Gas detection and quantification using iXblue Echoes high-resolution sub-bottom profiler and Seapix 3D multibeam echosounder from the Laacher See (Eifel, Germany)

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***Abstract*— Volcanic gases constitute the main fuel of explosive eruptions and volcanoes mostly emit massive amounts of gas during quiescence. They can also trigger limnic eruptions such as the 1986 eruption at Nyos volcano (Cameroon) that killed more than 1500 people. Contrary to atmosphere, gases are easily detected in water column, particularly using hydro-acoustic methods [1]. Two pioneering studies have monitored gas venting into Kelud Crater Lake (Indonesia) from a hydroacoustic station shortly before a Plinian eruption in 1990 [1] and, nearly two decades later, by empirically quantifying CO2 fluxes by acoustic measurements in the same lake just before a non-explosive eruption [2]. However, despite hydroacoustic detection capabilities, fundamental advances are limited by technology performances. Overall acoustic detection of a bubble field is easy, while its quantification remains complex due to the 3D structure of clouds and the acoustic interactions between bubbles. It is thus necessary to accurately map the different bubble clouds, to monitor their evolution and to dissociate different gas origins to reduce the volcanic risk, which is major in aqueous environments. Here, we present preliminary results from near-surface geophysics of sedimentary deposits and water column gas distributions and quantification from an Eifel crater lake (Germany), using iXblue Echoes high-resolution sub-bottom profiler and Seapix 3D multibeam echosounder. Derived from Seapix analyses, backscatter profiles of elements in the water column allowed to distinguish fish and gas bubbles, which demonstrates a potential for the development of an automatic gas detection module using the Seapix software. Ongoing research on the Target Strengh (TS) of bubbles suggest they are of very small size (35 µm), much smaller than observed elsewhere using single beam echosounders, which might also explain why, in the same spot, we did not observe gas bubbles using camera mounted on ROV. This also raises new perspectives to improve CO2 estimates from volcanic bubbles release. Meanwhile, the Echoes 10 000 provided high-resolution images of the architecture of the lake deposits and visualized in real time using Delph Software. More than 30 m of penetration with a theoretical 8 cm-resolution highlight paleoenvironmental and paleoclimatic reconstruction perspectives, 3D modeling of remobilized materials and tephra deposits from volcanic activity, as well as differentiation between shallow and deep gas diffusion derived from organic matter decomposition and volcanic activity respectively. Next step is to use Delph Seismic Interpretation to construct DTM of all main reflectors, thus providing 3D modeling of the sedimentary infill and to allow interpretation in terms of sedimentary dynamics. Echoes/Delph & SeapiX complement each other to follow gas flares in underwater environments. This complementarity allows to verify that the vertical acoustic signal attributed to gas flares is not an artefact potentially related to macrophytes or other plants. Indeed, fusion of all geophysical data using Delph Roadmap allow to verify if each gas plume in water column coincides with gas diffusion within the sediment. Our geophysical scientific approach contributes to a wider scientific effort to increase forecasting of volcanic and limnic eruption and improve early warning systems through constant collaborations with academic research.**

Keywords*— *hydroacoustic; volcanic eruption; gas bubbles; backscatter; multibeam echosounder; multi split beam; seismic reflexion; paleoenvironment; SeapiX, Echoes

I. INTRODUCTION (*HEADING 1*)

Volcanic gases are the main trigger of volcanic eruptions. They determine whether volcanoes erupt effusively or explosively, and they can also impact on the volcanic plumbing systems during periods of quiescence [3]. During such quiet periods, passive (noneruptive) volcanic degassing can release critical amounts of carbon dioxide (CO2) into the air [4], and these emissions influence atmospheric and oceanic CO2 budget at regional and global scales [5].

Gases can be detected in water column using hydro-acoustic methods [1]. Lakes situated within the caldera of volcanoes previously erupted, and still active, represent an excellent natural laboratory to explore and monitor volcanic gas activity. They can inform on the status of a volcano and the related hazards particularly important to protect the surrounding population [6];[7];[8].

Here, we present geophysical study combining 3D multibeam echosounder and sub-bottom profiling in Lake Laacher See, a crater lake ontop of an active volcano in Eifel region (Rhenanie-Palatinat, Germany). Our scientific approach provides (1) 3D modeling of the volcanic degassing in some active part of the lake, (2) water column gas distributions and quantification, (3) preliminary results on micro-bubbling size determination and, (4) consistent spatial continuity between gas diffusion in sediments and water column and (5) high-resolution geo-hazard related sedimentary deposits.

II. Laacher See volcanic history

Laacher See volcano produced a Plinian eruption about 12,900 years ago, spewing ash as far away as Greece. It erupted 20 cubic kilometers of the rocky fragments known as tephra, a dense-rock equivalent of 6.3 cubic kilometers of magma [9], making it similar in magnitude to the Pinatubo eruption of 1991. Since this large-scale eruption, a lake formed in the caldera, and the volcano has been quiet. In recent years, however, significant plumes of gas bubbles have been observed in the lake [10], and high concentrations of dissolved CO_2 have been measured.
Although we did not study bubble compositions in the present work, according to recent geochemical analyses, the CO_2 contained within the lake appears to be of magmatic origin, and the CO_2 content of the soil gas ranges between atmospheric values (0.03%) and 100% [11]; [12]. A recent study documented deep and low-frequency earthquakes, inferred to have been caused by magma movements beneath the volcano [13], although there are presently no signs of upcoming volcanic activity in the near future.

III. iXblue sismo-acoustic methods

The 2019 Laacher See fieldwork provided new insights of underwater volcanic degassing, its relation to sedimentary structures, and its potential for use in monitoring degassing and thermal stratification. Several sismo-acoustic methods were used to highlight the potential of the Lake.

A. SeapiX – 3D Multibeam Echosounder

SeapiX is a multibeam echosounder (MBES) using a steerable symmetric Mills Cross. This configuration allows to image water column and sea bottom in both athwartship and fore-and-aft directions. Steering capability in transmit and receive allows a volume coverage of $120^\circ \times 120^\circ$ under ship with $1.6^\circ \times 1.6^\circ$ beam aperture on the antenna axis. 64 beams are acquired per ping in the frequency range of 145–155 kHz using monochromatic or frequency modulated bursts. Transmitted beams are stabilized in roll or pitch according with the transmitted mode and receiving beams are motion compensated using an embedded inertial motion unit.

B. Echoes 10 000 – sub-bottom profiler

Echoes 10 000 is a high-resolution sub-bottom profiler for shallow water environments (< 150 m). Seven transducers based on a Tonpilz design & Chirp technology. It ranges from 5 to 15kHz, with low distortion amplifier. It produces seismic-reflexion data at a theoretical resolution of 7.5 cm. At Laacher See, this system performs until 40m in clayey-silty sediments interrupted by reworked sandy deposits.

C. Delph Seismic geophysical software

Delph Seismic is an acquisition, processing and interpretation geophysical software package designed to provide geologists and geophysicists with all data collected from high-resolution seismic systems and sub-bottom profilers. Delph Seismic interpretation were used to post-treat seismic reflexion data, to track gas flares within the sediments and to compare its location with those detected using SeapiX.

D. Remotelly controlled USV cataraft

SeapiX & Echoes were alternatively implemented on a small USV cataraft (Fig. 1). It was remotely controlled until 1.5 km distance from the lake shorelines. Equipped with a GPS, we were able to compare location of gas flares detected by both geophysical systems.

IV. Results

A. Gas flares origin of backscatter vertical structures

In the Laacher See deep basin, i.e. from 30 to 50m of water depth, backscatter of water column elements derived from SeapiX measurements show vertical structures of about 10-20m size situated at the water-sediment interface. Fish and gas flares are clearly distinguishable (Fig. 2). These structures could be associated to two main origins: macrophytes or gas flares from volcanic activity. Macrophytes are present close to the shorelines, but they rapidly disappear with depth. A ROV equipped with an optical camera did not find indeed any aquatic plant deeper than 20m. Finally, seismic reflexion data show gas bubbles at the water-sediment interface at the same spot SeapiX detected these vertical structures (Fig. 3).

B. Gas bubbles acoustic signature

Target Strengh (TS) of the backscattered signal from SeapiX measurements were systematically determined for each bubble flare. In a single flare, the corresponding TS distribution is centered around -75 dB (Fig. 4). This very weak acoustic signature is related to a most probable small bubble size.

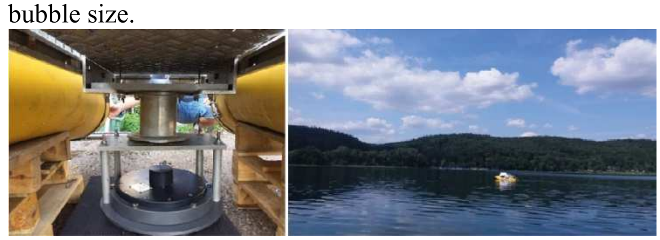

Figure 1: (left) Echoes 10 000 implemented on the USV cataraft; (right) remotelly controlled cataraft on Lake Laacher See during the field campaign in 2019

To determine the size of these bubbles, we used a simple uncoated bubble model from a wideband acoustic method for direct assessment of bubble-mediated methane flux [14]. Fig. 5 shows that the determination of the bubble size is situated below the bubble resonance. This model provides a mean bubble size around 0.04mm.

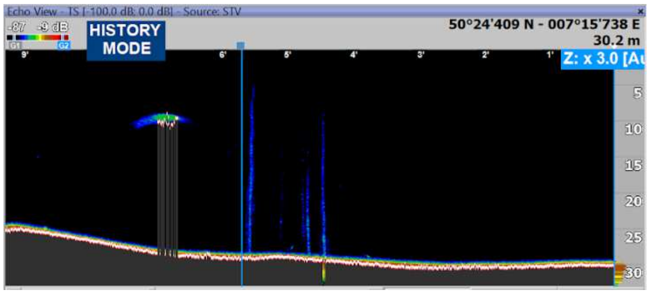

Figure 2: Echogram showing both fish (parabolic signature on the left) and bubble signals (right)

C. Sedimentary architecture and deposits

Seismic reflexion survey provided high resolution images of sediment layers. Using Delph Seismic software, we used real-time observation of seismic profiles to define the best 3 coring locations. Collaborators from UGhent University collected several tens of meters of sediment composites sections. Ongoing PhD Thesis results will detail all remobilized sediments visible in the core opening session, suggesting a great potential to reconstruct climate/geohazard at millennial time-scales. Next step is to use Delph Seismic Interpretation to construct DTM of all main reflectors, thus providing 3D modeling of the sedimentary infill and to allow interpretation in terms of sedimentary dynamics.

V. DISCUSSION

Volcanic gas bubbles strongly scatter the acoustic energy in water and are generally dominantly composed of carbon dioxide [2]. This study have revealed bubble radii as small as 0.04 mm but radii as large as 220 m have been hypothesized to explain infrasound signals associated with eruptions at Bogoslof volcano [15].

We derived a first empirical law to estimate CO2 fluxes in volcanic lakes using single-beam echo-sounders [2], but more advanced instruments are required to provide reliable quantification. Therefore, next step is to use this novel and high-resolution multibeam equipment, the multiple split beam Seapix from iXblue, to image bubble clouds in 3D in shallow environments. Building-up on existing schemes and calibrated innovative instruments, we will aim at quantifying bubble sizes, investigate their shapes (ellipsoidal, spherical), but also their evolution in the water column.

Our geophysical scientific approach contributes to a wider scientific effort to improve forecasting of volcanic and limnic eruptions and participates to improve early warning systems by constant collaborations with academic research.

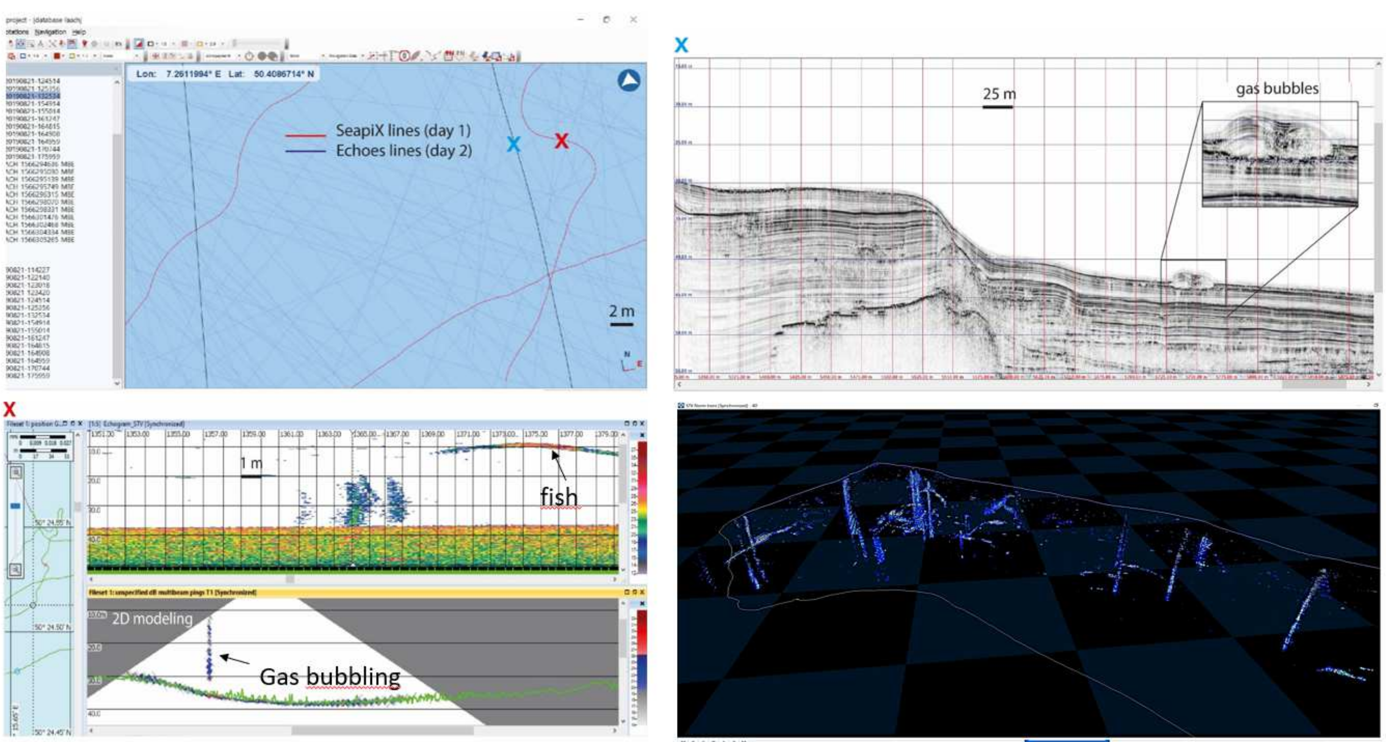

Figure 3: (upper left) zoom on survey lines for SeapiX (red) and Echoes (blue). Note the very close distance between the two crosses. (Upper right) Seismic reflexion data showing gas bubbles (blue cross), where (lower left) gas flares are detected in t

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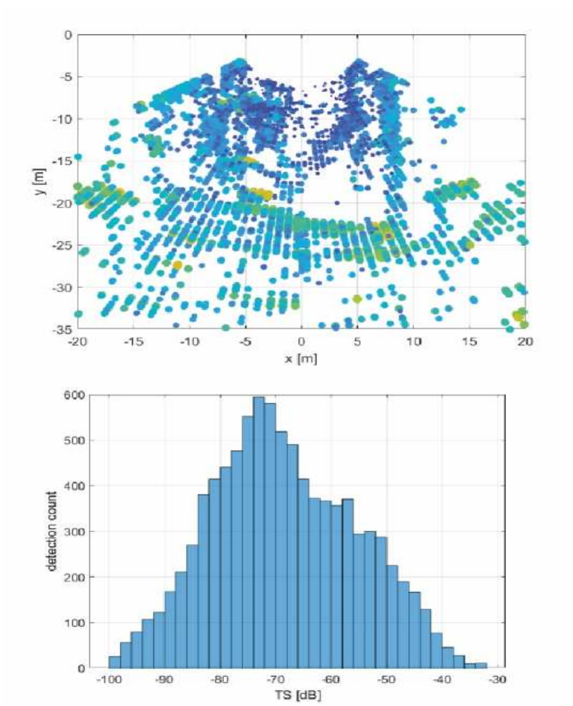

Figure 4: (Top) Cumulative TS measurement plot for a single gas flare, and (bottom) histogram of TS values

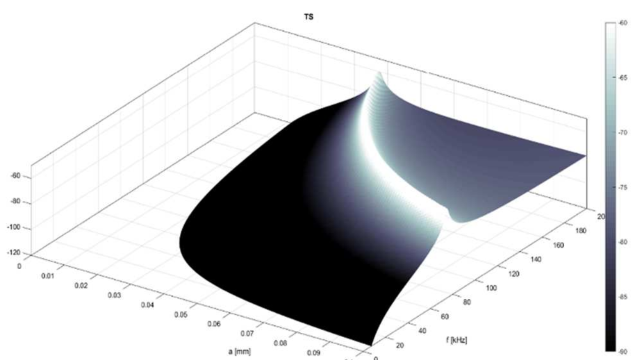

Figure 5: Determination of bubble size using a wideband acoustic method for direct assessment of bubble-mediated methane flux (Weidner et al. 2018)

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