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Paleo-earthquakes in passive-margin settings, an example from the Paleocene of the Golfo San Jorge Basin, Argentina

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ABSTRACT

Paleocene sedimentary rocks in the Golfo San Jorge Basin include the marine Salamanca Formation and the continental Río Chico Formation. Both units contain soft-sediment deformation features and evidence of contemporary tectonics, which include: 1) sediment-filled fissures, hosted in muddy marine sediments of the Salamanca Formation ("Fragmentosa" Section), where the sandy infill of the fissures took place from above; 2) synsedimentary normal faults in the uppermost levels of the Salamanca Formation, with vertical throws rarely exceeding 1 m; 3) fault-graded beds in the "Banco Negro Inferior" (marine–continental transition), which show a deformed sequence with small-scale normal faults at the bottom and intraformational breccias on top; and 4) liquefaction and/or fluidization pillars, "V" or funnel-shaped, with vertical extension of up to 5 m and preserved into fluvial channels of the Río Chico Formation. Deformed strata are bounded by undisturbed horizons and some of these features can be correlated along 60 km of exposures.

The suite of soft-sediment deformation structures is considered a secondary evidence of synsedimentary paleo-earthquakes (seismites) in this portion of the South American passive margin. This work shows new evidence of syndepositional tectonic activity in the lowermost Paleogene of the Golfo San Jorge Basin.

1. Introduction

Seismic activity is a phenomenon commonly associated with compressional and orogenic zones, probably due to higher earthquake magnitude and damages produced in these tectonic settings. However, earthquakes recorded in extensional or passive-margin settings are also frequent (Seth et al., 1990; Mohindra and Bagati, 1996; Bhattacharya and Bandyopadhyay, 1998; Stollhofen, 1998; Vanneste et al., 1999; Bezerra and Vita-Finzi, 2000; Enzel et al., 2000; Rossetti and Góes, 2000; Bezerra et al., 2001, 2005; Kullberg et al., 2001; Van Loon, 2002; Rossetti and Santos, 2003, 2004; Obi and Okogbue, 2004; and references herein).

Soft-sediment deformation structures have been attributed to pore-pressure changes, mainly caused by fluid escape during fluidization and liquefaction (Lowe, 1975; Owen, 1987). The recognition of earthquake-induced structures in the ancient record is not always unambiguous, because the same or similar structures can be produced by non-seismic processes: storm waves, cryogenic/thermokarstic perturbations, subglacial hydrofracturing, gravitational gradient or rapid sediment accumulations (Lowe, 1975; Van Loon and Wiggers, 1976; Johnson, 1977; Nataraja and Gill, 1983; Postma, 1983; Martel and Gibling, 1993; Li et al., 1996; Rijsdijk et al., 1999; Van Vliet-Lanoë et al., 2004; Horváth et al., 2005; Le Heron and Etienne, 2005). However, deciphering earthquake-induced structures is possible applying some criteria for correlating deformation features with seismic events.

Though the word "seismite" (Seilacher, 1969) has been defined as deposits deformed during earthquake perturbation and used for a wide range of deformational structures, liquefaction features are mentioned as the most common type of soft-sediment deformation related to earthquakes (Obermeier, 1996). Earthquake-induced structures represent different sedimentary responses to seismic shaking and depend on several interrelated factors (e.g. lithology, consolidation, saturation, depth, seismic magnitude and epicentral distance, among others).

Paleocene sedimentary rocks in the Golfo San Jorge Basin are represented by the marine Salamanca Formation and the continental Río Chico Formation, deposited in a passive-margin setting (Legarreta et al., 1990; Legarreta and Uliana, 1994). The aim of this work is threefold: 1) to document the nature and distribution of the deformation structures preserved in the Salamanca and Río Chico Formations, 2) to discuss the processes responsible for their genesis and analyse the possible influence of paleoseismic events as the trigger mechanism of these structures, and 3) to analyse the results in a regional tectosedimentary framework.

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2. Geological setting

2.1. Structural framework

The Golfo San Jorge Basin is a dominantly extensional basin superimposed on a Paleozoic continental crust. This basin is broadly E–W orientated and located between the North Patagonian Massif and the Deseado Region, in southern Argentina (Fig. 1A). The origin of the basin is related to the fragmentation of the Gondwana paleocontinent, during Jurassic and early Cretaceous times.

The Golfo San Jorge Basin has been divided into five major regions according to their tectonic style (Figari et al., 1999): North Flank, South Flank, Centre of Basin, San Bernardo Fold Belt, and Western Flank (Fig. 1B). The North Flank, South Flank and Centre of basin regions are located in the eastern part of the basin, where an extensional style is dominant. Typical structures are high-angle, WNW–ESE striking, listric normal faults that reach down the basement. The North Flank is steeper than the southern one, where major normal faults dip SW (Fig. 1C). Fossa-Mancini (1932, 1935) reported thickness changes across fault planes in the Salamanca Formation, related to synsedimentary normal fault activity. Foix and Paredes (2004) recognized syntectonic deposition in the lowermost Tertiary using subsurface information; these data showed that the vertical displacement of the faults decreased upward in the Tertiary owing to reduced intensity of the extensional faults activity. Normal faults dipping up to 70° are exposed in outcrops of the Patagonia Formation northward of Comodoro Rivadavia city (Giacosa et al., 2004).

2.2. Stratigraphy

The initial infilling of the basin is represented by the “Neocomiano” or Las Heras Group, a marine to transitional megasequence deposited under synrift conditions during the uppermost Jurassic and early Cretaceous times (Figari et al., 1999). The remaining of the Cretaceous is represented by a continental volcano–sedimentary sequence known as Chubut Group (Feruglio, 1949; Fitzgerald et al., 1990; Hechem et al., 1990; Paredes et al., 2007). The uppermost Cretaceous and Cenozoic evolution of the basin took place in a passive-margin setting (Legarreta et al., 1990; Legarreta and Uliana, 1994). The deposition of the marine Salamanca Formation occurred during the Maastrichtian and Danian (Barcat et al., 1989; Legarreta et al., 1990), and represents the oldest Atlantic transgression in the basin, with a maximum thickness of 200 m (Feruglio, 1949). The marine sediments are conformably covered by the continental Río Chico Formation, late Paleocene in age (Simpson, 1933). Andreis et al. (1975) divided the Río Chico Formation into two fluvial sub-cycles, both composed of high sinuosity fluvial channels and ephemeral, shallow lagoon settings. The remaining of the Cenozoic succession is completed with the Sarmiento Formation (Eocene to lower Miocene pyroclastic deposits), the Patagonia Formation (lower Miocene shallow marine and off-shore deposits), the Santa Cruz Formation (middle Miocene fluvial and aeolian deposits) and glaciofluvial gravel strata known as “Rodados Tehuelches” or “Rodados Patagónicos” (Pliocene to Pleistocene). Fig. 2A shows the distribution of the main units in the basin.

3. Local geology

The study area is located in the North Flank of the Basin, close to the basin margin (Fig. 2B). The base of the Salamanca Formation is not exposed in this locality, but 10 km northward it overlies volcanic rocks of the Marifil Formation (Middle Jurassic). The Salamanca Formation here is composed of three lithological packages, representative of distinctive depositional environments. The lower section is up to 130 m thick and consists of poorly consolidated claystones and siltstones, and is locally known as “Fragmentosa” Section (Feruglio, 1949) (Fig. 3). These deposits are internally laminated or massive and show variable bioturbation, being attributed to an inner-shelf marine environment (Legarreta et al., 1990; Legarreta and Uliana, 1994). The upper section is 8–15 m thick and is composed of light-green coloured, fine to medium sandstones with glauconitic grains, locally known as “Banco Verde” (Feruglio, 1949). These strata contain trough cross-bedding, parallel lamination, mud drops, variable bioturbation and fossil remains of selachians, molluscs and trunks up to 0.30 m in diameter. The “Banco Verde” Section has been interpreted as part of an estuarine sandstone complex (Legarreta et al., 1990; Legarreta and Uliana, 1994) and is used in the field as a datum.

The marine–continental transition package, informally known as “Banco Negro Inferior” (Feruglio, 1949) is composed of tabular, massive

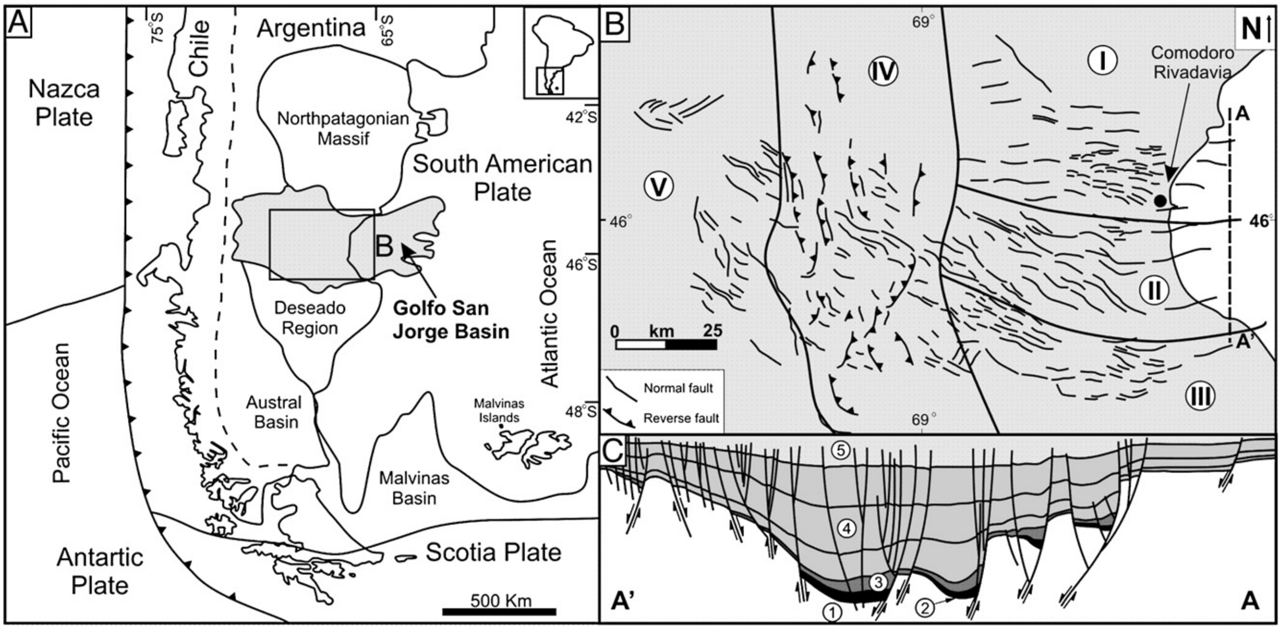

Fig. 1. A — Paleozoic cratons and main Mesozoic sedimentary basins, with location of the Golfo San Jorge Basin. B — Main structural regions of the Golfo San Jorge Basin (modified from Figari et al., 1999). Key = I: North Flank, II: Centre of Basin, III: South Flank, IV: San Bernardo Fold Belt and V: Western Flank. C — North–South seismic section (A–A′) showing the asymmetry of the basin profile and distribution of principal units: Key: 1) Paleozoic basement. 2) Marifil Formation (Jurassic). 3) Las Heras Group (Neocomian). 4) Chubut Group (Cretaceous). 5) Tertiary.

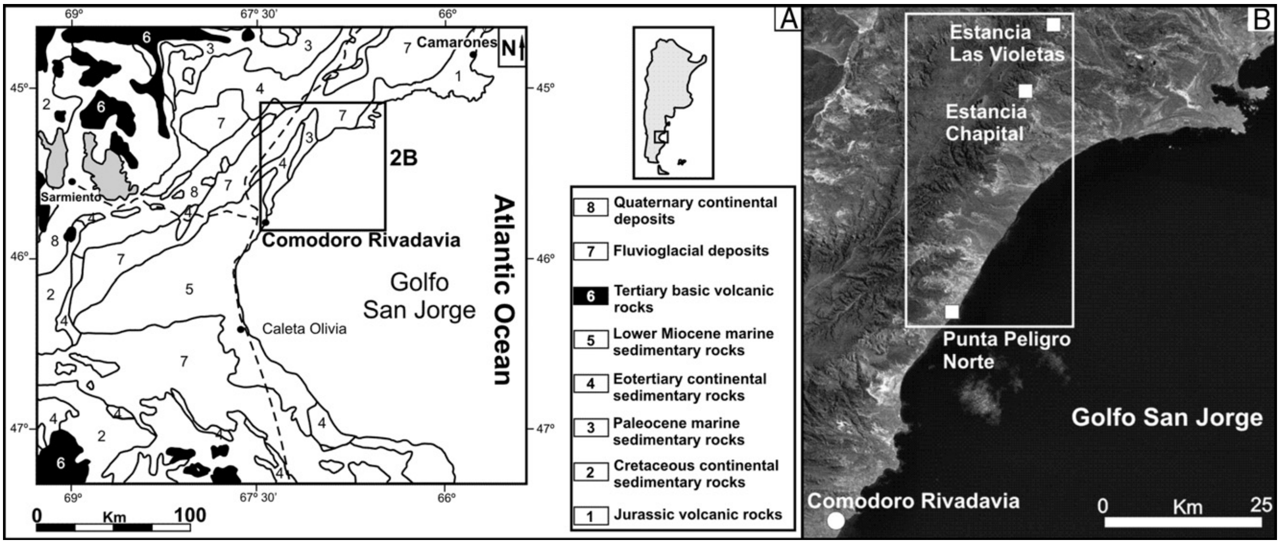

Fig. 2. A — Simplified geological map of the Golfo San Jorge Basin. B — Satellite image with location of the study area.

or horizontally-laminated black mudstones (Fig. 3), which are locally interbedded with thin sandstones. The "Banco Negro Inferior" is related to marsh, swamp and mangrove, poorly-drained anoxic depositional environments (Feruglio, 1949; Andreis et al., 1975; Legarreta et al., 1990; Legarreta and Uliana, 1994).

The Río Chico Formation was deposited mainly by fluvial systems. Fluvial channels are filled by moderate-to-well sorted, cross-stratified, fine conglomerate and coarse to medium sandstones, and they commonly show several fining-upward cycles. Floodplain deposits are represented by poorly consolidated, laminated or massive mudstones, frequently bioturbated.

4. Deformation structures

The soft-sediment deformation features will be described in ascending vertical order, as recorded in the study area.

4.1. Sediment-filled fissures

These features are actually exposed during low tide stages in the abrasion platform (locality of Punta Peligro, see Fig. 2B), where at least 23 near-vertical and discordant sediment-filled fissures were described. The fissures are hosted in muddy sediments of the "Fragmentosa" Section and show sharp boundaries.

The group of fissures range in size from 0.2 cm to 30 cm in width, and could be traced along strike by 15–20 m (Fig. 4A and B). Most of the fissures are near-parallel, they are locally connected to each other by short, orthogonal segments. Major filled fissures branch to the tips into smaller-scale splays (Fig. 4C). Fissures are filled by well sorted, massive, medium to fine sandstones with glauconitic grains, provided by the overlying "Banco Verde". Some fissures contain angular mud fragments up to 4 cm in size (hosted rock) (Fig. 4A). The average strike-trend azimuth of the filled fissures is 39°. The lack of vertical relief makes impossible to define the 3-D development of these features, which only can be observed in plan view.

Sediment-filled fissures were only recognized in Punta Peligro Norte. These strata are poorly exposed in other sections of the North Flank.

4.1.1. Interpretation

The unique mention of similar features described in the basin corresponds to Windhausen (1924), who observed a WNW–ESE striking "sand dyke" in the locality of Punta Peligro Norte (reproduced as Fig. 5) in rocks of the "Fragmentosa" Section. This outcrop was destroyed by coastal erosion, but the vertical feature was 10–13 m in depth and 1–1.5 m in width, and showed a slightly wedge-shaped. The wedge shape and the filling of the "sand dyke" by green sandstones of the overlying "Banco Verde" led Windhausen (1924) to state that the sediments were introduced from overlying strata. Legarreta et al. (1990) and

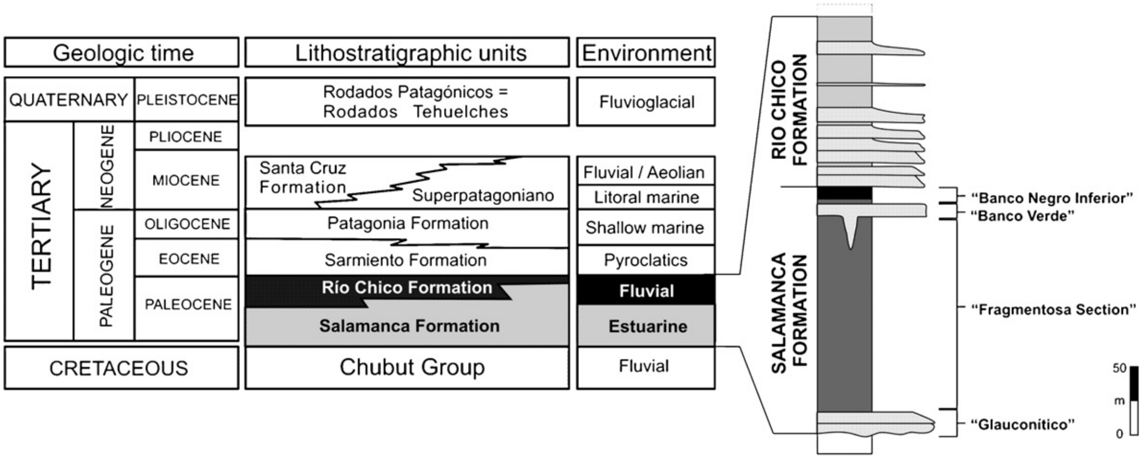

Fig. 3. Tertiary chronostratigraphic framework (modified from Figari et al., 1999) and schematic lithological profile of Salamanca and Rio Chico Formation (after Legarreta and Uliana, 1994).

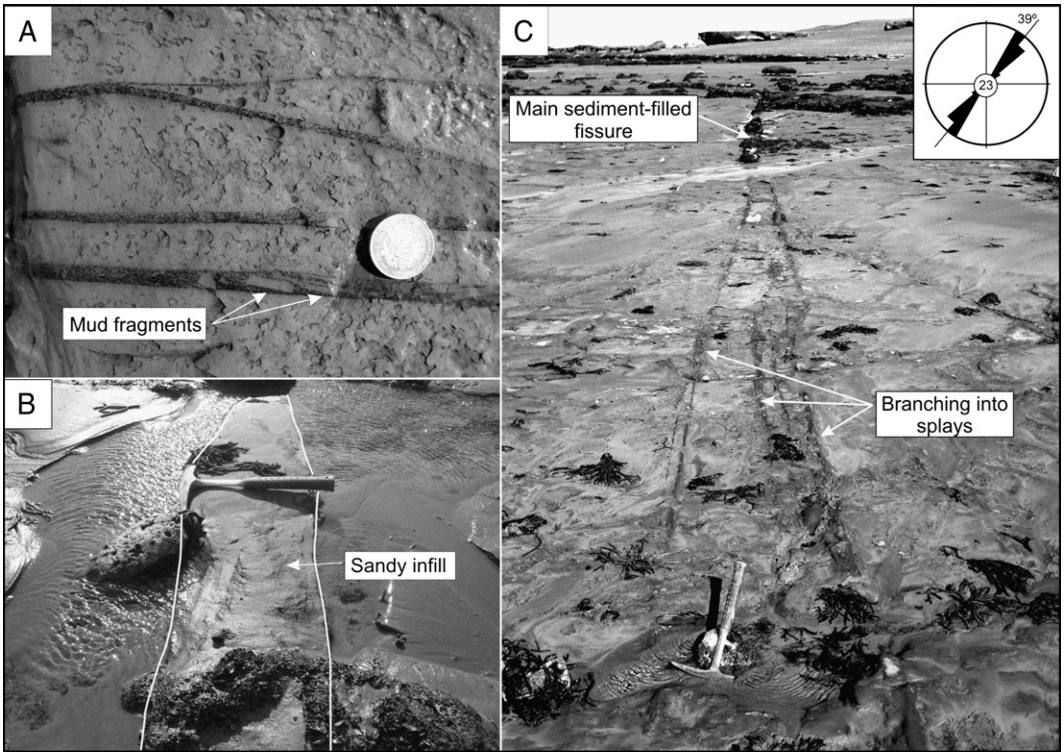

Fig. 4. Plan view of sediment-filled fissures at Punta Peligro Norte. A — Thin filled fissures with angular mudstone fragment. Light coloured, muddy hosted rock corresponds to the “Fragmentosa” Section. Note a short, orthogonal segment connecting two parallel features. Coin is 2 cm in diameter. B — Sediment-filled fissure about 0.3 m in width. C — A NE trending sediment-filled fissure branching into smaller-scale splays. Hammer is 0.3 m long See Fig. 11 for vertical distribution of soft-sediment deformation structures.

Legarreta and Uliana (1994), in accordance with Windhausen (1924), considered the filled fissures as fractures produced during uplift movements and infilled by overlying deposits.

Although the term “clastic dyke” has been used for foreign sediment bodies hosted in fractures, infilled from above or by upward injection (Reineck and Singh, 1986), the first meaning has been rarely used. The vertical features here observed could be better interpreted as sediment-filled fissures.

Fissures would have opened after the deposition of the “Fragmentosa” Section (hosted rock), but previously to the consolidation of the “Banco

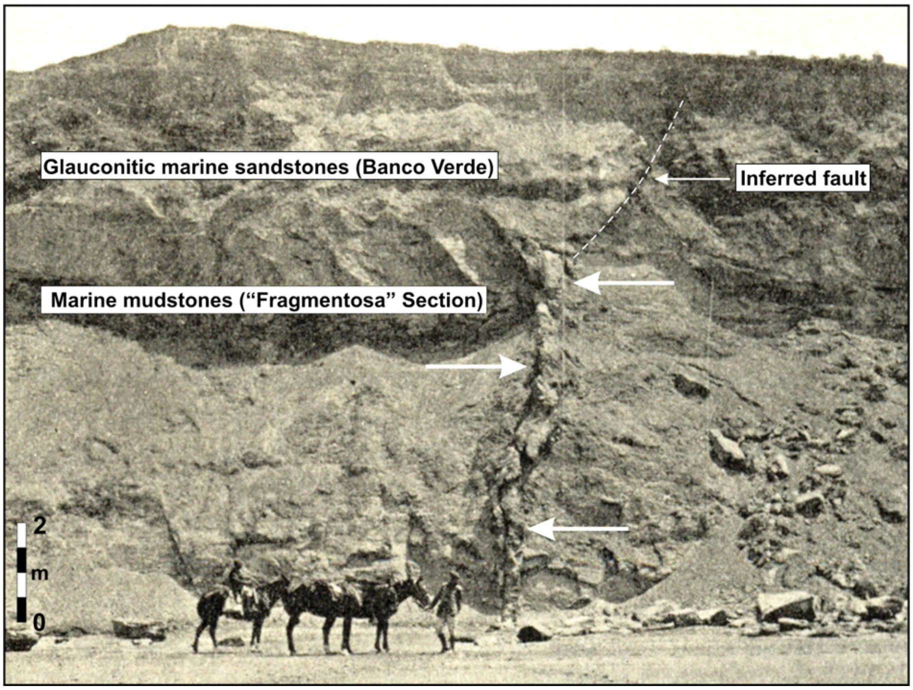

Fig. 5. Vertical cliff composed of marine sediments of the Salamanca Formation at Punto Peligro Norte (see Fig. 2 for location). Arrows point to a sediment-filled fissure (after Windhausen, 1924).

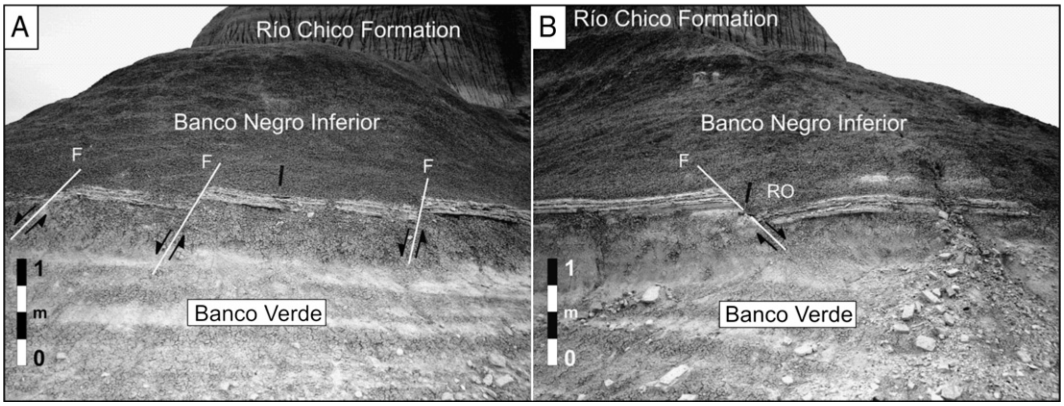

Fig. 6. A — Synsedimentary normal faults (F) with domino geometry. B — Normal fault (F) with associated roll-over anticline (RO). Both structures are preserved in a sandstone stratum in the uppermost Salamanca Formation, near Estancia Las Violetas. See Fig. 11 for vertical distribution of soft-sediment deformation structures.

Verde" (infilling source rock), because the later stratum provided the granular material for the infill of the open fissure. This temporal relation explains the genesis and development of these soft-sediment deformation structures in the uppermost levels of the Salamanca Formation. Similar features have been described for unstable and steep slopes (Rowe et al., 2002), but the Salamanca Formation was deposited in a shallow siliciclastic marine platform with very low gradient (Andreis et al., 1975; Andreis, 1977; Legarreta et al., 1990; Legarreta and Uliana, 1994), so we ruled out this origin.

The sediment-filled fissures related to tectonic processes are not randomly distributed, but they have a preferential orientation in relation to main tectonic structures (Schlische and Ackermann, 1995; Stollhofen, 1998; Bezerra and Vita-Finzi, 2000; Hunt et al., 2002; Rossetti and Santos, 2003). Numerous synsedimentary normal faults were recognized in the uppermost levels of Salamanca Formation, originated contemporary to filled fissures (see below). The WNW–ESE orientation of major sediment-filled fissure described in Punta Peligro Norte by Windhausen (1924) is roughly parallel to the regional trending of major normal faults observed in the subsurface of the basin (see Fig. 1B).

The average orientation of sediment-filled fissures in Punta Peligro Norte shows an angle of 60° with the orientation of measured normal fault in the area. This geometrical relationship is consistent with an oblique-extensional stress regime (Morley et al., 2004). A similar behaviour for Neogene normal faults in the basin has been documented by Giacosa et al. (2004), who identified extensional fractures oriented to high-angle to the strike of the main faults.

Sediment-filled fissures can be interpreted as soft-sediment deformation structures related to extensional tectonic activity. The trigger mechanism is discussed in Section 5.1.

4.2. Normal faults

Small-scale normal faults were observed in the three studied localities (Fig. 2B) in uppermost strata of the Salamanca Formation.

4.2.1. Estancia Las Violetas

Seven small-scale normal faults with dip-slip kinematic were identified in a 0.2 m-thick sandbody intercalated in a 3 m-thick section of interbedded sandstones and mudstones of the "Banco Negro Inferior". The faults show vertical throws less than 0.4 m, display a domino-pattern and show well-developed roll-over folds (Fig. 6A and B). These faulted strata are bounded upward and downward by non-faulted strata.

4.2.2. Estancia Chapital

Thirty planar or slightly-listric normal faults were observed in the upper part of the "Fragmentosa" Section, which here consists of a 60 m-thick section of thin-bedded mudstones (1–5 cm in thickness) containing minor sandstone bodies. Measured dip-slip displacement ranges from few centimeters to 0.75 m. Drag and roll-over folds and vertical relay zones were identified. The vertical throw of many faults rapidly decrease upward until it becomes negligible few decimeters above the main displacement point.

4.2.3. Punta Peligro Norte

In the uppermost levels of the Salamanca Formation, 39 synsedimentary normal faults were described and interpreted. The vertical throws of most faults decrease upward with a maximum dip-slip displacement of 1 m. The "Banco Negro Inferior" is not affected by the faulting. The synsedimentary nature of the faults is evidenced by thickness changes across the fault planes, with maximum thickness variations of 0.40 m (Fig. 7). Fault planes are more steeply dipping in sandstone strata (range 55°–65°), while in mudstone dominated ones the angle doesn't exceed 25–30°.

In Estancia Las Violetas and Punta Peligro Norte normal faults have a NNW–SSE dominant trend (Fig. 8A and B), while in Estancia Chapital they have no preferred orientations (Fig. 8C). In the former two localities the NNW–SSE trending normal faults are arranged in conjugate Andersonian sets with dip-slip kinematics, with most of the planes dipping SW. A total of 78 normal faults with an average strike of 159° were described in the study area (Fig. 8D), faults having a dip average of 60°.

4.2.4. Interpretation

Two independent criteria support the synsedimentary nature of the normal faults preserved in the uppermost strata of the Salamanca Formation: (1) Thickness changes across fault planes, with increasing of the preserved thickness in the hanging-wall block, a criteria generally considered as the typical feature of synsedimentary faulting (Leeder and Gawthorpe, 1987; Gawthorpe et al., 2003; Nicol et al., 2005). This feature has been observed in the three studied localities; (2) presence of faulted horizons between undisturbed beds, as observed in Estancia Chapital and Las Violetas (see also Cojan and Thiry, 1992; Pratt, 1994; Pope et al., 1997; Bhattacharya and Bandyopadhyay, 1998; Stollhofen, 1998; Rossetti and Góes, 2000; Bezerra et al., 2001; Kahle, 2002).

4.3. Fault-graded beds

The "Banco Negro Inferior" is represented in Estancia Las Violetas by a black-coloured, finely laminated mudstone about 3.3 m thick. In addition to the described small-scale normal faults preserved in the lower half of the "Banco Negro Inferior" (Fig. 6A and B), the uppermost 0.5 m of this section shows disruption of the parallel lamination, with the occurrence of a matrix-supported intraformational breccia (Fig. 9B) in an exposure of 15 m in width. Mudstone fragments are subangular to angular in shape and range in size from 0.5 to 2.5 cm. They are surrounded by a well-sorted matrix of fine sandstones sourced from

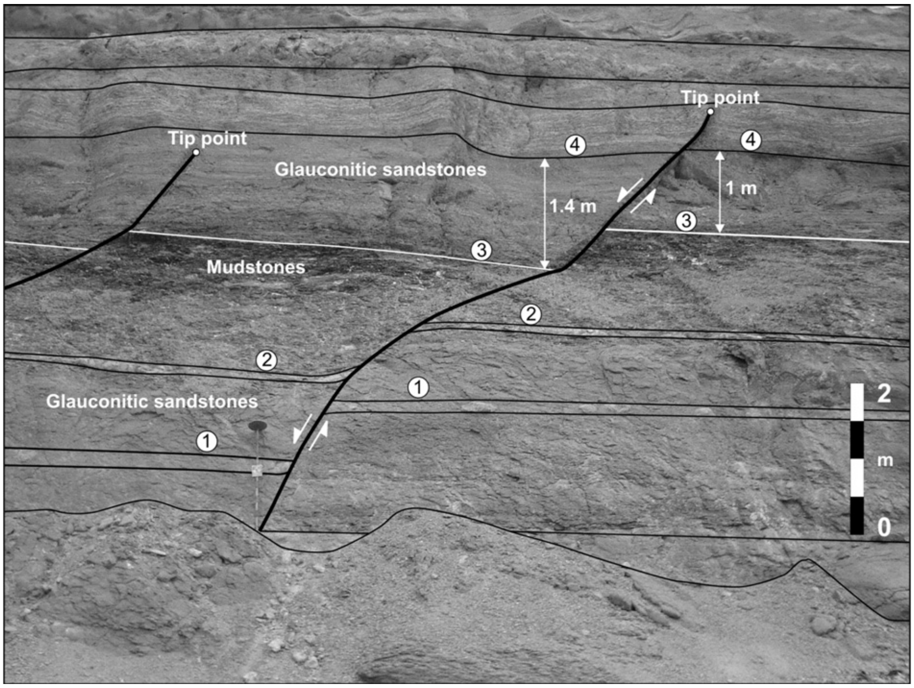

Fig. 7. Synsedimentary normal fault in Salamanca Formation (near Punta Peligro Norte), showing an increased preserved thickness in the hanging-wall block. Numbers refer to the same horizons across the fault plane. Note the change in the dip angle of the fault plane, which is low in the mudstone and increase in the sandstone layers.

the overlying strata. The strata lack any preserved evidence of hydraulic sorting by flows (e.g. cross-bedding, imbrication of clasts or vertical grain-size variation) and have a no channelized, erosive basal surface. Instead, the following succession is present, from base to top: undeformed laminated mudstones, breccia with low matrix, and undisturbed, tabular-shaped fluvial channel deposits.

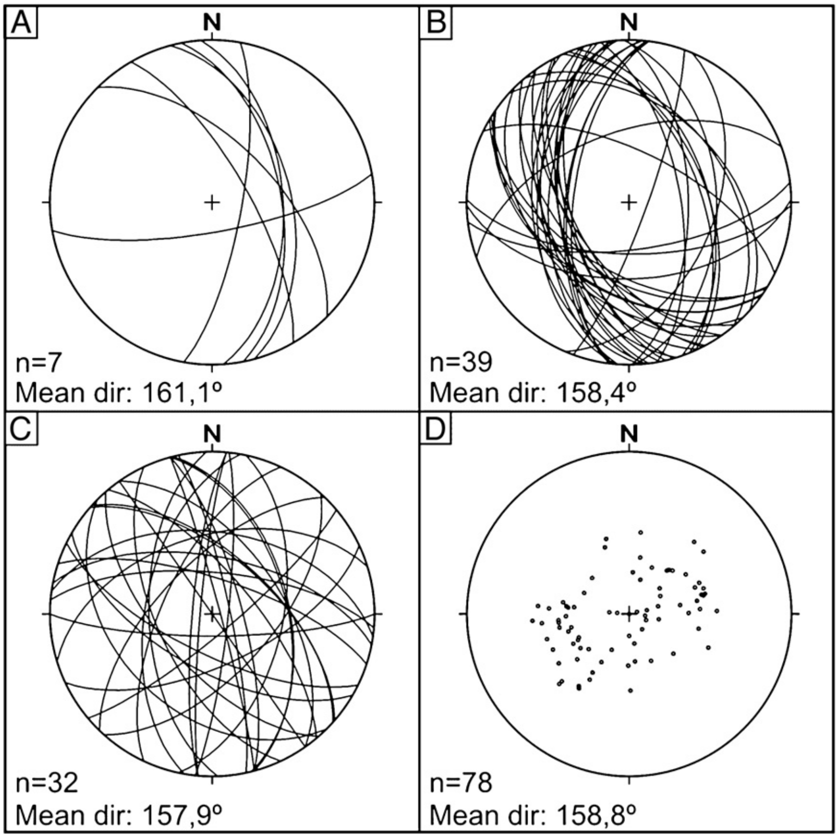

Fig. 8. Polar Wullf equal-angle, lower hemisphere representation of meso-scale normal fault planes. A — Data from Estancia Las Violetas. B — Data from Punta Peligro Norte. C — Data from Estancia Chapital. D — All data represented as poles.

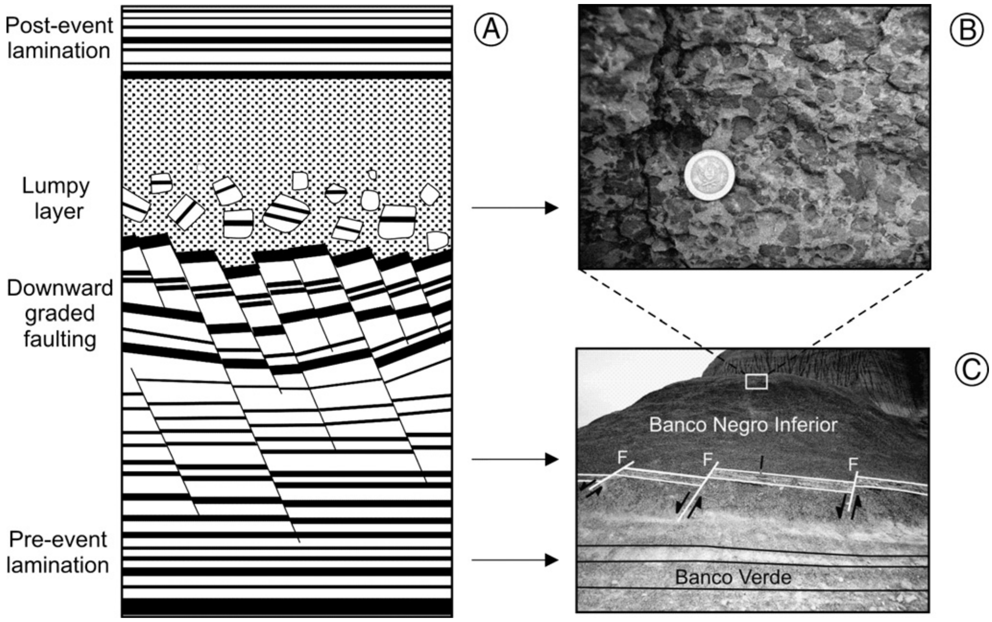

Fig. 9. A — The "ideal seismite" model after Seilacher (1991). B — Lumpy layer is represented by a matrix-supported intraformational breccia, with dark, angular, mudstone fragments embedded into a light coloured, sandy matrix provided by the overlying strata C — Synsedimentary, normal faults with domino geometry. Faults are restricted to a sedimentary interval about 0.8 m thick.

4.3.1. Interpretation

Intraformational breccias can be produced by fragmentation/resedimentation during short time events, with downward migration of the still-unconsolidated sandy matrix around mudstone fragments (soft-sediment deformation). In spite of the multiple origin attributed to intraformational conglomerates and breccias, these deposits have been often related to seismic events (Spalletta and Battista Vai, 1984; Pratt, 1994; Pope et al., 1997; Stollhofen, 1998; Rossetti and Góes, 2000; Kahle, 2002; Onasch and Kahle, 2002; Pratt, 2002; Rossetti and Santos, 2003; Upadhyay, 2003; Juyal et al., 2004; McLaughlin and Brett, 2004; Bachmann and Aref, 2005).

The vertical gradation from synsedimentary faulted strata to in-situ brecciated strata has been considered by Seilacher (1969, 1984) as a suite of structures related to shaking during earthquakes, using the specific term of fault-graded beds. These consist of a step-faulted zone that grades upward into a rubble zone, and then a liquefied zone (Seilacher, 1969). Fault-graded beds have been interpreted as seismites by other authors (Stollhofen, 1998; Onasch and Kahle, 2002).

Anoxic and restricted environments are the most favourable for seismite preservation because bioturbation is absent (Seilacher, 1991). The type and vertical distribution of the deformation structures exposed in the "Banco Negro Inferior", their dimensions and type of sedimentary rocks affected are analogous to Seilacher's (1969, 1991) ideal "seismite" (Fig. 9A).

4.4. Pillars

Cross-bedded sandstones and conglomerates deposited in tabular-shaped, fluvial channel of the Río Chico Formation contain abundant deformational structures. These are vertical features up to 5 m in vertical extension, "V" or funnel shaped and projected downwards (Fig. 10A, B and C). Up to 97 of these features were described in the study area, and they sharply intercept primary sedimentary structures and strongly deflect the surrounding strata downward. The plastic nature of the sediments is supported by the continuity of primary lamination into the pillars. In some cases, the fill of the pillars show a fining-upward trend, evidenced by the concentration of pebbly sandstones in the apex of the structure. The plan view morphology of these features is rarely exposed, but some of them show subcircular cross section (Fig. 9B). The structures can be isolated or arranged in groups of 2–5 pillars developed at the same tratigraphic level; they are interbedded with undisturbed strata (Fig. 9C) of highly-consolidated mudstones and can be recognized in near-equivalent stratigraphic position along 60 km of exposures.

4.4.1. Interpretation

The general characteristics of these soft-sediment deformation structures are similar to previous descriptions of pipes (Allen, 1961; Van Vliet-Lanoë et al., 2004), elutriation columns (Wentworth, 1966; Corbett, 1972), type B pillars (Lowe, 1975) or "pillars" (Lowe and LoPiccolo, 1974; Mills, 1983; Postma, 1983; Van Loon and Brodzikowsky, 1987; Rossetti, 1999; Bezerra et al., 2005).

Pillars were early defined by Lowe and LoPiccolo (1974) as postdepositional structures formed during compaction and dewatering of unconsolidated beds of silt, sand or fine gravel. These authors interpreted pillars as vertical water escape structures formed in response to pore-pressure gradients during liquefaction and/or fluidization, representing columnar or planar flow paths. Liquidization (Allen, 1982) is a process where a granular material in a solid state is induced to behave like a liquid. If liquidization is induced by a sudden increase in the pore pressure, the process is known as liquefaction (Seed and Idriss, 1971), whereas if it is produced by a vertical flow, the term fluidization (Kunii and Levenspiel, 1969) is preferred. Impermeable or semi-permeable barriers within the sediment promote the development of localized regions with elevated pore pressure (Lowe and LoPiccolo, 1974; Postma, 1983; Obermeier, 1996), generally represented by fine-grained strata.

The suite of preserved structures and the relations of permeable–impermeable rocks in the Rio Chico Formation evidence an origin of the V-shaped features related to fluidization/liquefaction processes.

5. Discussion

5.1. Trigger mechanisms

A number of possible explanations exist to account for the genesis of the deformation structures observed in the study area. Both

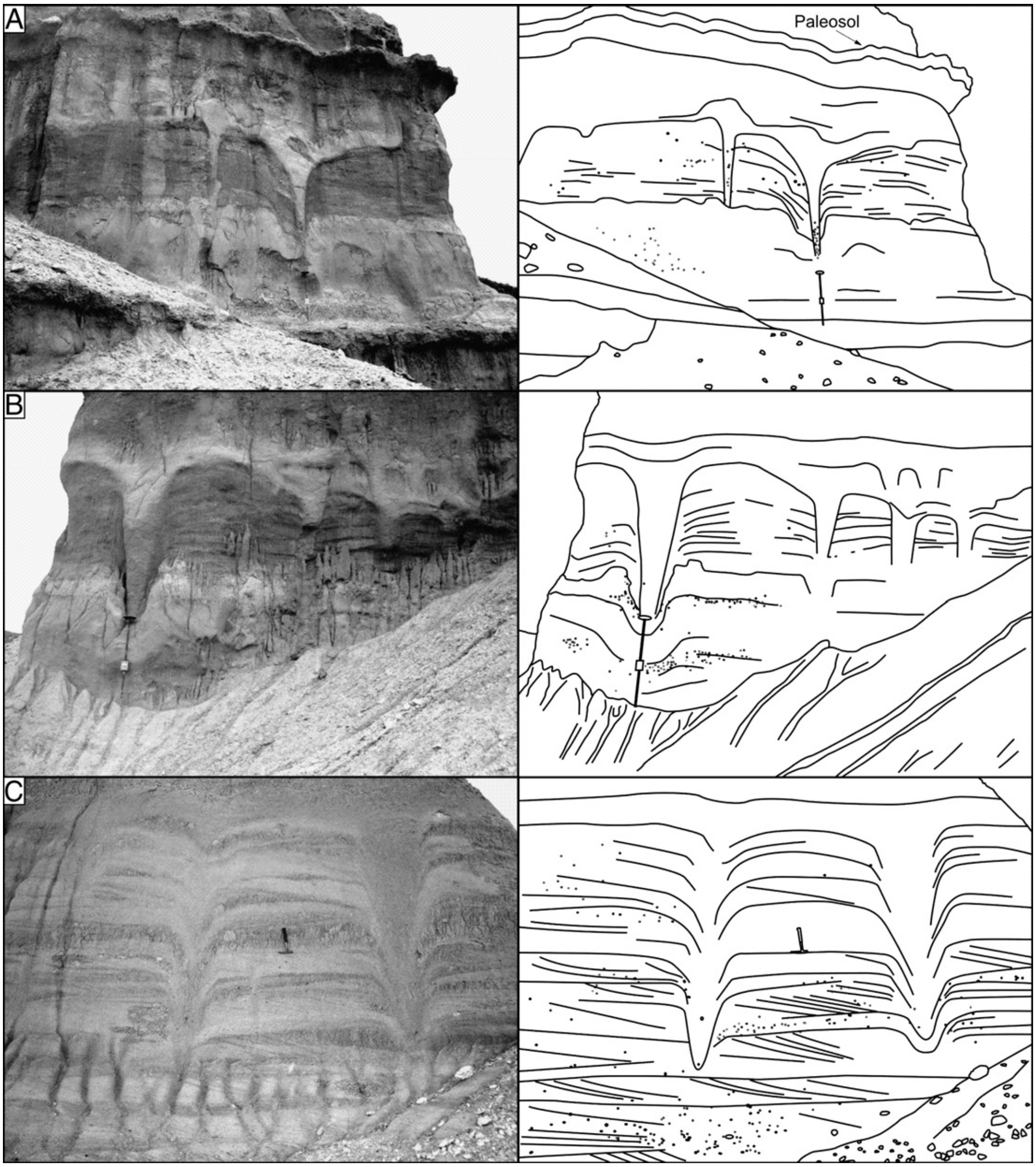

Fig. 10. A and B — "V" or funnel-shaped pillar structures in the fluvial Río Chico Formation near Estancia Las Violetas. Vertical features are projected downward up to 5 m. Paleosols in the upper part of the picture represent a low permeability strata and a barrier for vertical fluid migration. Jacob stick is 1.5 m long. C — Cross-bedded sandstone strata deformed by two liquefaction/fluidization pillars. Hammer is 0.3 m long. Río Chico Formation near Estancia Chapital. See Fig. 11 for vertical distribution of soft-sediment deformation structures.

liquefaction and fluidization could have a non-seismic or seismic origin. In the first case, the trigger mechanism could be the action of storm waves (Van Loon and Wiggers, 1976; Johnson, 1977; Nataraja and Gill, 1983; Martel and Gibling, 1993), cryogenic/thermokarstic perturbations (Van Vliet-Lanoë et al., 2004; Horváth et al., 2005), subglacial hydrofracturing (Rijsdijk et al., 1999; Le Heron and Etienne, 2005), steep depositional slope (Lowe, 1975; Postma, 1983) or rapid sediment accumulation (Lowe, 1975; Postma, 1983). The seismic trigger is, however, the most common mechanism of liquefaction and/or fluidization of poorly consolidated sediments (Seed, 1979; Obermeier, 1996, 1998; Owen, 1987, 1995; Mohindra and Bagati, 1996; Bhattacharya and Bandyopadhyay, 1998; Stollhofen, 1998; Rossetti, 1999; Bezerra and Vita-Finzi, 2000; Rodríguez-Pascua et al., 2000, 2003; Rossetti and Góes, 2000; Bezerra et al., 2001, 2005; Rossetti and Santos, 2003, 2004).

We ruled out a cryogenic/thermokarstic perturbation or subglacial hydrofracturing of the soft-sediment structures described herein because paleontological evidence shows a humid and warm climate in the Danian–Thanetian of central Patagonia (Pascual and Odreman Rivas, 1971; Legarreta and Uliana, 1994). The action of storm waves is rejected because some of the structures described here, for instance the pillars, occur in association with fluvial deposits of the Rio Chico Formation. Additionally, the influence of depositional high-gradient is also not favoured, as Paleocene rocks were deposited in a low-angle ramp setting (Legarreta et al., 1990), as evidenced by the horizontal distribution of sedimentary units and noticeable lateral continuity of individual layers.

Criteria for correlating deformation structures with seismic events were originally proposed by Sims (1975), and applied to particular areas by Hempton and Dewey (1983), Davenport and Ringrose (1987), Seilacher (1991), Mohindra and Bagati (1996), Enzel et al. (2000), Matsuda (2000), Ettensohn et al. (2002), Merriam and Föster (2002), Upadhyay (2003), Bowman et al. (2004), Bachmann and Aref (2005), among others.

The six criteria of Sims (1975) are met in the Paleocene deposits of the Golfo San Jorge Basin are as follow:

(1) *Proximity to a synsedimentary active seismic zone*. The synsedimentary nature of normal faults during the Paleocene was previously

recognized using subsurface data (Fossa-Mancini, 1932, 1935; Foix and Paredes, 2004) and also observed in outcrops of the study area (Fig. 7).

(2) *Presence of potentially liquefiable sediments (e.g. loosely consolidated sands).* The Rio Chico Formation contains an abundance of friable, fine-grained sandstone strata, which are suitable to liquefaction/fluidization processes.

(3) *Similarity with experimentally formed seismic features*. Pillar structures induced by seismically triggered liquefaction and/or fluidization have been reproduced with shaking table experiments (Owen, 1996; Moretti et al., 1999).

(4) *Structures related to liquefaction.* Almost a hundred of liquefaction and/or fluidization features were interpreted as pillar structures in the study area (Fig. 10).

(5) *Structures restricted to single stratigraphic intervals correlatable over large areas.* Liquefaction and/or fluidization pillars occur in sedimentary strata positioned between undisturbed parallel ones, which could be followed over at least 60 km of exposures.

(6) *Absence of slope influence and failures*. The Atlantic margin of the Golfo San Jorge Basin behaves as a low-gradient ramp setting (Legarreta et al., 1990; Legarreta and Uliana, 1994). The lack of slope and basin-floor deposits preserved into the basin reinforces the absence of a Paleocene shelf break.

Therefore, liquefaction and/or fluidization pillars meet the criteria proposed by Sims (1975), who relates deformation structures to seismic activity.

Vertical or subvertical tectonic cracks are commonly generated in the near-surface in extensional tectonic regimes under low hydrostatic fluid pressure levels (Sibson, 1998). Rossetti (1999) and Rossetti and Góes (2000) recognized some subvertical cracks/faults in sedimentary rocks as evidence of brittle deformation of unconsolidated or partially consolidated strata by instantaneous shocks. The presence of comparable open cracks and fissures in response to seismic shaking has been widely recognized (Minoura and Nakaya, 1990; Pratt, 1994; Shiki and Yamazaki, 1996; Rossetti and Santos, 2003). Several studies have also demonstrated the infilling was provided by the overlying horizon (Pratt, 1994; Stollhofen, 1998; Matsuda, 2000; Rossetti and Góes, 2000; Rossetti and Santos, 2004; Kuhn, 2005).

The normal faulting event during the Paleocene (Fossa-Mancini, 1932, 1935; Figari et al., 1999; Foix y Paredes, 2004) could have produce the horizontal tensile stress necessary for fissure opening in the Salamanca Formation.

Small-scale normal faults observed in sandstones of the Salamanca can be interpreted as a semi-brittle or brittle type of soft-sediment deformation, where the instantaneous stress applied was not enough to produce liquefaction (Vanneste et al., 1999). Alternatively, they could have also been due to a higher degree of compaction and reduction of saturation of the sandstone strata, favouring a brittle behaviour (Rossetti, 1999).

The suite of soft-sediment deformation structures, as identified in this study, has been mentioned as an example of seismically-induced features during extensional faulting (Pratt, 1994; Stollhofen, 1998).

5.2. Lateral extension of deformation features

Synsedimentary normal faults and liquefaction pillars can be recognized in equivalent stratigraphic position along 60 km of exposures. Sediment-filled fissures and fault-graded beds are locally restricted to Punta Peligro Norte and Estancia Las Violetas, respectively. Although the sediment-filled fissures were only documented in the “Fragmentosa” Section at Punta Peligro Norte, we should note that this stratigraphic interval is poorly exposed in most of the outcrops of the basin.

In Estancia Las Violetas the Salamanca Formation is deposited directly over volcanic Jurassic rocks of the Marifil Formation, and is quite close to the northern boundary of the basin. In this location, there is abundance of pillars and presence of small-scale normal faults and fault-graded beds. In southward exposures the abundance of pillars are less frequent, suggesting a more important influence of synsedimentary tectonics on the basin margin. The orientation of the outcrops and limitations in the available exposures preclude further interpretation about the 3-D distribution of the deformational features, making impossible to define a radial distribution around a hypothetical epicentre.

5.3. Vertical distribution of deformation features

Although the suite of deformational structures is not all present in a unique exposure (see above), a synthetic stratigraphic scheme could be recognized, showing the vertical (temporal) relationships between the described features (Fig. 11).

Synsedimentary normal faults and sediment-filled fissures of the Salamanca Formation probably represent the response of highly compacted sediments to the seismic shaking (Rossetti, 1999). Up in the section, sediment-filled fissures and intraformational breccias are concentrated into cohesive sediments of the Salamanca Formation. Fault-graded beds are preserved in fine-grained sediments of the marine–continental transition (swamp or mangrove deposits), and represent a vertical sequence from small-scale normal faults in the bottom (brittle behaviour) to intraformational breccias with evidence of liquefaction in the upper zone (brittle-plastic transition). This change in the behaviour of the sediments could reflect an in-depth increase in the compaction of the material from the water–sediment interface (Seilacher, 1969). Liquefaction/fluidization structures are located in fluvial channels of the basal section of the Río Chico Formation. These features are preserved in the uppermost level of the deformed succession, probably developed in uncompacted sediments or under more saturated conditions.

There is no relation between the soft-sediment deformation structures and a particular sedimentary environment. The rheological behaviour of sediments is mainly controlled by saturation conditions, strongly influenced by lithological properties. The suite of sedimentary deformation structures is concentrated in the transition of the Salamanca-Río Chico Formations (Paleocene), and affects a succession no more than 15 m thick. Our observations suggest that the observed deformational features could be related, at least, to three different seismic events. The oldest event is recorded by synsedimentary normal faults and sediment-filled fissures in the uppermost Salamanca Formation. A second seismic event is represented by the fault-graded beds in the younger “Banco Negro Inferior”. A third event is inferred by liquefaction pillars in fluvial deposits of the Río Chico Formation.

5.4. Origin and magnitude of paleo-earthquakes

Numerous examples of synsedimentary normal faults are related to seismic activity (Pratt, 1994; Mohindra and Bagati, 1996; Stollhofen, 1998; Obi and Okogbue, 2004; and others). Obi and Okogbue (2004) identified seismic-induced structures linked to normal faulting in Campanian–Maastrichtian rocks of the African passive margin. The existence of historic seismic records in the South American passive margin has been documented in Brazil (Ferreira and Assumpção, 1983; Takeya et al., 1989; Ferreira et al., 1998), where seismites related to synsedimentary faulting were identified (Bezerra and Vita-Finzi, 2000; Bezerra et al., 2001, 2005). In the study area, seismic energy appears to be related to the reactivation (and upward propagation) of Jurassic and Cretaceous normal faults during the Paleocene. Liquefaction and/or fluidization structures have been genetically related to seismic events of magnitude larger than 5 ($M>5$) (Atkinson, 1984; Allen, 1986; Ambraseys, 1988; Enzel et al., 2000; Rodríguez-Pascua

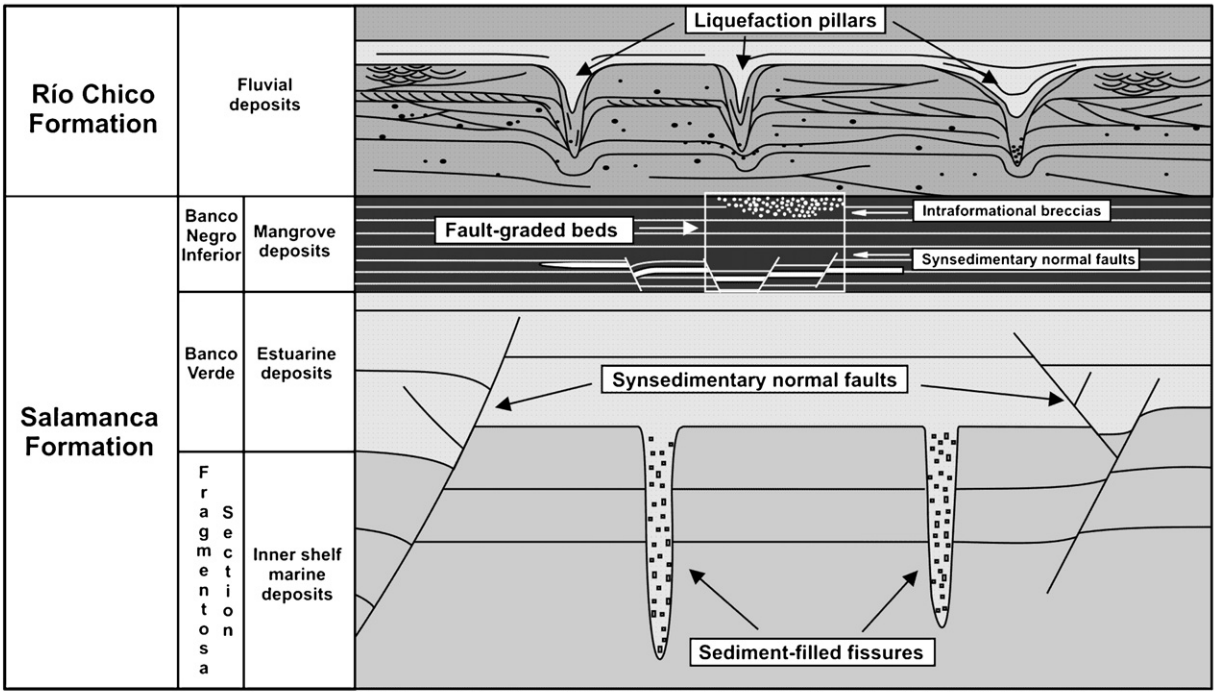

Fig. 11. Synthetic scheme with distribution of soft-sediment deformation structures observed in the Paleocene sedimentary rocks of Golfo San Jorge Basin. No vertical scale is implied.

et al., 2000, 2003; McLaughlin and Brett, 2004; Monecke et al., 2004), of approximately MMI=VI (modified Mercalli intensity) (Sims, 1975) or VII (Obermeier, 1996). Similar earthquake magnitude values were calculated from seismites in other Atlantic passive-margin settings (Bezerra and Vita-Finzi, 2000; Obi and Okogbue, 2004; Bezerra et al., 2005). This data suggest Paleocene seismic events at least of magnitude 5.

5.5. Stratigraphical implications

The relation between tectonics and sedimentation is commonly studied from sedimentary facies architecture (Gawthorpe et al., 1997; Gawthorpe and Leeder, 2000), but synsedimentary deformation structures have been used to support synsedimentary tectonic activity (Cliffton, 1988; Grimm and Orange, 1997; Obi and Okogbue, 2004). Episodic subsidence of the basin can be recorded in the type and distribution of seismically-induced soft-sediment deformation structures, which are synchronous with the marginal uplift of the basin and the increase in the accommodation basinward (Obi and Okogbue, 2004). However, the correlation between the stratigraphic distribution of seismites and the vertical pattern of cyclicity is not often demonstrated (Pratt, 1994).

The studied outcrops are located in the northern Golfo San Jorge Basin margin, where the suite of soft-sediment deformation structures could be interpreted as an indicator of a pulse of marginal uplift contemporaneous with sedimentation. The creation of accommodation in the basin during the deposition of the Salamanca Formation has been demonstrated using subsurface data by Fossa-Mancini (1932, 1935) and Foix and Paredes (2004).

6. Conclusions

1) Paleocene rocks in the North Flank of the Golfo San Jorge comprise the marine Salamanca Formation and the overlying fluvial Río Chico Formation. Numerous small-scale, synsedimentary normal faults are restricted to the uppermost strata of the Salamanca Formation, showing thickness variation across the fault plane. The data support the syntectonic deposition of Paleocene sedimentary rocks, related to reactivation of the Mesozoic normal faults of the basin.
2) A suite of soft-sediment deformation structures that are preserved in a 15 m-thick section of the upper part of the Salamanca Formation and basal strata of the Río Chico Formations is interpreted as seismites. The structures (from bottom to top) include (a) sediment-filled fissures, (b) small-scale normal faults, (c) fault-graded beds and (d) pillars. The vertical gradation of the deformation features most likely represents the sedimentary response to different degrees of compaction and saturation during seismic shocks, also influenced by lithological properties.
3) The lateral abundance and temporal distribution of the deformation features support the occurrence of at least three main seismic events. Considering the accepted threshold for liquefaction, the earthquake magnitude necessary to form pillar structures must be $M>5$.
4) The reliable identification of seismites in ancient sedimentary successions can help in interpreting the tectonosedimentary evolution of sedimentary basins.

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