BOTTOM GAS SEEPS AT LAKE NAHUEL HUAPI, PATAGONIA

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ABSTRACT

Gas emissions discovered on the Brazo Rincon sector of Lake Nahuel Huapi in Patagonia, are described and characterized through analysis of hydroacoustic targets rising from the bottom. Echograms target analysis allowed for the identification of two possible sources. The first one corresponding to multiple gas vents in a seep field in 30 m to 100 m water depths. The second consisting of gas, fluids, resuspended bottom debris, and sediments in near-shore shallow waters. The hydroacoustic characteristics of these plumes are described, and possible origins of gas emissions are considered in relation to geological characteristics associated to local volcanism and/or biological phenomena.

Keywords: *Hydroacoustics, Gas emissions, Lentic water bodies, Argentina.*

RESUMEN

Emisiones de gases desde el fondo del lago Nahuel Huapi, Patagonia.
Emisiones de gas en el brazo Rincón del lago Nahuel Huapi, Patagonia, son descriptas y caracterizadas en función del análisis de señales blancos ecoicos que migran desde el fondo hacia la superficie. Dichos blancos identificados como burbujas de gas, provienen en apariencia de dos fuentes distintas. Una de las señales resulta consistente con emanaciones de gases de múltiples fuentes de emisión, las cuales conforman un campo sumergido que se extiende entre los 30 y 100 m de profundidad. La otra consistente en el surgimiento de burbujas, arrastre de fluidos restos orgánicos resuspendidos y sedimentos de fondo en zonas litorales someras. Para ambos casos se analiza el posible origen de las emisiones en relación con condiciones geológicas asociadas a procesos volcánicos locales y/o a procesos biológicos.

Palabras clave: *Ecosondeos, Emisiones de gas, Cuerpos lénticos, Argentina.*

INTRODUCTION

For millennia natural oil and gas seeps have been recognised in many places around the world; hydrocarbon seeps were exploited as a natural resource long before the birth of the oil industry. Geothermal springs and geysers are also an accepted part of the landscape. Offshore, natural hydrocarbon seeps are known to be widespread in the world's seas and oceans, having been described from coastal, continental shelf and deep water areas (Judd and Hovland 2007), hydrothermal vents are known to be associated with ocean spreading centres, underwater volcanoes and seamounts (Fyfe 1994, Dando *et al.* 1995, Butterfield 2000), and submarine groundwater discharge is thought to be a common phenomenon around the coasts (Taniguchi *et al.* 2002, Burnett *et al.* 2003). Although less commonly reported, seeps and springs also occur in lakes. Examples include: hydrothermal and hydrocarbon seeps in Lake Baikal, Siberia (Crane *et al.* 1991, Van Rensbergen *et al.* 2002); hydrothermal springs in Lake Tanganyika (Tanganydro Group 1992, Cohen *et al.* 1997, Barrat *et al.* 2000); groundwater springs in Pavillion Lake, British Columbia (Laval *et al.* 2000). These and other examples of seabed and lakebed fluid flow are reviewed by Judd and Hovland (2007).

Lake Nahuel Huapi (Fig. 1), located in the Andean range of Patagonia at 754 m above sea level, with a surface area of 557 km^2, a volume of 87,449 hm^3, a maximum depth of 464 m and an average depth of 157 m, is the largest natural water body of Northern Patagonia (Quiros 1988). The lake formed as the result of glacial processes and the damming of the resulting valley by a frontal moraine (Cordini 1950, Rabassa *et al.* 1986). The lake has been classified as ultraoligotrophic, with a monomictic regime stratifying thermally in summer and having a mixed water column between autumn and spring (Pedrozo *et al.* 1994). The lake possesses a deep thermocline which according to our data can oscillate in relation to annual climate conditions between 20 to 50 m. Fed by snow melt, icemelt from Frias glacier and rains of an extensive (4260 km²) catchment which has a network of streams, rivers and smaller interconnected lakes its water residence time is of 12.3 years draining through a single outlet, the Limay River. The area is characterised by a strong climatic gradient in relation to the mountainous terrain of the slopes of the Andes in the west to the relatively flat terrain of the Patagonian steppe in the East. This controls precipitation and humidity differences that are responsible for the contrast between cold temperate forests in the west and xerophyl shrublands in the east.

Despite its historic importance as the demographic center of the region , the lake has been little studied, and knowledge about its abiotic and biotic characteristics is fragmentary. On summer 2005 during the course of a lake wide hydroacoustic fish resource assessment a submerged gas seep field was discovered in the Brazo Rincon sector of the lake. In turn, this discovery sparked the interest of the National Park Administration, the Municipality of San Carlos de Bariloche city and the Coast Guard in relation to the possible effects and dangers of gas emissions. This paper is thus concerned with the extent and nature of these previouslyunreported seeps in the lake. We present the results of a lake wide survey for possible gas seeps and details of a seep field with multiple active gas vents, describe the emission characteristics, and discuss their possible origin and their possible incidence on hydroacoustic evaluations of the lake's fish resources.

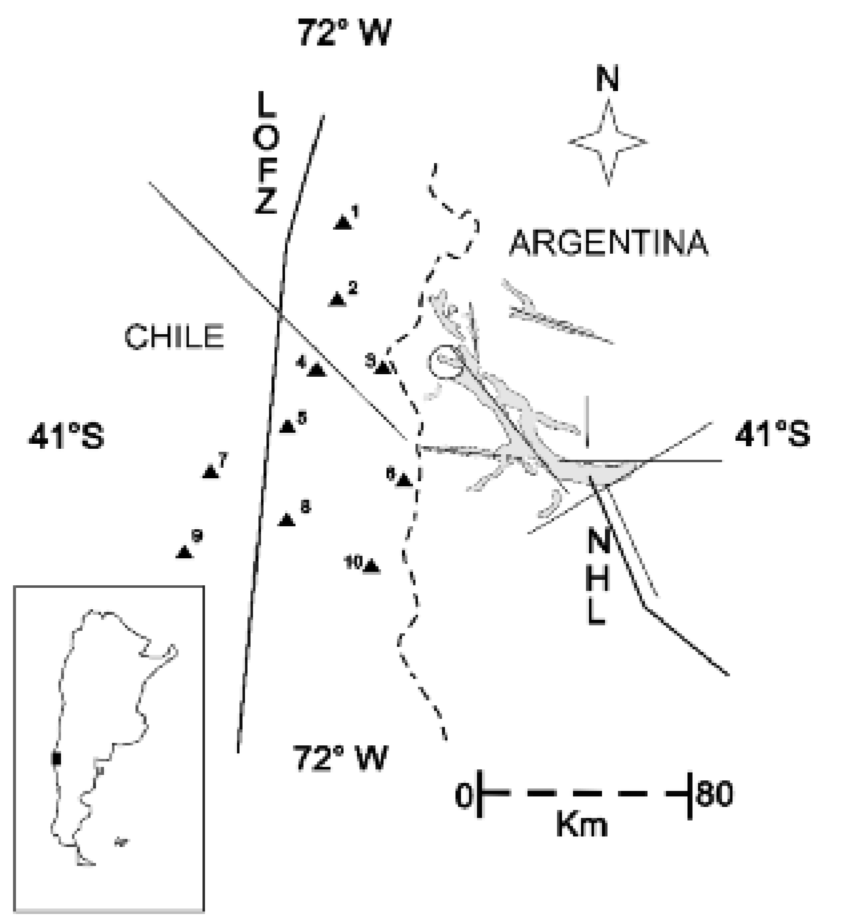

Figure 1: Location map showing the Nahuel Huapi lake sector, major (Liquiñe-Ofqui fault zone - LOFZ and Nahuel Huapi fault - NHL) and minor geological faults (black lines) and active volcanoes (▲ - numbered 1 to 10 in Table 1) in the surrounding area, and the Brazo Rincón seep area (black circle).

REGIONAL GEOLOGY

Lake Nahuel Huapi (Fig. 1) is located on the main Andean Cordillera which evolved between the North Patagonian Massif and the Chilean Coast Range (Cingolani *et al.* 1991), during the Late Jurassic as a response to the subduction of the Nazca Plate under the South American Plate (Cingolani *et al.* 1991).

Geologically the main Andean Cordillera is made of two litho-statigraphic units: a) a crystalline basement overlain by an igneous metamorphic complex, then by several metamorphic formations with igneous intrusions of various ages. b) a Mesozoic - Tertiary sedimentary volcanic cover.

Over both entities, volcanic rocks, glacial sediments, and volcanic ash sediments were deposited during the late Tertiary and the Quaternary (González Bonorino 1973). There are few specific studies about post glacial sediments (Valencio *et al.* 1982, Massoni and Sinito 1982, Sinito *et al.* 1985, Chapron *et al.* 2006, Villarosa *et al.* 2009). Sediment accumulation in the lake must have started with the retreat of the glaciers, thus the oldest sediments in the area according to Whitlock *et al.* (2006) obtained a calibrated age of 15,192 years before present (median probability) for the lower unit of the core, and a much older extrapolated basal date for El Trebol Lake a small water body related to the lower Nahuel Huapi basin. Annual sedimentation rates in the Nahuel Huapi are low having been estimated by Ribeiro Guevara *et al.* (1999) at 59 $mg.cm^{-2}.year^{-1}$ ($0.043\ cm.year^{-1}$).

With respect to the geological structure, the most obvious directional characteristic is the North-South lineament of the Andean Range, which is presumed to reflect the formation of the Andes on the crystalline basement of the North Patagonian massif. A principal structural feature is the Liquiñe-Ofqui fault zone which is approximately 900 km in length. Another noticeable structural lineament

is the Nahuel Huapi fault (Cingolani *et al.* 1991). The area between Nahuel Huapi fault and Liquiñe-Ofqui fault zone is criss-crossed by a series of minor faults (Fig. 1) (Gonzalez Bonorino 1973, Giacosa and Heredia 1999).
The orogenic movement that produced the faults resulted in the elevation of the Western sector and the depression of the Eastern sector (González Bonorino 1973, Ramos and Cortés 1984). The whole area has thus been characterized by intense orogenic movements, volcanism (Gonzalez Ferran 1985, Tormey *et al.* 1991) and the erosive action of glaciers (Clapperton 1993).

METHODS

The overall survey design included the revision of lake wide fish abundance hydroacoustic surveys held between February 2005 and April 2010 and the insonification of a criss-crossed pattern of transects over the sector of the lake where the seeps had been initially detected. Transects in this sector were insonified during summer 2005, winter 2006, summer of 2006 and on April 2010 in order to establish temporal continuity of gas seeps and emission characteristics. In order to gather information about seep characteristics particular seeps were insonified on several occasions by leaving the boat to drift over the Brazo Rincon seep site. In all cases the hydroacoustic information was generated using a Biosonics DE 4000 scientific echosounder, with two multiplexed transducers. One of them was a 6° single beam 208 kHz unit and the other a 6° split beam 120 kHz unit. The surface unit was also equipped with a built-in JRC DGPS locator with an average accuracy of 10 m. Signals were acquired and analyzed through the use of the VISACQ v 4.0, Vissual Analyzer v. 4.2 (Biosonics 2000) and Echoview ® (SonarDataPty Ltd, Hobart, Tasmania, Australia, 2003) software packages. The signal emission configuration was varied from one repetition to the other in an attempt to maximize the chance of collecting quality data on the seeps. A georeferenced map of the seep field was drawn through the use of the IDRISI ANDES v. 15 GIS system (Clarks Lab 2006) (Fig. 2).

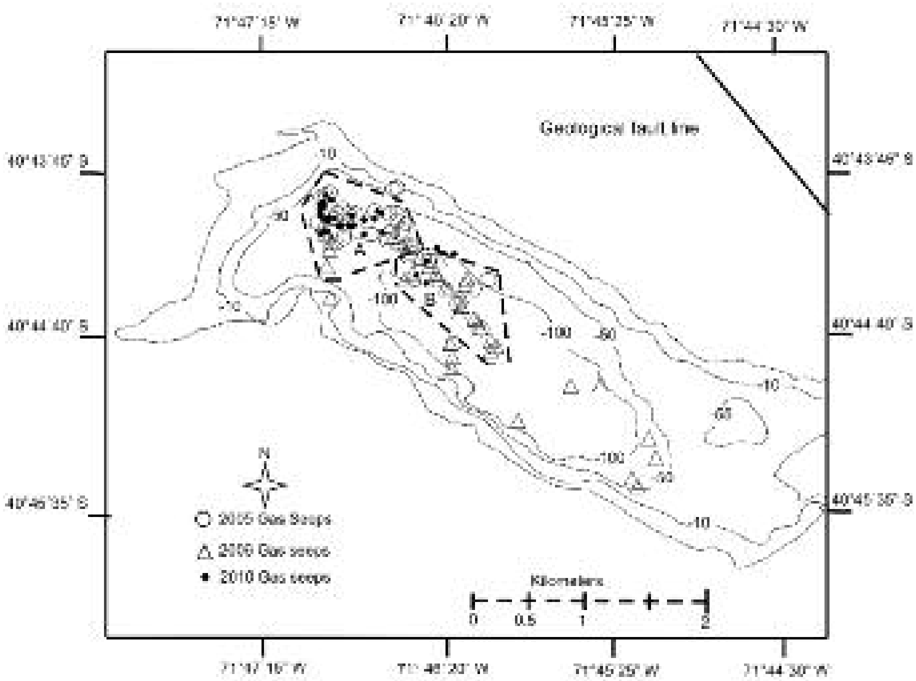

Figure 2: Lake Nahuel Huapi´s Brazon Rincón seep field emission points, (location shown in figure 1), black line geologic fault.

RESULTS AND DISCUSSION

Revision of the lake wide fish hydroacoustic survey held between 2006 and 2010 showed that only the initial discovery site the Brazo Rincon sector (Figs. 1 and 2) possessed an active seep field. Seepage activity was recorded in all surveys on this sector suggesting persistence over time. Activity of specific locations within the emission field seems to vary. However, at least one seep location seems constant, having been re- located on different occasions through out the study. Figure 3 show examples of echograms recorded in the Brazo Rincón sector of Lake Nahuel Huapi (Fig. 2). The two transects presented show the lake bed lying at a water depth of approximately 100 m (Fig. 3a) and 80 m (Fig. 3b), respectively. A range of acoustic targets are recorded in the water column, representing free gas bubbles and fish. In some locations attributing hydroacoustic targets to gas seepage is relatively straightforward, such as in the Black Sea where the anoxic water at depth precludes the presence of biota (Greinert *et al.* 2006). This is not the case in Lake Nahuel Huapi; therefore a number of criteria were established to differentiate between gas seeps and fish. Acoustic targets were interpreted to represent a gas seep when they demonstrated one or more of the following features:
The targets are highly structured and vertically orientated, forming column-like flares on the echogram (Fig. 3a: flares A-D and F-H, Fig. 3b: flares A and B); The targets comprise upwardly inclined high-backscatter lines, showing the features as rising through the water column with time (Fig. 3a: flares A-E, Fig. 3b: flares B-E); The targets are 'rooted' to the lake bed (Fig. 3a: flares A, B, D and H, Fig. 3b: flares B-D).
The remaining hydroacoustic targets in the echograms, most of which are horizontally or downwardly inclined features, are consistent with individual fish and/or shoals of fish (Fig. 3a, b) (*cf.* Ostrovsky 2003).

Comparable flares to those that are interpreted as gas seeps in Lake Nahuel Huapi (Fig. 3a, b) have been reported from many marine areas, and many have been confirmed as rising plumes of gas bubbles by analysing the chemical composition of the water (*e.g.*, Hydrate Ridge, Cascadian margin of North America: Suessa *et al.* (1999); offshore west Africa: Charlou *et al.* (2004)), by visual observation (*e.g.*, Santa Barbara Channel, California: Hornafius *et al.* (1999), Leifer *et al.* (2004) and North West Shelf, Australia: Rollet *et al.* (2006)) - or by both; numerous examples were discussed by Judd and Hovland (2007). Some of the vertically orientated flares that do not comprise upwardly inclined lines and are not 'rooted' to the lake bed (ie. only meet criteria A, *e.g.*, Fig. 3a - flare G) are tentatively interpreted as gas seeps, as such water column targets may also represent schools of fish (see Fig. 1d in Ostrovsky 2003).

The internal geometry of the vertical Brazo Rincón flares ranges from continuously high amplitude (Fig. 3a: flares D and H) to vertical stacks of individual, usually upwardly inclined, targets (Fig. 3a: flares A-C, Fig. 3b: flare B). These two forms are interpreted to represent continuous and intermittent bubble emissions from the lake bed, respectively. The lines in the echograms represent the rising of denser bubble clouds. The rising speed of the gas bubbles can be directly measured following the method documented in Greinert *et al.* (2006), by picking the time difference at two distinct depths at such a 'bubble-line' (Fig. 3b). Measuring the rise velocities of bubble lines in the Brazo Rincón flares gives values between 23 and 28 cm/s, which are consistent with the average rising speeds of bubbles with diameters between 10 and 17 mm (Greinert *et al.* 2006).

Hydroacoustic data from the split-beam echosounder were processed with a 'single target' operator in Echoview (Sonar Data 2003), with the aim of measuring bubble sizes and bubble shrinking rates based on real decibel values for single targets (Artemov 2006, Ostrovsky *et al.* 2008). This phase of processing was unsuccessful, likely due to the bubbles rising in 'clouds' (*e.g.*, Hornafius *et al.* 1999, Dimitrov 2002, Leifer and MacDonald 2003, Sauter *et al.* 2006) such that a single bubble was not insonified within a hydroacoustic cell as defined by the acquisition parameters.

The seep flares extend only part-way to the lake surface, because the bubbles dissolved, because they moved beyond the transmitted cone-shaped acoustic pulses from the echo sounder, or because the bubbles changed size such that they no longer resonated with acoustic frequency of the system (or a combination of these). Hydrocarbon bubble transport is a complex process where processes of gas "outflow" from the bubbles such as CH_4 into the water and "inflow" into the bubbles of atmospheric dissolved gases depend upon bubble hydrodinamics, dissolved gas concentrations, depth of gas release, speed of ascent, surface active substances, bulk fluid movements and temperature (Leifer and Patrol 2002, Ostrovsky 2003). This type of interactions may cause bubbles to increase or decrease size and eventually dissolve depending of the prevailing interactions. As no bubbles were observed at the lake surface in this area it is concluded that the bubbles dissolve in the water column as they rise from the bottom.

The seep field occupies a large area at the western end of the lake where the maximum water depth is approximately 114 m (Fig. 2). For the purpose of discussion two zones with relatively dense spatial distributions of seeps are identified in the lake: Zone A in approximately 5-85 m water depths, and Zone B in approximately 85-103 m water depths (Fig. 2). During the 2005 hydroacoustic survey of the lake numerous seeps were identified in both zones (11 seeps per line km of survey transect in Zone A and 14.8 seeps per line km of survey transect in Zone B). In contrast, during the 2006 hydroacoustic survey of the lake active seeps were abundant within Zone A (15 seeps per line km of survey transect) but were almost absent within Zone B (0.6 seeps per line km of survey transect) Despite that in 2010 the overall number of flares had decreased the described pattern repeated itself, with 4.2 seeps per line km in zone A and 1 seep per line km in zone B. Temporal variability in fluid seepage, ranging from decadal to sub-hourly periods, has been well documented in the literature (Leifer *et al.* 2004). This variability is typically attributed to external forcing by tides, swells, changing bottom current conditions (Linke *et al.* 1999, Tryon *et al.* 1999, Quigley *et al.* 1999, Tryon *et al.* 2002), man-made changes such as to the water table (Wever *et al.* 2006), or large-scale geological events like earthquakes (Obzhirov *et al.* 2004). In this sense it is worth noting that the last hydroacoustic survey on 2010, scarcely two months after the 8.8 MMS earthquake out of the coast of Chile, which produced a small lake Tsunami on Nahuel Huapi did not apparently increase the number or rate of emissions on the gas seep field. Another likely reason for variations in seep activity is the capturing of free gas in a small reservoir close to the sediment/water interface until the pressure building up overcomes the trapping forces (Greinert 2008).

During one of the surveys a surface phenomenon associated with bubble emission was detected in the shallow water close to the shore. This was characterized as a ring of bubbles (approximately 6 m in diameter) breaking the surface near the shore, over a soft bottom (7 m deep) just outside an inflowing stream, the event lasting no more than 15 minutes. Rising bubbles came to the surface accompanied by organic debris (*e.g.*, leafs, little twigs and branches), and resuspended fine-grained bottom sediments increased turbidity in surface waters (Fig. 4). Repeated passes above the phenomenon illustrated in figure 4 showed strong water column targets (Fig. 5). The three strong vertical water column targets shown in figure 5 extend from the lake bed to the lake surface in shallow water. It seems

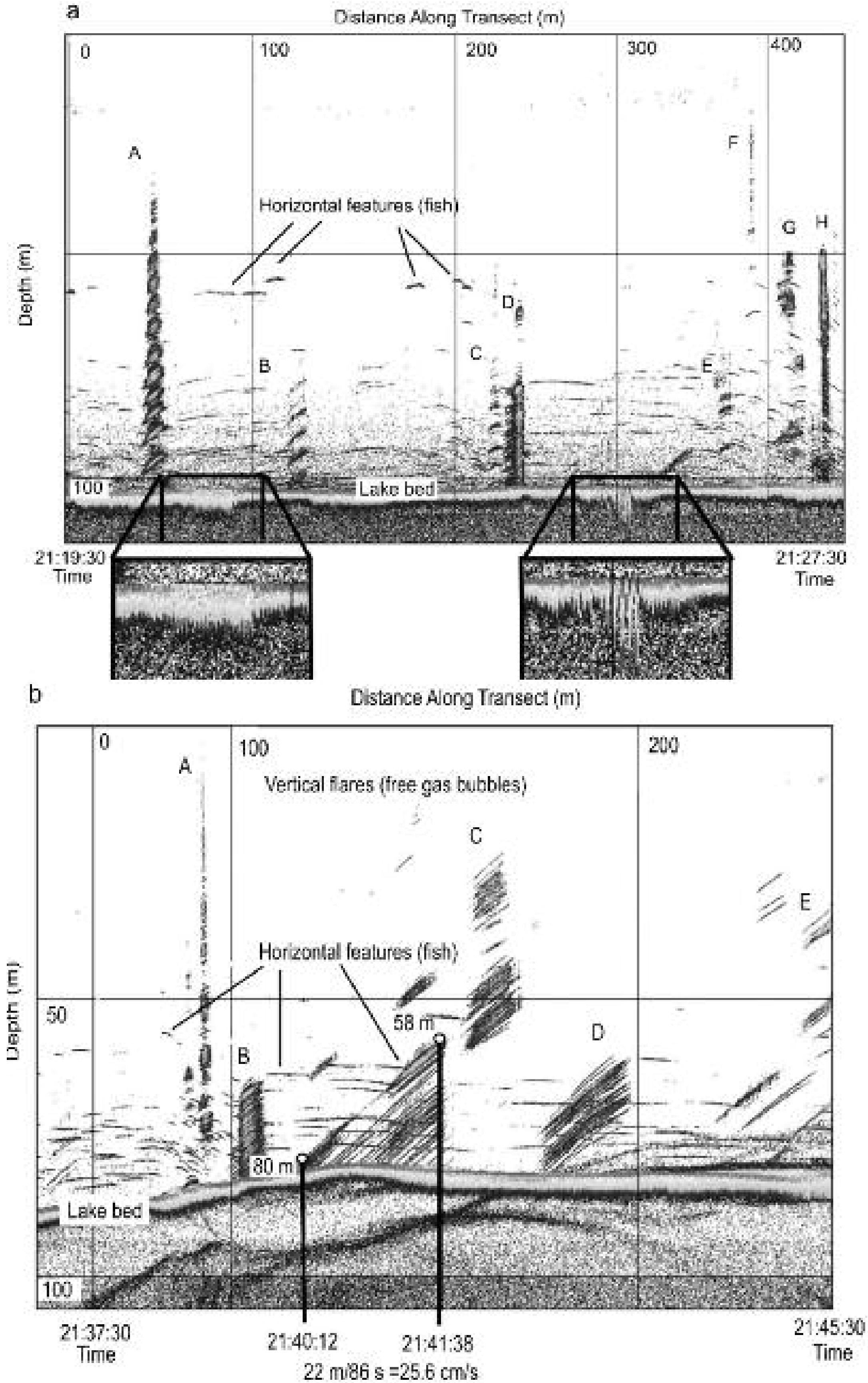

Figure 3: Echograms of 120 kHz echo sounder transects from the February 2005 survey showing a variety of water column targets including gas seeps and fish. Locations of transects shown in Figure 3, the horizontal scale represents a fixed period of time for both transects (8 min) but the distance along each transect during that time varies as a function of boat speed. a) Transect in approximately 100 m water depth at a relatively consistent speed of approximately 2 min for each 100 m; b) Transect in approximately 80 m water depth at variable speed; time for 0-100 m and 100-200 m was approximately 1.5 mins and 4 mins, respectively. Traversing slowly over seep sites extends the time during which the rising bubbles are within the transmitted pulse, extending the length of ‘bubble lines’. Flare C is interpreted to extend from the marker at 21:40:12 to the top of the feature adjacent to the label ‘C’.

that fluid, sediment and organic material are lifted to the surface where there is lateral spread (also evident on the photograph (Fig. 4); heavier material (sediment) then falls back towards the lake bed.

The nature and origin of the water column targets is not certain at this time. It is probable that only bubbles are responsible for the deep-water targets, whilst the shallow-water targets comprise bubbles, sediment and organic matter (and possibly water). The nearshore sediments are evidently rich in organic matter; in the relatively high summer water temperature (17 ºC) at this site it seems likely that this material will be actively decomposing and producing methane as a by-product. Apparently bubbles trapped within the sediment liberated and rise to the surface, lifting sediment and organic matter with it. Whilst it is tempting to invoke this process to explain the shallow-water phenomena, it is uncertain that the rate of organic decomposition and methane formation would be sufficient to produce upwelling on this scale even for a short lived phenomenon. Thus further studies of this particular type of shallow water emissions are required.

If we consider that water temperature in the deep area of the lake never exceeds 7ºC it seems unlikely that continuous gas seeps at high depths through out the surveyed years could be associated with biological decomposition. Two alternative explanations may be found on the geological context of this sector. The first one in relation to hydrocarbon deposits units known to exist in the Ñirihuau river basin, located East of Nahuel Huapi Lake. However, it seems unlikely that this could be the origin of the deep gas seeps described due to the fact that the isopach map of the Ñirihuau formation indicate that this is a marginal sector of the basin (Spalletti 1983). We have also to consider the fact that Brazo Rincón gas seep area (Fig. 1 and 2) associated with the Ventana Formation (González Bonorino and González Bonorino 1978). This 24 -34 Ma formation corresponding to the Oligocene period (Giacosa and Heredia 2001), is of volcanic origin making it extremely unlikely that it may contain hydrocarbon deposits. Brazo Rincón is surrounded to the north, west and south by volcanic and geothermal fields with post-magmatic manifestations such as thermal water emissions (Table 1, Fig. 1). Thus the general surrounding area is characterized by Holocene-Pleistocene stratovolcanoes, maars, cinder cones and scoria cones related to at least ten recognisable volcanic systems. Of these the closest ones, the Puyehue and Cordon-Caulle Volcanic Complex (PCCVC - 34 km away from Brazo Rincon) is a cluster of Pleistocene to recent volcanic vents at 40,5° S, 72,2° W aligned in a northwest - southeast trend oblique to the main volcanic front of the Southern Volcanic Zone (Lara *et al.* 2006) (number 2 on Fig. 1), which has experienced eruptions as recently as 1921, 1922, 1960 and 2011. Cordon Caulle is an active geothermal area in a 6 by 13 km wide volcano-tectonic depression, the largest such area of the Southern Andes (Smithsonian Global Volcanism Program 2007). Thus it seems probable that the seeps may be related to the volcanic activity that is evident in the area. Hydrothermal springs are present at the Termas de Puyehue resort about 46 km away. Recent analyses of Brazo Rincón sediments by neutron activation analysis have shown mercury concentrations that correspond to low industrial contamination levels (Ribeiro Guevara *et al.* 2005); however, this is a relatively isolated area of the park where there has been no anthropogenic activity that would have caused contamination on this scale. Mer-cury in Brazo Rincon sediments could have two different origins. The first would imply dissolution of sulphides present in surrounding tertiary volcanic rocks. These minerals are abundant in several exposures around the northern limits of Nahuel Huapi Lake (Villarosa *pers. comm.*). The second would be in relation to hydrothermal vents which have been associated elsewhere with high mercury concentrations (Stoffers *et al.* 1999), vicinity to the PCCVC suggest that mercury levels found on Brazo Rincon sediments could be derived from hydrothermal activity. Whether or not this explains the origin of the seeping fluid, it seems probable that seepage occurs where fluid migration is focussed, probably by faulting. Several authors indicate that

TABLE 1: Volcanic formations and geothermal areas in proximity of Brazo Rincón, Nahuel Huapi Lake; numbers (left-hand column) correspond to the locations marked on figure 1.

Nº on Fig.1	Formation	Volcanic Type	Distance & bearing to Brazo Rincón	Hydrotherma Emissions	Recent Eruptions	Lat. / Long.
1	Carran - Los Venados	Pyroclastic cones, Maars, Stratovolcanoes	50 km NW	YES	1955 / 1979	40.35ºS / 72.07W
2	Puyehue - Cordon Caulle	Stratovolcano, Calderas, Fissure vents	34 km W	YES	1921/1922/1960/2011	40.59ºS / 72.11ºW
3	Cerro Pantoja	Stratovolcano, Cinder cone	15 km W	NO	-------	40.77ºS / 71.95ºW
4	Antillanca Group	Stratovolcanoes, Cinder cones, Maars	32 km W	YES	-----	40.77ºS / 72.15ºW
5	Puntiagudo-Cenizos	Stratovolcano, Cinder cones, Fissure vents	50 km SW	NO	1850 / 1930	40.96ºS / 72.26ºW
6	Tronador	Stratovolcano Pyroclastic cone	50 km S	NO	------	41.15ºS / 71.88ºW
7	Osorno	Stratovolcano / Scoria cones / Lava domes	74 km SW	NO	1869	41.10ºS / 72.49ºW
8	Cayutué-La Viguería	Pyroclastic cones / Maars	72 km SW	NO	-------	41.25ºS / 72.27º W
9	Calbuco	Stratrovolcano / Lava domes	97 km SW	NO	1893/1894/1917/ /1929/1961	41.32ºS / 72.16ºW
10	Cuernos del Diablo	Stratovolcano / Pyroclastic cones	77 km SW	NO	--------	41.40ºS / 72.00ºW

Figure 4: Bubble rings probably produced by fluid upwelling in shallow (7 m) water near the lake shore. The area of the ring (approximately 6 m in diameter) is indicated by the surfacing bubbles and the discoloration of the water by rising sediment.

the Serrucho-Catedral fracture zone extends along the northern zone of Nahuel Huapi lake (González Díaz and Nullo 1980, González Bonorino 1979, Giacosa and Heredia 1997). Thus it is possible that a nearby geological fault (Fig. 2), that continues beneath this part of the lake intersects the lake bottom in this area. Because of the high frequency of the echo sounder source, penetration of the lake bed is limited. However, the variability of the nature of the reflection suggests some variability in the character of the lake bed. Sharp changes and disturbances on the lake bed (Fig. 3a inserts) are consistent with some form of small-scale topographic feature, potentially the lake-bed expression of near surface faults. Attempts to measure possible water quality variations as indirect prove of the volcanic origin of the gas flares have not provided conclusive evidence one way or the other. Thus, whereas temperature profiles do not show significant variations with regards to other parts of the lake, some variation has been detected in terms of decreasing pH values. However, obtained values are within range of those of other areas were seeps are not present. We also have to consider that lack of variation in terms of temperature and pH could be due to cold gas emissions and rapid water mixing due to underwater currents and Seiche effects.

Finally we have to consider that gas bubbles rising from the bottom can bias hydroacoustic estimates of fish densities and abundance (Rudstam and Johnson 1992, Ostrovsky 2003, Ostrovsky *et al.* 2008). However, the restriction of the gas seeps fields to the Brazo Rincon sector of Nahuel Huapi Lake, the described emission patterns and the possibility of differentiating fish targets from bubbles according to the described criteria allows for exclusion of bubble plumes reducing bias on density and abundance estimates.

FUTURE WORK

The work reported in this paper clearly leaves a number of questions unanswered, most notably the nature and origin of the seeping fluids. Future work to further investigate both types of phenomena might include: a) Water and gas sampling and analysis - to ascertain the com-

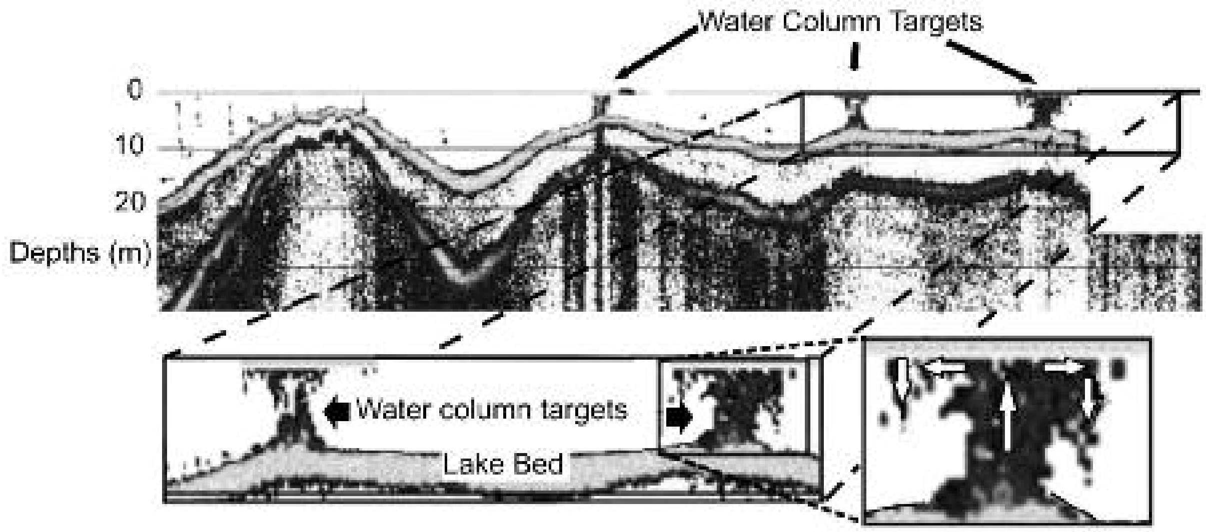

Figure 5: Echogram of a nearshore 120 kHz echo sounder transect showing strong water column targets, corresponding to the lake surface phenomenon illustrated in figure 4. Because of the shallow water (<20 m) prominent multiple echoes are evident. Note the three strong vertical water column targets, each extending from a topographic high on the lake bed to the lake surface. Insets A and B show details of water column targets; the arrows on Inset B suggest the direction of motion. It seems that fluid, sediment and organic material are lifted to the surface where there is lateral spread (also evident on the photograph (Fig. 4); heavier material (sediment) then falls back towards the lake bed.

position of the seeping fluids and whether they are dominated by hydrothermal gases such as CO_2, or by by-products of organic decomposition such as CH_4; b) Sediment sampling and analysis - to determine if high CH_4 and organic contents are present indicating organic decomposition, or do concentrations of Hg and other elements indicate association with hydrothermal activity; c) Shallow seismic profiling - to investigate the lake bed and ascertain the presence of faulting and /or of gas accumulations within the sediments.

In June 2011 at the time this paper was in print the the Puyehue-Cordon Caulle erupted, activity which as December 2011 still remains. Thus it has become important to determine if such activity has has any bearing on the described gas emissions.

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