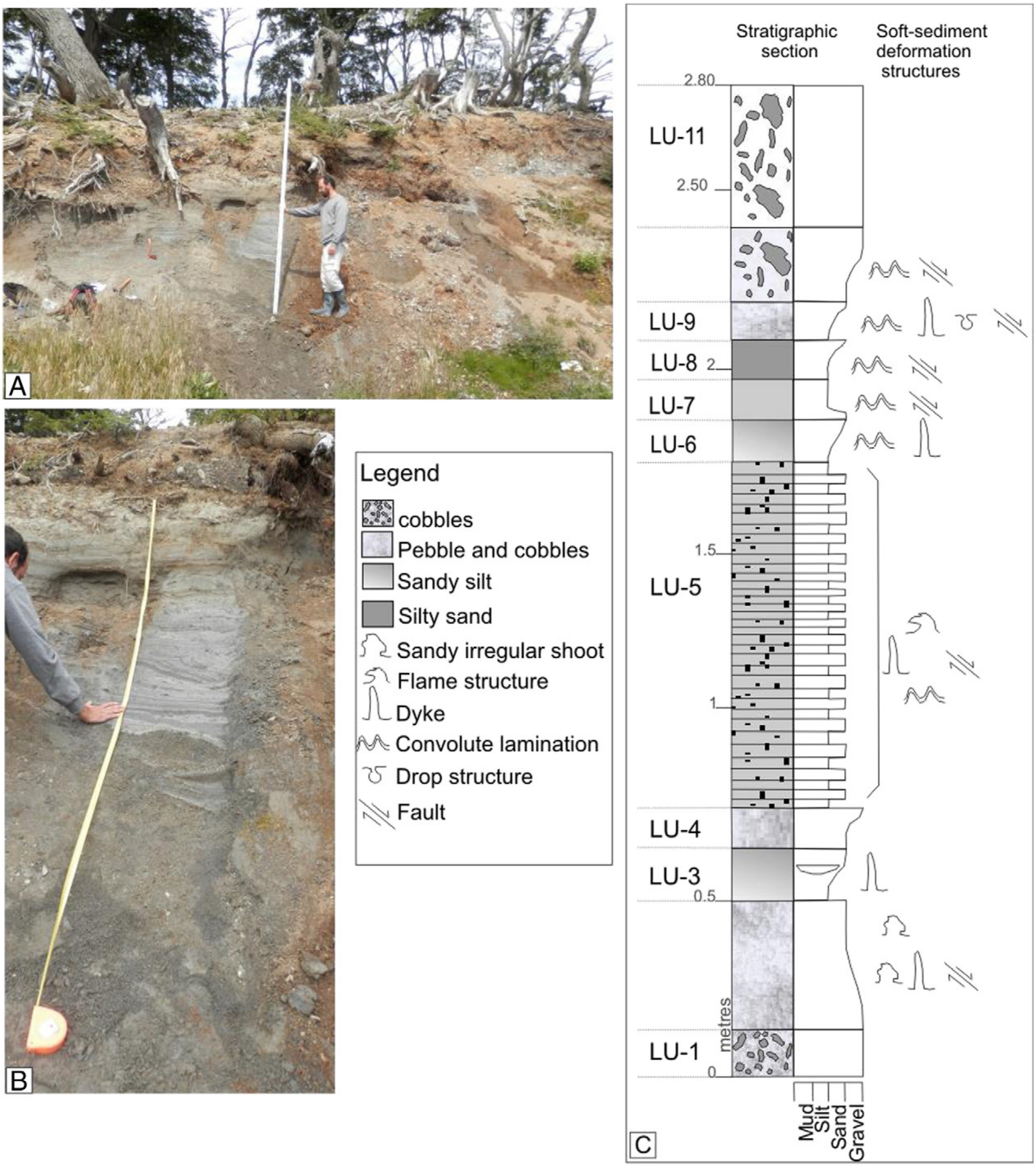


**Fig. 3.** A) and B) Overview photo of outcrop. C) Sedimentary logs with deformation structures in the Udaeta pond area.

Unit LU-4 is composed of coarse sands, fine gravels, and darkish gray cobbles.

Unit LU-5 extends for 1.05 m, from the top of the unit LU-4 down to the base of LU-6, occupying most of the section. This unit has been divided into 7 sub-units, based on grain-size characteristics. Several alternating layers of varying thickness, interpreted as rythmites, form a glaciolacustrine unit within LU-5. The deformation structures described below have been identified in this level, and extend to the top of the stratigraphic profile (LU-5). Grain-size measurements reveal a large percentage of silt with a consistent value of 80–90%, and where the percentage of silt decreases, the percentage of sand increases. The clay content is low, having a mean value of 15% throughout the whole of unit LU-5. Unit LU-6 reveals silt dominance (90%) at the base, decreasing towards the top of the unit (70%). Its color varies vertically from light gray to reddish gray with the bulk of the outcrop revealing strong oxidation. Unit LU-7 is generally light gray in color, and the color contrast within the rhythmites is small. Unit LU-7 is mostly composed of silts, with very low clay and sand content. Towards the upper part of the stratigraphic section, unit LU-8 reveals a higher percentage of silts near its base and alternating silts and sands near its top. Unit LU-9 contains an average of 70% silts, with an increase of sand content near the top. Roots first appear in Unit LU-9. Units LU-5 to LU-9 are highly distorted, with an abundance of soft-sediment deformation features, among them clastic dykes, convolutions, flame structures, and faults.

Unit LU-10 is highly disturbed by roots, and reveals leached deposits with mottled staining, likely due to podzolic soil processes. At its base it contains gravels and very coarse sands.

At the surface, the outcrop is covered by the modern soil (unit LU-11), which reveals burnt roots and fallen trees, and in this unit no deformation structures were recognized. The age of this sedimentary sequence is not known. However, 500 m northwest of the outcrop, the roadcut exposes a 1.70 m thickness of Sphagnum sp. bog deposits. Like all peatlands in the region, the bog has developed on silty clay deposits laid down in a shallow lake or river floodplain. About 1.50 m below the present landscape surface, the peat contains a 5 cm thick layer of gray-green volcanic ash. Organic matter located immediately underlying and overlying the tephra layer yielded a radiocarbon age of 7184 ± 47 ka B.P. and 5124 ± 47 ka B.P., respectively (Table 1). These radiocarbon ages suggest that the tephra represents one of the mid-Holocene eruptions of Hudson Volcano, in the Southern Volcanic Zone (SVZ) of the North Patagonian Andes (45°54′S/72°58′W) (Naranjo and Stern, 1998; Stern, 2007). Hudson ashes are composed of medium to high $K_2O$ calc-alkaline rocks that are also relatively rich in $TiO_2$, $Na_2O$, and have unique trace elements, including large-ion-lithophile (LIL), rare-earths (REE), and high-field-strength (HFSE) elements, when compared with tephras of similar silica content from other volcanoes in both the Andean SVZ and AVZ (Stern, 1991). Additionally, samples from the Hudson Volcano have higher $^{87}Sr/^{86}Sr$ ratios than other volcanoes in the southern SVZ.

### 5.2. Soft-sediment deformation structures (SSDSs): morphology, deformation mechanism; driving force system and possible trigger agent

The SSDSs described in the outcrops of Udaeta pond were characterized in terms of their geometry, and were grouped by morphological types: clastic dykes, convolute laminations, load structures and faulted soft-sediment deformation features.

#### 5.2.1. Clastic dykes (D)

Three clastic dykes were recognized in the Udaeta pond area (Fig. 4). They generally form discordant and nearly-vertical conduits that cross the surrounding sub-horizontal sedimentary laminae. One of these has a dominant silty composition, and corresponds to a smaller sized dyke, having a length of 25 cm and an average width of 1 cm (Fig. 4A). The other two dykes are mostly composed of oxidized sands, and have lengths of 30 cm and 60 cm, and maximum widths of 2 cm respectively (Fig. 4B, C). The dykes dip towards the west with values ranging from 30° to 45°. The silty dyke occurs along a normal fault that in turn, truncates convoluted laminations. The dykes end to the upper layers and appear to have been filled with sediments, lacking a clear internal structure, but derived from an underlying source.

Clastic dykes are typical sediment-injection structures (Owen et al., 2011) originated by fluidization processes when sediment with a low minimum fluidization velocity (Lowe, 1975) is transported by water escape. Interstitial pressure can rise after complete liquefaction when the presence of permeability barriers does not allow an upward-directed simple filtration of water. Rupture of overlying permeability barriers induces the formation of vertical conduits filled by water and the escape of finer sediments, which intrude hosting coarser sediments until they reach the water/sediment interface. It is possible to consider the vertical shear stress as the driving-force system.

Owen et al. (2011) suggest that some critical data coming from both detailed morphological description and facies analysis represent key criteria to distinguish between possible triggering processes linked to the sedimentary environment dynamics (endogenic trigger) and others of external origin (exogenic triggers). In this case, clastic dykes formed by intrusion of liquidized sands resulting from liquefaction triggered by seismic shocks.

#### 5.2.2. Convolute lamination (Cl)

These have been recognized mostly in the upper portion of the stratigraphic column, where the silt layers are dominant and several levels are faulted (Fig. 4B). Folds show dimensions up to 6 cm high and 7 cm amplitude. These features appear to be post-depositional convoluted laminations, according to the classification of Allen (1982). Some of the sedimentary units in the outcrop are folded, and show anticlines and synclines. The anticlines are crossed with steep linear dykes, and the escaping fluids appear to have generated flame structures (Fs) (Figs. 4A, 5). These structures are comparing with similar SSDS described by Ezquerro et al. (2015) and Moretti and Ronchi (2011). The folds shown in Figs. 4A, 5 are bent towards the east. Anticlines have steep interlimb angles whereas synclines show rounded hinges. These structures are restricted to single stratigraphic layers separated by undeformed beds. Deformation disappears near the top and base of each affected level.

Convolute lamination is considered to be the result of reversed density stratification (Anketell et al., 1970) and/or dissimilarities in resistance against upward directed forces of extruding pore water (Wunderlich, 1967) or air (Stewart, 1956). In addition, external shocks (earthquakes etc.) have been suggested as the mechanism causing liquefaction with the resulting mobility of the sediment. Besides, submarine sliding and slumping (Rich, 1950, cit. Davies, 1965) and intrastratal flow (Williams, 1960) have been suggested as possible modes of origin (De Boer, 1979). However, the latter has been excluded in the study area since they are not compatible with the observed sedimentary environment.

As the upper contacts of these layers with the overlying strata are nearly flat, an internal flow within the sand layers could cause the convolutions. We suggest that in the Udaeta pond area, the silty clay was deformed as a result of the combined effects of liquefaction and shear stress, generated by the passage of seismic waves.

#### 5.2.3. Load structures

We have recognized deformed beds with load structures. The observed superposition of gray fine to coarse-grained sands (heavy) on whitish fine-silt and clayey silt is a driving force system (sensu Owen, 1987) related to a gravitational instability (Rayleigh–Taylor instability, or reversed density gradient system of Anketell et al., 1970). The formation of load-structures was induced by a partial gravitational readjustment that acted simultaneously with the loss of shear strength in the sediments. The water-escape features can be directly related to gravitational readjustment (upward-directed movement of underlying light sands), and/or it can be the result of selective fluidization processes arising from the restoration of grain supported packing after complete liquefaction (Allen, 1982; Owen, 1987; Moretti et al., 1999).

Drop structures (Figs. 4A, B, D, 5) are formed by the sinking of load casts into water-saturated fine sediments, and have a similar origin to load casts but are associated with a more advanced stage of deformation (Alfaro et al. 1997). The identified drop structures (Figs. 4B, D, 5B), have a sub-spherical morphology and occur mainly in the upper portion of the stratigraphic sequence.

**Table 1**
$^{14}C$ and calibrated ages of peat below and above a tephra layer deposited in the West Udaeta peat-bog. Program Shcal13.14c is part of Calib Radiocarbon Calibration Program, after Stuiver and Reimer (1993) and Hogg et al. (2013).

| | $^{14}C$ age | Laboratory code | 2σ calibrated age (B.P.) | Confidence value |
|---|---|---|---|---|
| Overlying peat | 5124 ± 47 | AA62814 | 5710–5927 | 0.98 |
| Underlying peat | 7184 ± 47 | AA62813 | 7844–8047 | 1 |

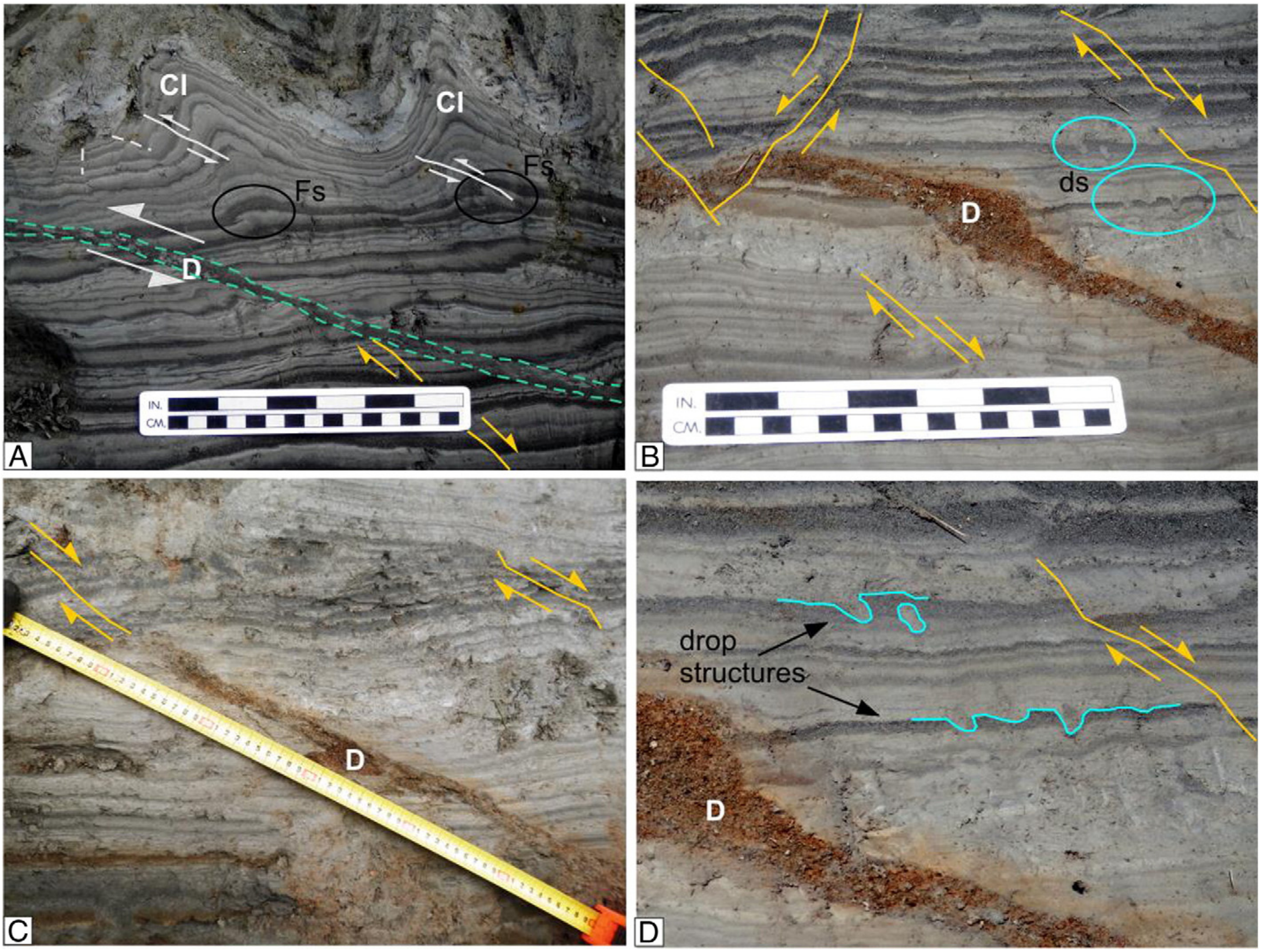


**Fig. 4.** A) A major SSDS predominantly composed of a silty *dyke (D)*; this dyke occurs alongside a reverse fault (white), and at its lower right portion it has a minor normal fault (yellow). The *Convoluted lamination (Cl),* with faulted anticlines and *Flame structures (Fs)* as indicated by circles. B) A predominantly sandy *dyke (D)* of reddish color, implying a high degree of oxidation, and the normal faults that affect it; the *drop structures (ds)* are highlighted in circles. C) A predominantly sandy *dyke (D)*, deeply oxidized, is not affected as in the previous example, but normal faults are exposed in the upper portion of the image, affecting only the beds of finer sediments. D) Detail of drop structures in Fig. 4B, the *dyke (D)* and a normal fault affecting the bed containing drop structures.

This load structures formed by an overloading process (driving-force system) that was able to induce liquefaction in the soft substrate and allowed partial gravitational re-adjustment. We considered that the possible trigger mechanisms are earthquakes.

#### *5.2.4. Faulted soft-sediment deformation features*

Sub-parallel faults affect many soft-sediment deformation structures in the Udaeta pond sequence (Fig. 6A, B, C, D). Most are normal faults with centimeter displacements and dipping angles varying between 40° and 80°. Fig. 6C shows stepped and parallel normal faults, whereas Fig. 6B shows a sand dyke (Sd), with a similar inclination to the main normal fault. The SSDS are mostly affected by normal faults, indicating that the dominant stress field is locally extensional.

Owen (1987) pointed out that brittle deformation corresponds to cohesive behavior, where increase in pore water pressure is not enough to liquefy sediments. Rossetti and Góes (2000) considered these to be associated with unconsolidated or partly consolidated sediments. Normal faults recognized in the Udaeta pond area indicate a tectonic environment controlled by extensional movement and they are evidence of the neotectonic activity of the MFFS. This is consistent with previous characterization of the Udaeta pond as a Quaternary pull-apart basin (Perucca et al., 2015).

## 6. Discussion

The analyses carried out on the soft-sediment deformation structures of the outcrops of Udaeta pond allow us to establish the mechanism of deformation and the driving force system for deformation, and so to infer the most probable trigger agent for this features.

The studied outcrop contains several sedimentary units with deformation structures for which the grain size is predominantly silts and sands. Such grain size fractions are highly susceptible to liquefaction. Deformation structures identified in this study can be compared with numerous examples studied elsewhere around the world (eg.: Alfaro et al., 2002; Rodríguez-López et al., 2007; Sandeep and Arvind, 2007; Martín-Chivelet et al., 2011; Ezquerro et al., 2015) where SSDS are closely related to seismic events.

A topic of interest is the sedimentary environment in which the SSDS are located. During the Late Cenozoic, the Isla Grande de Tierra del Fuego was affected by a succession of glacial advances that modified the central region of the island (Caldenius, 1932; Auer, 1959; Bujalesky et al., 1994; Rabassa, 2008; Coronato et al., 2009; Coronato and Rabassa, 2011), and Quaternary glaciations reached the study area during the Middle Pleistocene. These glaciations preceded the Last Glacial Maximum (LGM), whose better defined, easternmost

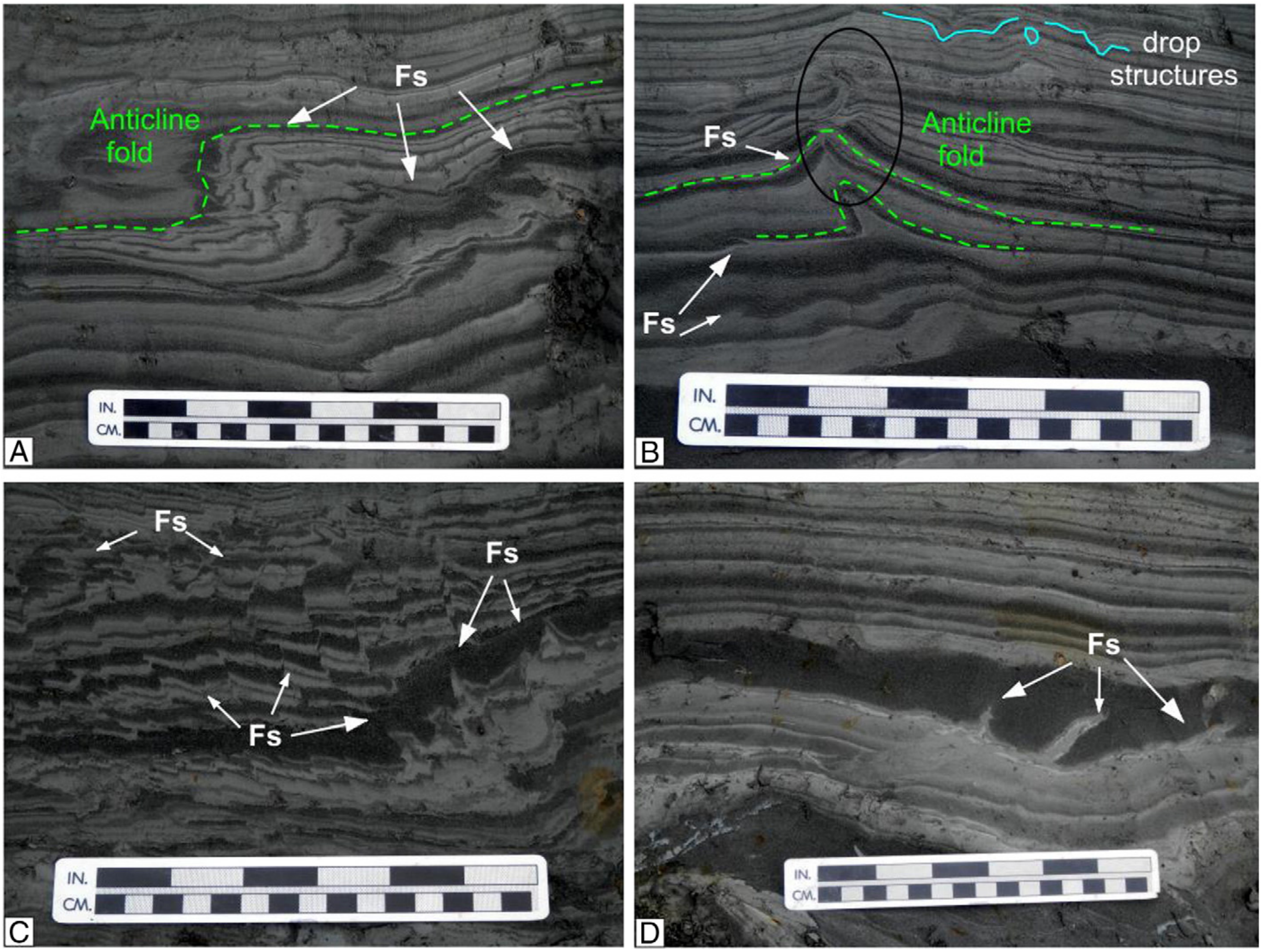


**Fig. 5.** A and B) *Flame structures (Fs)* and folds, show anticlines and fluid escape with drop structures in 5B, C and D), *Flame structures (Fs)*.

boundary is located 15 km NW of Udaeta pond (Coronato et al., 2009; Meglioli, 1992).

Since the deposits accumulated in paleo-drainages that carried water from melting glaciers of the Sierra de Irigoyen, located at the S–SW of Udaeta pond, they should not be older than the Last Glacial Maximum (LGM) or the Late Glacial, suggesting that a glaciotectonic origin can be ruled out. Gravels, sands and silts were deposited by paleostreams whose elevations were closely related to paleolake levels.

The analysis of SSDS features such as clastic dykes and flame structures, suggests the upward movement and escape of fluids. Folds are bent towards the east and show rounded synclines and abrupt anticlines. We suggest a seismic triggering as the cause of complex convoluted folding and normal faulting within lacustrine sediments and propose that escaping water-sediment mixtures from a liquefied source bed was responsible for the adjacent clastic injections. Parallelism of clastic dykes and adjacent normal faults as well as the upward injection of sand along joints is more consistent with seismically induced features, as shown by Rodríguez-Pascua et al. (2000). The local dendrochronological data reported by Pedrera et al. (2014) was obtained only a few meters distant from the SSDS site, and suggests a rupture on the MFFS fault scarp in 1883 $\pm$ 5 and 1941 $\pm$ 10, coincident with the February 1, 1879 (Modified Mercalli Scale, VI) and the December 17, 1949 (Ms 7.8) earthquakes in Tierra del Fuego. This allows us to infer unequivocally that the study area was affected by several seismic events.

Besides, the magnitudes of palaeo-earthquakes can been tentatively estimated in the area by noting the regional extent and size of liquefaction features and comparing these data to similar features resulting from known earthquakes in similar settings (Munson et al., 1995; Obermeier, 1994, 1998). For example, seismically induced pseudonodules require earthquake magnitudes probably exceeding a magnitude of 6.5 for their formation and clastic dykes have been interpreted as related to earthquakes of magnitudes ranging from 5 to 8 (Obermeier et al., 2001).

## 7. Conclusions

Several soft-sediment deformation structures, including clastic dykes, convolute laminations, load structures and faults developed during sedimentation in a Holocene lacustrine environment.

These soft-sediment deformation structures in the Udaeta pond area are interpreted as seismites that have been caused by earthquake-related shocks, MFFS have prehistorical, historical and instrumental seismic events with M>5 (Sabbione et al., 2007a, 2007b) and so it was likely to be the probable seismogenic source that produced the seismites in Udaeta pond area.

It would be desirable in the future to find new evidences of SSDS in other outcrops along the MFFS and to carry out more precise dating to propose a pre-historic earthquake chronology. The identification and study of new soft sediment deformation structures, combined with

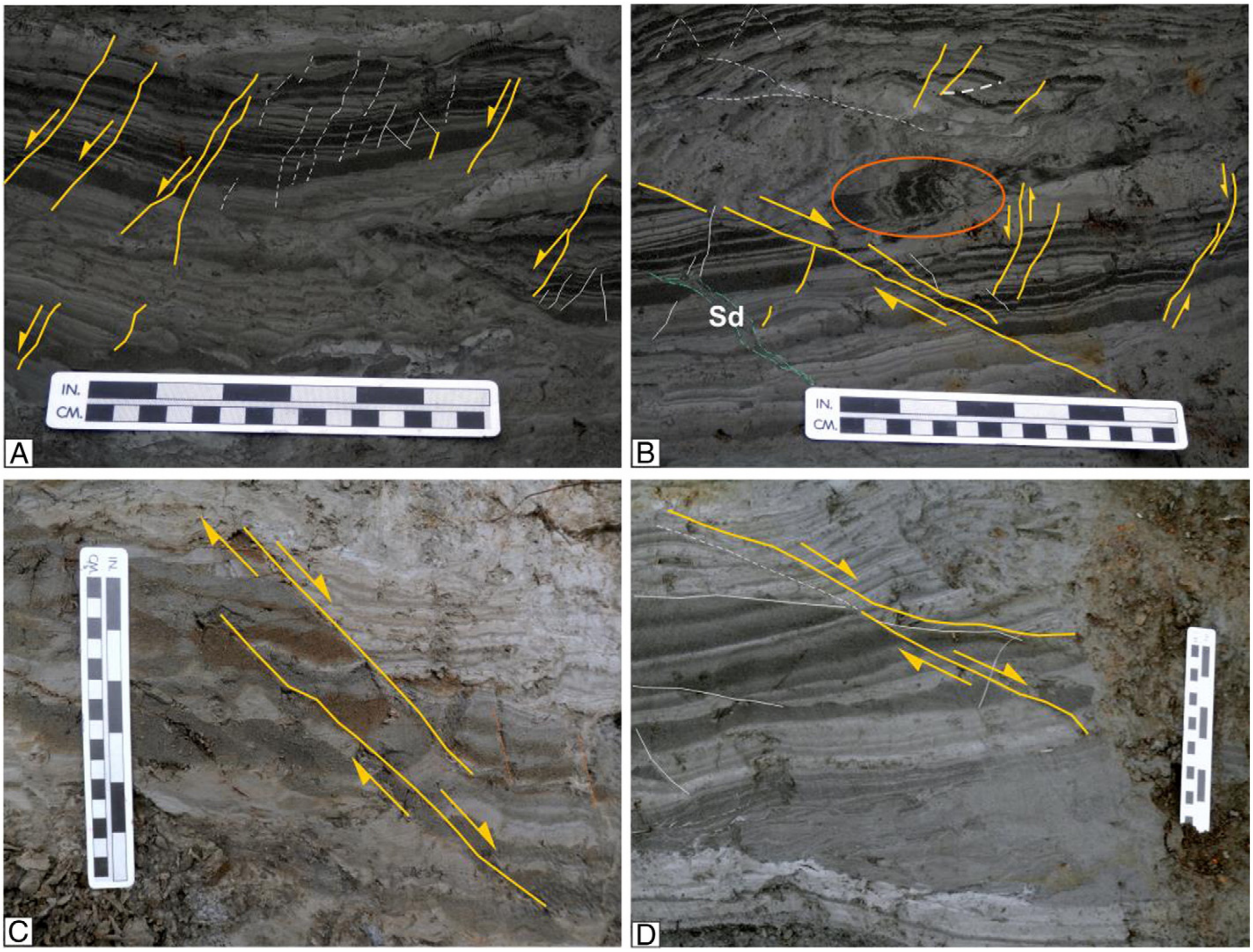


**Fig. 6.** Faulted soft-sediment deformation features. A and B) parallel normal faults and a sand dyke (Sd), with a similar inclination to the major normal fault were identified. In B), an orange circle depicts a rotated block, which has been displaced from the beds affected by the main fault. C and D) the faults affect oxidized sandy beds, as in 6C.

detailed analysis of the local sedimentology and stratigraphy, can serve as a useful tool in evaluating the potential seismic hazard of the Isla Grande de Tierra del Fuego and specifically, of the city of Tolhuin, which is located in the MFFS trace.

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