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Occurrence of shallow gas in the easternmost Lago Fagnano (Tierra del Fuego)

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ABSTRACT

High-resolution seismic profiles acquired in the eastern sector of Lago Fagnano, the southernmost ice-free lake in the world, have shown the presence of very shallow gas-bearing layers in the upper sedimentary sequences. The gas-related features observed on seismic profiles include a typical, very strong reflection with reversed polarity, multiple reflections and acoustic blanking that hide subsurface sedimentary and structural features. The top of the acoustically high-amplitude layer is located between 0.3–1.7 m below the lake floor. It generally forms a sharp boundary, often marked by a varying offset probably due to different levels of gas penetration, which could be related to the lithology of the overlying sediments. To confirm the presence of gas, some gravity cores were recovered in places where the blanking effect was most relevant and in the supposed gas-free zone. Sediment core analyses have highlighted the occurrence of significant organic-rich components within the uppermost, largely unconsolidated sedimentary layers, in correspondence of the seismically-detected gassy zone, whereas only a few organic layers were found in the gas-free zone. We assume that the main origin of gas is linked to the presence of a shallow, thin peat-rich layer of Middle-Late Holocene age. In fact, the mapped gassy zone occurs in correspondence of the outlet of the Rio Turbio, the principal tributary of Lago Fagnano, which discharges waters coming from a relatively small sag pond located immediately to the east of the eastern shore of the lake. To date, this is the first evidence of shallow gas in Tierra del Fuego lakes.

INTRODUCTION

Lago Fagnano is the southernmost ice-free reservoir of water in the world. It lies in the central part of Tierra del Fuego (Fig. 1a), one of the most important and extensive Late Pleistocene glaciated regions of South America. The 105-km long, E-W elongated water basin occupies a deep tectonic depression developed along the Magallanes-Fagnano transform fault (Lodolo *et al.* 2002, 2003). This fault forms a principal segment of the present day South America-Scotia plate boundary. In addition to its tectonic origin, the lake has undergone a series of glacial-related events that have both generated complex depositional features and profoundly modified its Late Quaternary morphological setting.

A series of geological and geophysical field surveys have been conducted in Lago Fagnano and Tierra del Fuego both onshore and offshore since 1998. These studies have allowed us to derive a quite detailed morphological, tectonic and structural setting of the region (see Lodolo *et al.* 2003; Menichetti *et al.* 2008, among others). Recently acquired very high-resolution seismic profiles in Lago Fagnano have revealed in the easternmost sector of the basin an area marked by poor seismic penetration that was supposed to be caused by the presence of shallow gas layers. In addition, sedimentary cores have been sampled both in the supposed gas-bearing zone and in the gas-free zone (Fig. 1b). This paper presents a qualitative study on the evidence of the gas-bearing layers, through a detailed analysis of the seismic signal and also attempts to explain the origin and source of natural gas. A multi-disciplinary approach is proposed here, which includes a combination of geophysical, sedimentological and laboratory based geochemical techniques.

GEOMORPHOLOGICAL CONTEXT

Lago Fagnano is located in a tectonic depression in the heart of Tierra del Fuego, where repeated and intense glaciations have been documented since latest Miocene (Mercer 1976; Clapperton 1990). During the Quaternary, several glaciers descended a number of times from the Cordillera Darwin ice-cap to cover most of

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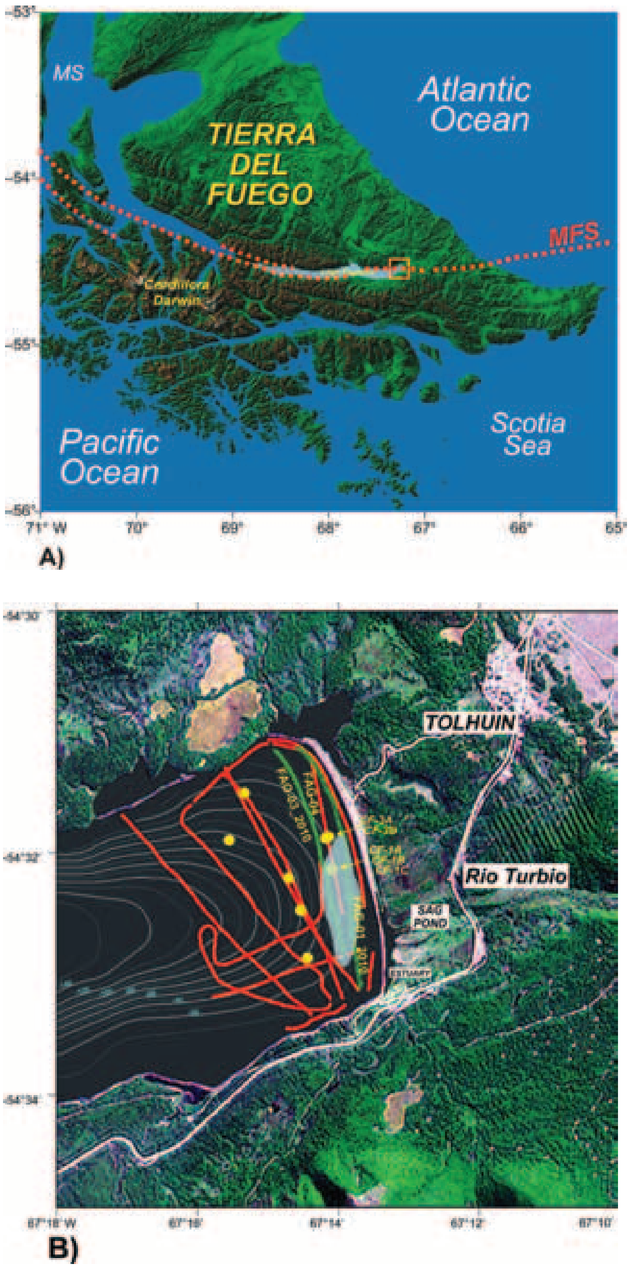

FIGURE 1

a) General morphological map of Tierra del Fuego, traversed by the Magallanes-Fagnano transform system, with the location of Lago Fagnano. MS indicates the Magallanes Strait; MFS indicates the Magallanes-Fagnano transform system. Red box indicates the easternmost sector of the lake where data have been acquired. b) SPOT image of the eastern Lago Fagnano area, with superposed the map of the high-resolution single-channel seismic profiles and gravity cores (yellow dots) acquired during Campaign 2009 (lines in red) and 2010 (lines in green). The blue area located near the estuary of the Rio Turbio indicates the occurrence of shallow gas. Bathymetric contours every 10 m.

the Tierra del Fuego. Glacial sediment accumulation probably covers the entire Holocene and may even date back to the Last Glacial Maximum (Bujalesky *et al.* 1997) that occurred about 18 000 years ago. Based on lake depth and altitude of the erosional glacial features along the valley slopes, a maximum ice thickness for the Fagnano paleoglacier was crudely estimated at 1 km (Coronato *et al.* 2009). It generated the morphological evolution of the region and modelled its landscape. Currently, the climate of this region is alpine, with a strong winter sub-polar Antarctic influence and under the south-westerly wind effect during austral summers, which brings moisture and humidity to the region.

The lake is a large pull-apart basin developed within the principal displacement zone of the Magallanes-Fagnano transform system (Lodolo *et al.* 2003) and comprises two major E-W trending sub-basins: a smaller, deeper basin in the east reaching a maximum depth of 206 m (Zanolla *et al.* 2011) and an elongated, shallower basin in the west with a maximum water depth of 120 m. The total area of the lake is 609 km^2. Only its westernmost tip (about 15 km) is part of the Chilean territory. Lago Fagnano is located in a tectonically active region, therefore its sedimentary record may also archive regional tectonic events. In fact, recent fault scarps and displacement of glacio-lacustrine sediments along the transform lineament indicate ongoing tectonic activity (Menichetti *et al.* 2007, 2008). Moreover, fluvial drainages in the region are clearly influenced by the presence of E-W striking structures related to the Magallanes-Fagnano fault system.

The first seismostratigraphic study of Lago Fagnano sediments was conducted by Waldmann *et al.* (2008). Data show that the entire sedimentary record reaches a thickness of more than 100 m in the eastern basin, whereas it reaches 60 m in the western basin. This thickness discrepancy suggests either different sedimentation rates in the sub-basins or a longer temporal record in the east. Three main seismic units within the lake basin were recognized, based upon their seismic facies differences: a) a bedrock complex at the base, overlain by b) an ice-contact glacier-derived deposit, which in turn are superimposed by c) a glacio-lacustrine succession infilling topographic lows. The seismic images generally indicate a relatively even sedimentation often interrupted by chaotic and transparent seismic facies that can be interpreted as mass-wasting events. These episodic facies are most probably triggered by paleo-earthquakes along the Magallanes-Fagnano fault zone (Ariztegui *et al.* 2008). A complex set of submerged frontal, central and lateral moraines covered by lacustrine sediments have been identified by seismic stratigraphic analysis (Waldmann *et al.* 2010). These authors interpreted the preserved frontal moraines as having been formed during at least 20 re-advance stages of the glacier within a long-term deglaciation interval following the Last Glacial Maximum. A multi-proxy study of selected cores of the uppermost sedimentary cover of Lago Fagnano has allowed the characterization of a Holocene sedimentary record (Waldmann *et al.* 2008, 2009). Petrophysical, sedimentological and geochemical studies of a complete lacustrine laminated sequence revealed variations in major and trace elements, as well as organic content, suggesting high variability in environmental conditions.

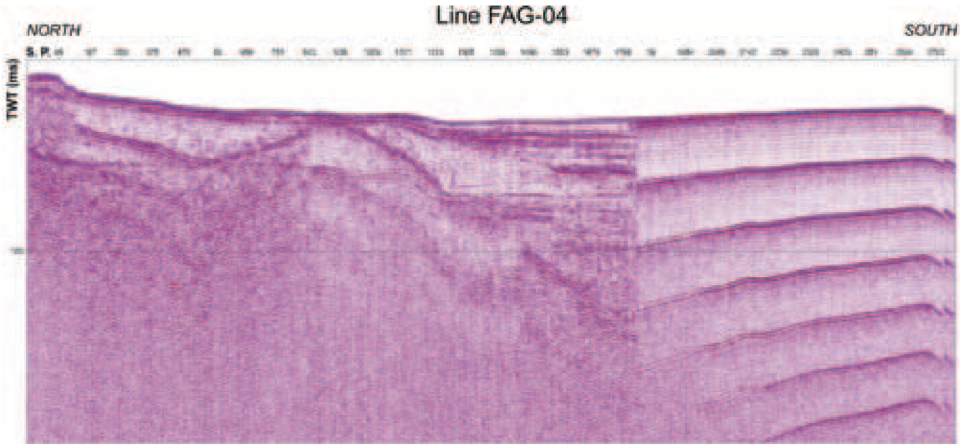

FIGURE 2
High-resolution seismic line FAG-04 (see Fig. 1b for location), where the evidence of shallow gas is particularly remarkable (southern part of the line).

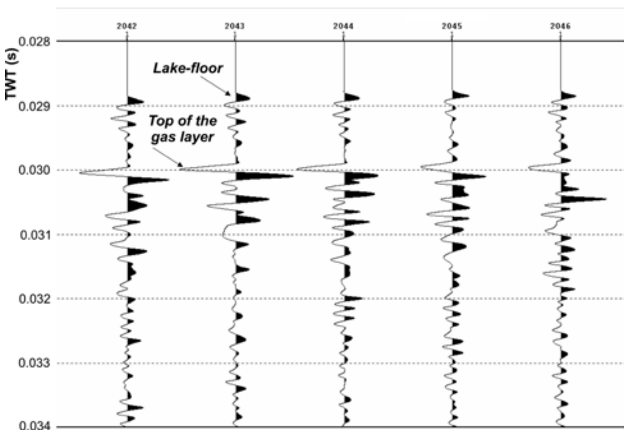

FIGURE 3
The characteristic amplitude polarity change occurring at the sediment/gassy sediment interface, with respect to the lake floor horizon.

The lowlands that characterize the eastern sector of Lago Fagnano are mainly covered by peaty zones and widespread forests. Coastal cliffs formed by glacial and glacio-deltaic sedimentary strata are mainly found along the south-eastern shore and were deposited during an ice advance prior to the Last Glacial Maximum (Bujalesky *et al.* 1997). The Claro, Milna, Valdez and Turbio rivers are the principal inputs of Lago Fagnano, whereas the Azopardo river at the western extreme of the lake is the only outlet towards the Pacific Ocean through the Magallanes Strait.

DATA ACQUISITION

High-resolution single-channel seismic reflection profiles were acquired in November 2009 and March 2010 in Lago Fagnano using a 150 kJoule Boomer source (shooting rate: two shots/second) and a single-channel, 10-hydrophones solid-state streamer. The acquisition was carried out on board of a small ship at a speed of about 3 knots. The position was determined by a differential GPS directly connected to the acquisition system. The pulse has a wide frequency range (400–9000 Hz), allowing a decimetric-scale vertical resolution (Zecchin *et al.* 2008). These data complement and complete the bathymetric and seismic surveys carried out previously in Lago Fagnano (Lodolo *et al.* 2007; Waldmann *et al.* 2008). Moreover, during the March 2010 Campaign, 10 gravity piston cores (with recovered sediment samples lengths from 80–170 cm) were collected to analyse the stratigraphy of the most recent (Middle to Late Holocene) sedimentary cover in the eastern sector of the basin (see Fig. 1b).

SEISMIC EVIDENCE OF SHALLOW GAS

Along some high-resolution seismic profiles of the south-easternmost sector of Lago Fagnano, the possible presence of shallow gas layers has been inferred (Fig. 2). The gas-related features observed on the seismic profiles include a strong amplitude reflector located a few milliseconds TWT (two-way traveltime) beneath the lake floor that creates multiple reflections and a typical acoustic attenuation ('blanking effect') (Best *et al.* 2004). Beneath this acoustic interface, it is impossible to derive information about eventual structures and sediment geometry. The presence of gas in marine and lacustrine sediments was identified about fifty years ago (Koyama *et al.* 1953; Emery and Hoggan 1958). Subsequently, more geophysical studies focused their attention on the acoustic behaviour of gassy sediments (Garcia-Gil *et al.* 2002; Missiaen *et al.* 2002; Bertin and Chaumillon, 2005; Gwang *et al.* 2005). The gas abundance is well detected in the seismic section because the sediment/gassy sediment interface has a strong impedance contrast that generates a characteristic seismic reflector. Since acoustic impedance is a product of sound speed and density, such a reflector implies an abrupt decrease in P-wave velocity or/and in bulk density, which can generally be attributed to gas occurrence. For these reasons, a sediment/gassy sediment interface presents reversed polarity with respect to the lake floor reflector (Fig. 3), which is characterized by normal polarization due to the positive water/sediment impedance contrast. Free-gas bubbles in sediments have a typical resonance frequency and can strongly vibrate and scatter energy when stimulated at this frequency. Experiments conducted on gassy sediments (Anderson and Hampton 1980; Wilkens and Richardson 1998;

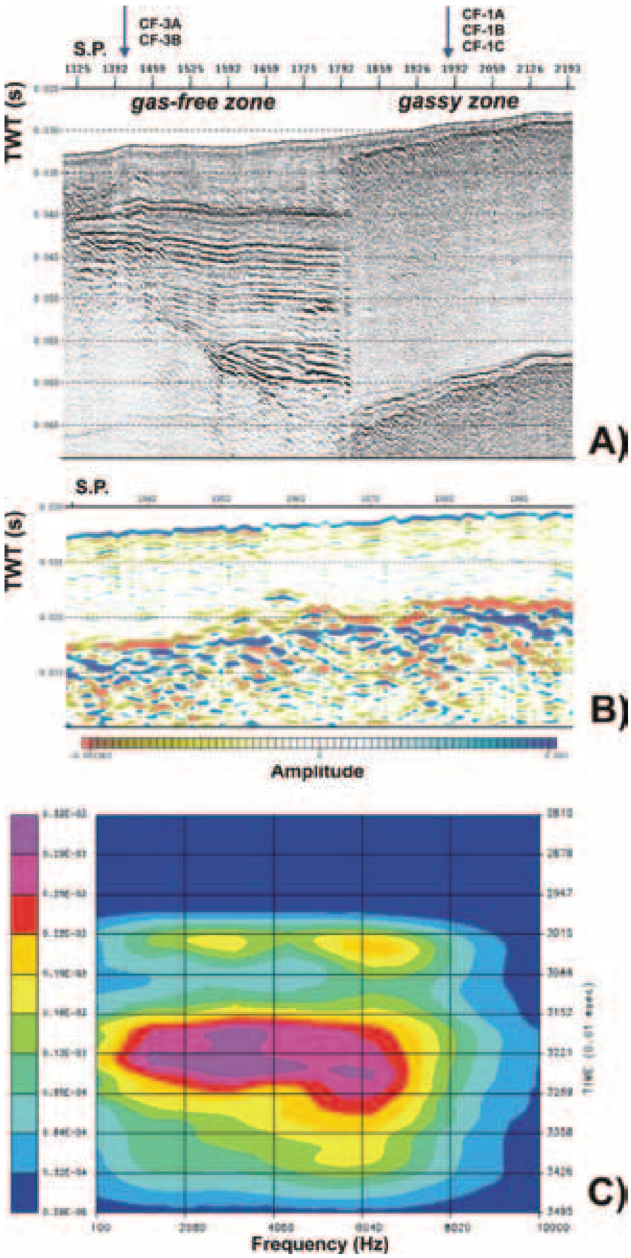

FIGURE 4

a) Part of the high-resolution seismic profile FAG-04 with the gas-bearing sediments visible in the right part; the locations of the gravity cores along the profile are also shown. b) Colour-coded, variable-area amplitude display showing the strong sediment/gassy sediment interface with respect to the lake floor interface. c) Time-frequency analysis of 100 traces from profile FAG-04: the lake floor is at 30 ms TWT and the sediment/gassy sediment interface at 32 ms TWT.

Best *et al.* 2004) have shown that the resonance frequency depends on bubble radius, the thermal properties of gases, the dynamic shear modulus, the density of the sediments and the hydrostatic pressure. It is observed that in the vicinity of the resonance frequency, there is strong attenuation because most of the seismic energy is reflected or scattered. With seismic profiles, this situation corresponds to the so-called ‘acoustic turbidity zone’, i.e., the masking of sedimentary horizons by absorption and scattering of seismic energy due to free gas bubbles, as extensively described by Hovland and Judd (1988) and Judd and Hovland (2007).

The spectral analysis of the sediment/gassy sediment interface (Fig. 4a–c) conducted on our data shows that the gas-related seismic event persists over a wide range of frequencies (400-6100 Hz): this suggests the presence of gas bubbles occupying sediment pores that create a resonance effect in the Boomer frequency range. This reflector generally forms a sharp boundary, often marked by varying offset probably due to different levels of gas penetration, which could be related to the lithology (poorly consolidated muddy layers) of the overlying sediments. The shallow gas-bearing horizons are all located in the south-eastern sector of Lago Fagnano, where water depths vary from 16–27 m (see Fig. 1b). After the manual picking of the sediment/gassy sediment interface and of the lake floor horizons, we plotted these reflections to analyse their behaviour, after travel time-depth conversion. We used a sound velocity of 1432 m/s for the lake water (Zanolla *et al.* 2011) and 1500 m/s for the shallower, generally unconsolidated sedimentary cover. The choice of this value for the acoustic speed, in absence of laboratory measurements, was adopted by considering the average values obtained for the shallowest lake sediments in many alpine lakes (Finckh *et al.* 1984). We may in fact assume similar environmental and sedimentary conditions for the central sector of Tierra del Fuego. This work was done by focusing on the three more representative seismic lines where the presence of gas is seismically more evident. Along profile FAG-01_2010 (Fig. 5a), the top of the gas layer appears in correspondence of shot point (SP) 3080, at 0.6 m below the lake floor. Following an initial part where the trend is quite discontinuous, the gas-bearing layer approaches the lake floor at a depth of 0.1 m below it. This occurs in the morphological depression located between SP’s 5250–6050 in the far south. When water shallows at 13 m depth, the gas layer deepens to 0.5 m below the lake floor. Along line FAG-04 (Fig. 5b), we see only a limited part of the shallow gas layer, which is acoustically visible from about SP 1790. In the initial part of the area where gas is occurring, the depth of the gas horizon is maximum, i.e., 1.7 m below the lake floor. Continuing southwards, the gas reflector is quite irregular up to about SP 2150. At the southern end of the line, in correspondence of the outlet of the Rio Turbio, the top gas surface becomes generally parallel to the lake floor horizon. Line FAG-03 (Fig. 5c) is the westernmost profile presented; here the top gas lies at 1.5 m below the lake floor at SP 2380 and is fairly constant throughout the shallow gas zone. In general, seismic lines show that the separation between the two horizons (gas-bearing layer and lake floor) increases with water depths, because the increment in pressure favours the entrapment of gas within the sediment pores.

LABORATORY ANALYSES

To analyse the sediment characteristics of the area where the occurrence of gas was seismically detected, some gravity cores were acquired. Gas was not sampled from the cores, mostly because it was almost completely released in the lake water during the core recovery. It is suggested that the reduction of hydrostatic pressure from 20–24 m water depth at which the samples were retrieved to atmospheric pressure, has favoured the immediate dispersion of gases in the water column. Laboratory analyses were carried out on the recovered sediments to possibly detect the presence of heavier gases. The following describes the methodology used to study gas characteristics in the cores (Fig. 6) that were taken in the eastern sector of Lago Fagnano. The gas phase present in the headspace of the specimen was extracted at a constant flow by means of a peristaltic pump connected to the sample holder through a Teflon® pipe provided with a needle; the pipe end was immersed in a vial containing a known volume of methanol. The system was subjected to mild depression and the flow was adjusted with the aid of a safety valve located upstream of the vial itself so as to minimize possible stripping of volatile organic compounds present in the headspace of the specimen. The entry of the needle in the sample holder was sealed in order to prevent possible leakage of the gas from the headspace. A test tube was also connected downstream of the vial in order to collect any volatile compounds (e.g. CH_4 or other hydrocarbons with very low boiling point) which might have escaped the methanol trap. The extraction of the gas phase lasted until no more bubbling inside the vial was observed. The analysis of the absorption solution in the vial and of the gas phase collected in the test tube - performed by means of high-resolution gas chromatography with a mass spectrometry detector - did not show the presence of volatile organic hydrocarbons. We do not exclude the presence of CO_2, since it is well- known that CO_2 production accompanies the methanogenic phase in

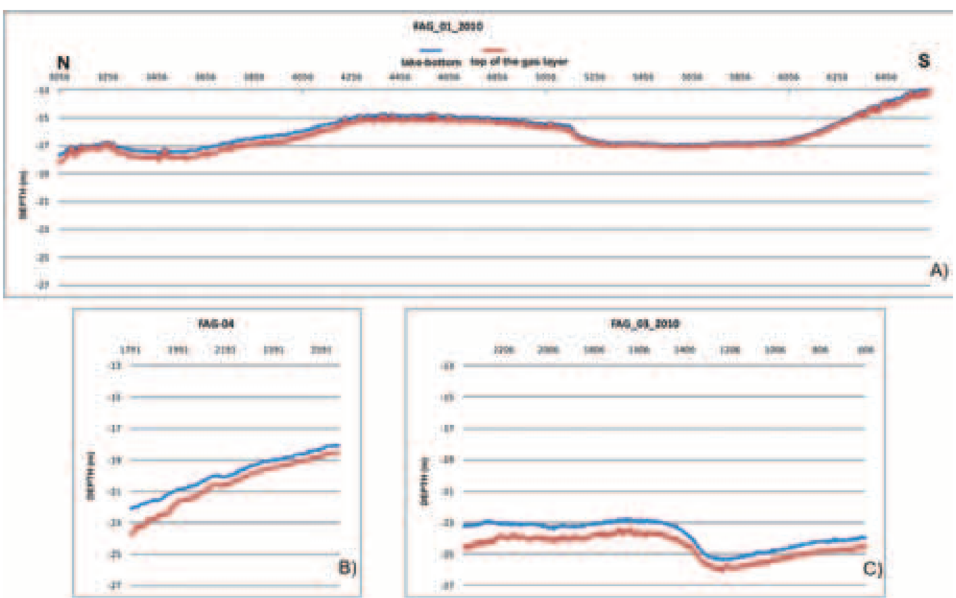

FIGURE 5
Top of the shallow gas layer with respect to the lake floor, after depth conversion, along three representative high-resolution seismic profiles where the occurrence of gas is particularly remarkable. See text for details.

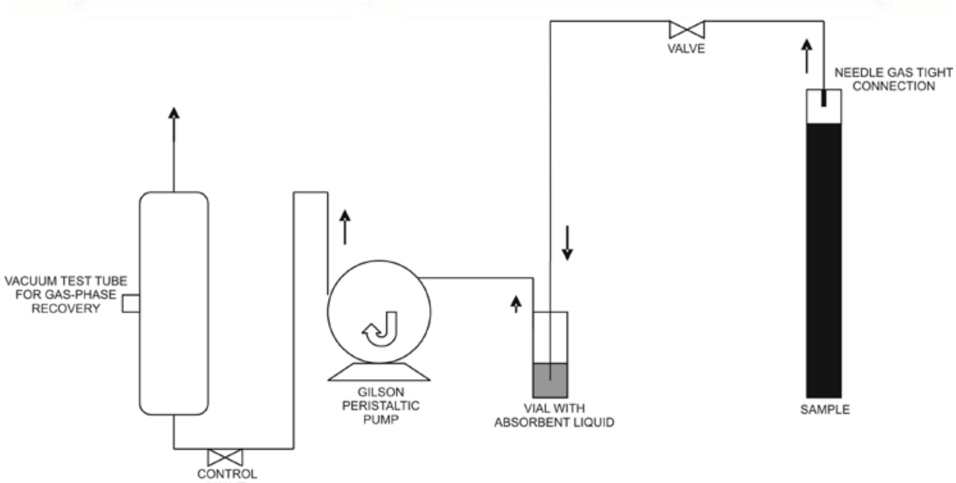

FIGURE 6
Sketch of the laboratory system used for detecting volatile gas in the sediment specimens.

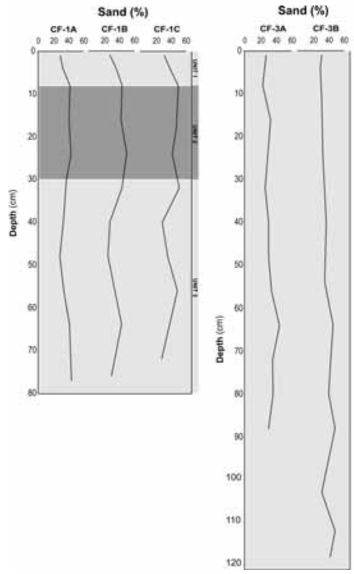

FIGURE 7

Percentages of sand quantity in the analysed sedimentary cores. Left panel refers to cores recovered in the gassy zone. Right panel refers to cores recovered in the gas-free zone. See text for details.

anaerobic decomposition processes. It can be found in the gas phase in percentages ranging from 20–30% in pore-space volume, depending on the specific process conditions. For these reasons, we can assume that the concentration of CO_2 in the gas phase within the Fagnano sediment pores falls within the mentioned percentage range.

SEDIMENT-CORE ANALYSES

A total of 65 sediment samples were analysed (Fig. 7) from five cores taken in correspondence of the high-resolution seismic profiles in both places where the blanking effect was most relevant and in areas where shallow gas was not evident (see Fig. 1b). The analysis was performed to calculate sand and silt in percentage composition. Wet sediments were dried in an oven at 40° C and hence weighted. Specimens were subsequently disaggregated with hydrogen peroxide, washed through a 0.063 mm sieve, dried and weighted to obtain the percentage values.

Piston cores CF-1A, CF-1B and CF-1C were taken at water depths of 21 m, 20.4 m and 20.8 m, respectively and recovered 79 cm, 76 cm and 75 cm of lacustrine deposits. The examined sedimentary succession of the three cores is very similar and consists of silt to fine sand that are interlaminated with silt and clay, forming planar lamination. Three lithological units (Unit 1, Unit 2 and Unit 3) were identified in these three cores. Unit 3, from bottom up to 30 cm, consists of grey silt that contains scarce vegetal remains, sometimes found in small lens. The CF-1A core sedimentary succession is interrupted by two layers of peat at a depth of 70 cm and 30 cm. A peat layer is also present in core CF-1C at 30 cm depth, whereas scattered patches of peat are found at 30 cm depth in core CF-1B. Unit 2, from 30 cm to 4.0 cm, consists of fine sand and silt laminae 1.0–2.5 mm thick. The abundance of lens and layers of vegetal remains give a dark-grey colour to these sediments. Unit 1, from 4.0 cm to the top of the three cores, consists of 2.0–3.0 mm thick brown silt and clay laminae with scarce vegetal remains. In this unit, there is a decrease of organic material and sand. The progressive increase of sand contents from Unit 3 to Unit 2 and the increase of vegetal remains, with a maximum concentration in Unit 2, testify the proximity of fluvial input, which is probably more dominant in Unit 2.

Piston cores CF-3A and CF-3B were retrieved at water depths of 19.8 m and 23.0 m, respectively and recovered 92 cm and 121 cm of lacustrine deposits. The sedimentary succession of these cores consists of 1.5–2.0 mm thick dark-grey silt laminae, alternating with slightly lighter-coloured layers of clayey silt and silt of 1.0–2.0 mm in thickness. Several layers composed of peat are found along the sedimentary succession of the two cores. Most of them are 2.0–3.0 mm thick but the thicker peat layer (about 6 mm) is found at 108 cm depth in core CF-3B. The sand contents along the sedimentary succession are slightly low and do not show great fluctuations thus evidencing less influence from fluvial input.

Core data show that the presence of shallow gas layers seen in seismic profiles is intimately related to the organic material carried from the Rio Turbio that discharges the waters of the relatively small peatland located immediately to the east of the eastern shore of Lago Fagnano. Fine to very-fine silty layers may act as a trapping cap for the escape of gas bubbles to the surface.

DISCUSSION

Several characteristics in the seismic data collected in Lago Fagnano indicated the presence of gas-bearing layers in the uppermost sedimentary cover. The signal analysis of the sediment/gassy sediment interface shows a phase inversion with respect to the acoustic reflectors associated with the lake floor and the depositional sequences. Comparing the seismic sections where gas-bearing layers are present and to the ones without gas, the ‘acoustic blanking’ effect appears remarkably evident (Fig. 8). The sediment/gassy sediment interface on our data generally appears as an irregular diffracted reflector with strong amplitude, with a significant decrement of the signal energy below it. The Boomer signal amplitude decay in gassy sediments (where the lake floor is at 29 ms TWT) and in gas-free sediments (where the lake floor is at 31 ms TWT), is displayed in Fig. 9. Under the sediment/gassy sediment interface, the signal has a strong energy decrement and it loses about 20 dB in a time interval of about 10 ms with respect to the normal decay trend in sediments where gas is not present. This result agrees with the resonance model of gassy sediments (Tuffin *et al.* 2000; Mathys *et al.* 2005), because our Boomer frequency range is centred at the typical bubble resonance curve in correspondence to these frequencies.

Single-channel data do not allow to calculate P-wave velocities and this is a strong limitation for deriving the gas volume in sediment pores (Anderson and Hampton 1980; Baltzer *et al.* 2005). To quantify the volume of the gas present in the sediments, it would be necessary to use special coring that is able to maintain *in situ* conditions of temperature and pressure, which is quite cost-consuming equipment. We have no available information about either the P-wave velocity or the percentage of volume of gas in the sediment pores, so our analyses are necessarily qualitative.

We can assume a relationship between the occurrence of shallow gas in the eastern Lago Fagnano basin and the presence of a sag pond located in the estuary of the Rio Turbio (Fig. 10). A sag pond is generally regarded as a small depression, in some cases entirely or partially occupied by water, which forms between two strands of an active strike-slip fault. The relative motion of the two fault strands results in a stretching of the land between them, causing it to subside. Abundant morphological evidence of tectonic activity of the fault is found in the area surrounding Lago Fagnano, as seen in a cross-stratified Quaternary glacio-fluvial sand and gravel outcrop in small quarries located just to the east of the eastern shore of Lago Fagnano. Here, several sets of WNW-ESE trending, sub-vertical SSW-dipping normal faults with throws of a few decimetres are present (Lodolo *et al.* 2003). Fault-slip data and kinematic analysis for the fault arrays in this outcrop have revealed a prevalent NNE-SSW extensional strain tensor (Menichetti *et al.* 2008). This structural geometry is consistent with a general left-lateral transtensional mechanism related to the principal wrench deformation that crosses the Lago Fagnano depression in an E-W direction. Photographic comparisons show that the present-day gravel barrier that closes to the east Lago Fagnano and now represents its eastern shore, was formed during a historical (17 December 1949), Mw = 7.5 earthquake. Landslides occurred along the west coast of Tierra del Fuego and along the banks of Lago Fagnano and the epicentre was presumably located on the fault structure that includes Lago Fagnano (Lomnitz 1970).

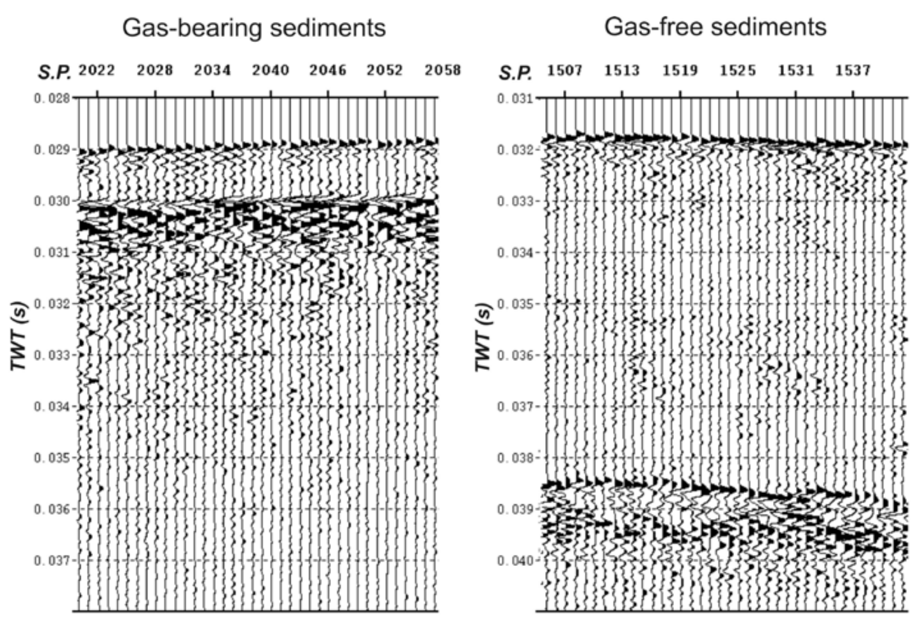

FIGURE 8
Comparison between seismic sections showing gas-bearing sediments (left panel) and gas-free sediments (right panel).

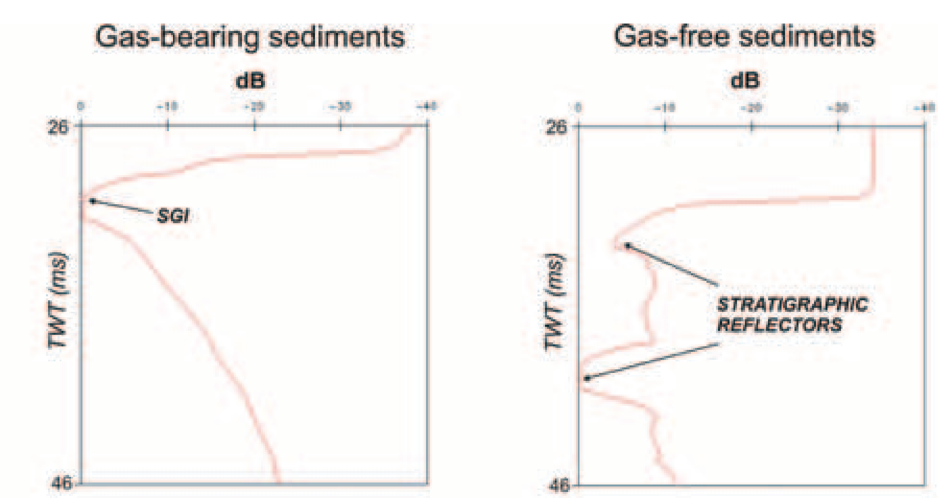

FIGURE 9
Comparison of Boomer signal amplitude decays in gassy sediments (left plot) and in gas-free sediments (right plot). Amplitude is calculated within a sliding analysis window as a function of time. SGI indicates the sediment/gassy sediment interface.

FIGURE 10
The Rio Turbio estuary and the sag pond, located immediately to the east of the Lago Fagnano eastern shoreline.

This gravel barrier acted as a dam for the water discharge of the Rio Turbio, enclosing a sag pond of the lower Rio Turbio valley and definitively changed the morphological setting and the drainage system of the eastern Lago Fagnano area. Independent geophysical data evidence the involvement of the Magallanes-Fagnano fault system in the formation of the sag pond at the estuary of the Rio Turbio, where a Bouger gravity minimum suggests the presence of a small and elongated basin there (Tassone *et al.* 2005; Lodolo *et al.* 2007). A sag pond may be viewed as a particular example of a peatland – areas occasionally or frequently covered by water where the soil contains a high amount of dead organic matter. They cover 3% of the world's total land area and represent half of the Earth's wetland areas. Some studies have calculated that peatlands contain globally at least 600 gigatonnes of carbon (Yu *et al.* 2011): equivalent to all other terrestrial biomass (forests, grass and shrublands, etc.) and twice as much as all carbon stored in the world's forests. In the sub-polar zone, peatlands contain on average 3.5 times more carbon per hectare than above-ground ecosystems on mineral soils. Radiocarbon dates demonstrate that the development of the current circumarctic peatlands began about 16 500 years ago and expanded explosively between 12 000 and 8000 years ago in concert with high summer insolation and increasing temperatures. Their rapid development contributed to the sustained peak in CH_4 and modest decline of CO_2 during the early Holocene and likely contributed to CH_4 and CO_2 fluctuations during earlier interglacial and interstadial transitions (MacDonald *et al.* 2006).

Tierra del Fuego is a region in which several types of peatlands are well represented. The maritime, cold temperate climate in the region and the particular alpine climate of the area of Lago Fagnano, provide the necessary conditions for the preservation of peatlands. The period that followed the Last Glacial Maximum contributed to the peatlands formation because of the abundant melt water and the widespread presence of closed morphological depressions (Coronato *et al.* 2009). For these reasons we think that the presence of shallow gas in the eastern sector of Lago Fagnano is due to the anaerobic decay of the organic matter contained in the peat found in core samples. The absence of higher molecular weight hydrocarbons may be explained by both the low temperature and shallow (low pressure) source of the organic levels and their relatively young age (Middle-Late Holocene). An alternative hypothesis about the origin of gas in the shallow sediments could be linked to the presence of faults and discontinuities associated with the E-W wrench deformation that crosses Lago Fagnano, along which fluids could rise to the surface. However, the acquired seismic data and available information did not reveal either gases in correspondence of these structures or gas-related morphologies like gas seeps, pockmarks or acoustic chimneys.

CONCLUSIONS

Gas-bearing sedimentary layers were found on high-resolution seismic profiles acquired in the easternmost sector of Lago Fagnano, the largest water basin of Tierra del Fuego. The presence of gas is clearly recognizable on the seismic section because the sediment/gassy sediment interface is manifested by a high-amplitude reflector with reversed polarity with respect to the lake floor reflector. Acoustic blanking hides sedimentary and structural features eventually present below the sediment/gassy sediment interface. The top of the acoustically high-amplitude layer is located between 0.3–1.7 m below the lake floor. Analyses performed on sediment gravity cores highlighted the occurrence of significant organic-rich components within the uppermost, largely unconsolidated sedimentary layers, in correspondence to the seismically-detected gassy zone, whereas only small traces of organic material were found in the gas-free zone. Seismic data analysis showed that the gassy zone occurs principally in correspondence to the outlet of the Rio Turbio, the principal tributary of Lago Fagnano, which discharges waters coming from a small sag pond located immediately to the east of the eastern shore of Lago Fagnano. We assume that the main origin of gas is linked to the presence of a shallow, thin peat-rich layer of Middle-Late Holocene age. To date, this is the first evidence of shallow gas layers in Tierra del Fuego lakes.

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REFERENCES

Anderson A.L. and Hampton L.D. 1980. Acoustics of gas-bearing sediments I. Background. *Journal of the Acoustical Society of America* **67**, 1865–1889.

Ariztegui D., Anselmetti F.S., Gilli A. and Waldmann N. 2008. Late Pleistocene environmental change in Eastern Patagonia and Tierra del Fuego – A limnogeological approach. In: *The Late Cenozoic of Patagonia and Tierra del Fuego* (ed. J. Rabassa), pp. 241–253. Elsevier.

Baltzer A., Tessier B., Nouzé H, Bates R., Moore C. and Menier D. 2005. Seistec seismic profiles: A tool to differentiate gas signatures. *Marine Geophysical Researches* **26**, 235–245.

Bertin X. and Chaumillon E. 2005. New insights in shallow gas generation from very high resolution seismic and bathymetric surveys in the Marennes-Oléron Bay, France. *Marine Geophysical Researches* **26**, 225–233.

Best A.I., Tuffin M.D.J., Dix J.K. and Bull J.M. 2004. Tidal height and frequency dependence of acoustic velocity and attenuation in shallow gassy marine sediments. *Journal of Geophysical Research* **109**, B08101. doi:10.1029/2003JB002748

Bujalesky G., Heusser C., Coronato A., Roig C. and Rabassa J. 1997. Pleistocene glaciolacustrine sedimentation at Lago Fagnano, Andes of Tierra del Fuego, Southernmost South America. *Quaternary Science Reviews* **16**, 767–778.

Clapperton C.M. 1990. Quaternary glaciations in the southern hemisphere: An overview. *Quaternary Science Reviews* **9**, 299–304.

Coronato A., Seppälä M., Ponce J.F. and Rabassa J. 2009. Glacial geomorphology of the Pleistocene Lake Fagnano ice lobe, Tierra del Fuego, southern South America. *Geomorphology* **112**, 67–81.

Emery K.O. and Hoggan D. 1958. Gases in marine sediments. *AAPG Bulletin* **42**, 2174–2188.

Finckh P., Kelts K. and Lambert A. 1984. Seismic stratigraphy and bedrock forms in perialpine lakes. *Geological Society of America Bulletin* **95**, 1118–1128.

Garcia-Gil G., Vilas F. and Garcia-Garcia A. 2002. Shallow gas features in incised-valley fills (Ría de Vigo, NW Spain): A case study. *Continental Shelf Research* **22**, 2303–2315.

Gwang H. Lee , Dae C. Kim, Han J. Ki, Hyeong T. Jou, Young J. Lee (2005): Shallow gas in the central part of the Korea Strait shelf mud off the southeastern coast of Korea. *Continental Shelf Research*, 25, 2036-2052.

Judd A.G. and Hovland M. 2007. *Seabed Fluid Flow: The Impact of Geology, Biology and the Marine Environment*. Cambridge University Press.

Koyama T. 1953. Measurement and analysis of gases in lake muds. *Journal of Earth Sciences (Nagoya University)* **1**, 107–118.

Lee G.H., Kim D.C., Kim H.J., Jou H.T. and Lee Y.J. 2005. Shallow gas in the central part of the Korea Strait shelf mud off the southeastern coast of Korea. *Continental Shelf Research* **25**, 2036–2052.

Lodolo E., Lippai H., Tassone A., Zanolla C., Menichetti M. and Hormaechea J.-L. 2007. Gravity map of the Isla Grande de Tierra del Fuego, and morphology of Lago Fagnano. *Geologica Acta* **4**, 307–314.

Lodolo E., Menichetti M., Bartole R., Ben-Avraham Z., Tassone A. and Lippai H. 2003. Magallanes-Fagnano continental transform fault (Tierra del Fuego, southernmost South America). *Tectonics* **22**, 1076. doi:10.1029/2003TC001500

Lodolo E., Menichetti M., Tassone A., Geletti R., Sterzai P., Lippai H. and Hormaechea J.-L. 2002. Researchers target a continental transform fault in Tierra del Fuego. *EOS Transactions* **83**, 1–5.

Lomnitz C. 1970. Major earthquakes and tsunamis in Chile during the period 1535 to 1955. *Geologische Rundschau* **59**, 938–960.

MacDonald G.M., Beilman D.W., Kremenetski K.V., Sheng Y., Smith L.C. and Velichko A.A. 2006. Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. *Science* **314**, 285–288.

Mathys M., Thießen O., Theilen F. and Schmidt M. 2005. Seismic characterisation of gas-rich near surface sediments in the Arkona Basin, Baltic Sea. *Marine Geophysical Research* **26**, 207–224.

Menichetti M., Lodolo E. and Tassone A. 2008. Structural geology of the Fuegian Andes and Magallanes fold-and-thrust belt – Tierra del Fuego Island. *Geologica Acta* **6**, 19–42.

Menichetti M., Lodolo E., Tassone A., Hormaechea J.-L. and Lippai H. 2007. Geologia dell'area del Lago Fagnano in Terra del Fuoco (Sud America). *Rendiconti della Societa' Geologica Italiana* **4**, 251–254.

Mercer J.H. 1976. Glacial history of southernmost South America. *Quaternary Research* **6**, 125–166.

Missiaen T., Murphy S., Loncke L. and Henriet J.-P. 2002. Very high-resolution seismic mapping of shallow gas in the Belgian coastal zone. *Continental Shelf Research* **22**, 2291–2301.

Tassone A., Lippai H., Lodolo E., Menichetti M., Comba A., Hormaechea J.-L. and Vilas J.F. 2005. A geological and geophysical crustal section across the Magallanes-Fagnano fault in Tierra del Fuego. *Journal of South American Earth Sciences* **19**, 99–109.

Tuffin M.D.J., Best A.I., Dix J.K. and Bull J.M. 2000. Temporal variability of P-wave attenuation due to gas bubbles in a marine sediment. Acoustical Oceanography. *Proceedings of the Institute of Acoustics Conference*, 9–12 April 2001, Southampton Oceanography Centre, Expanded Abstracts, 291–298.

Waldmann N., Ariztegui D., Anselmetti F.S., Austin J.A. Jr., Dunbar R.B., Moy C.M. and Recasens C. 2008. Seismic stratigraphy of Lago Fagnano sediments (Tierra del Fuego, Argentina): A potential archive of paleoclimatic change and tectonic activity since the Late Glacial. *Geologica Acta* **6**, 101–110.

Waldmann N., Ariztegui D., Anselmetti F.S., Austin J.A. Jr., Moy C.M., Stern C. *et al*. 2009. Holocene climatic fluctuations and positioning of the Southern Hemisphere westerlies in Tierra del Fuego (54°S), Patagonia. *Journal of Quaternary Science* **25**, 1063–1075. doi:10.1002/jqs.1263

Waldmann N., Ariztegui D., Anselmetti F.S., Coronato A. and Austin J.A. Jr. 2010. Geophysical evidence of multiple glacier advances in Lago Fagnano (54°S), southernmost Patagonia. *Quaternary Science Reviews* **29**, 1188–1200.

Wilkens R.H. and Richardson M.D. 1998. The influence of gas bubbles on sediment acoustic properties: *In situ*, laboratory, and theoretical results from Eckernförde Bay, Baltic Sea. *Continental Shelf Research* **18**, 1859–1892.

Yu Z., Beilman D.W., Frolking S., MacDonald G.M., Roulet N.T., Camill P. and Charman D.J. 2011. Peatlands and their role in the global carbon cycle. *EOS Transactions* **92**(12), 97–108.

Zanolla C., Lodolo E., Lippai H., Tassone A., Menichetti M., Baradello L. *et al*. 2011. Bathymetric map of Lago Fagnano (Tierra del Fuego Island). *Bollettino di Geofisica Teorica e Applicata* **52**, 1–8.

Zecchin M., Baradello L., Brancolini G., Donda F., Pizzetto F. and Tosi L. 2008. Sequence stratigraphy based on high-resolution seismic profiles in the late Pleistocene and Holocene deposits of the Venice area. *Marine Geology* **253**, 185–198.

