Monitoring underwater eruptions using networks of hydrophones in the SOFAR channel

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Abstract: *Most volcanic eruptions occurring in the ocean remain undetected. Hydroacoustic monitoring, a widely used method among seismologists due to its sensitivity to T-phases associated with the low-level seismic activity in remote oceanic regions, can address this knowledge gap. Indeed, near volcanic areas, such as spreading ridges or undersea volcanoes, acoustic data recorded by moored hydrophones display numerous impulsive signals of short durations (5-15 s) and high energy (up to 100 Hz), that we attribute to interactions between hot lava and cold seawater. Most likely, thermal cracking is the process that generates these signals, which can be used as proxies to detect and locate new lava flows. These impulsive events were found in three different networks located in the Indian Ocean: (i) the large-scale OHA-SISBIO network, composed of 6-9 autonomous hydrophones encompassing 1000-km-long sections of the three Indian mid-oceanic ridges; (ii) the small-scale MAHY network, with 4 autonomous hydrophones 50 km away from a new-born volcano off Mayotte Island, Mozambique Channel; and (iii) the hydroacoustic stations of the International Monitoring System, consisting of cabled-to-shore triplets of hydrophones. In all these areas and data, we identified clusters of impulsive events, within clusters of seismic events, related to volcanic activity. To further optimize eruption monitoring, we developed automatic AI-based detection, classification and localisation tools. Implementing such automatic detection of volcanic events in real-time hydrophones, as the IMS stations, would be a major advance for organizing in-situ studies of active submarine volcanoes. When real-time stations are not available, we deployed innovative autonomous hydrophones equipped with small messengers to enable data retrieval from a small vessel of opportunity, should a major cluster of events occur in a monitored area.*

Keywords: *Hydroacoustics, Volcanic activity, Impulsive events, Thermal cracking.*

1. INTRODUCTION

Underwater earthquakes generate T-waves by conversion of seismic energy into low-frequency hydroacoustic energy at the seafloor. Recording T-waves with a network of hydrophones has been widely used by seismologists since the seminal work of Fox et al. [1], particularly for monitoring the low-level seismic activity along mid-ocean ridges [e.g. 2]. This is because they can propagate in the SOFAR channel over thousands of km and their sources can be localized by trilateration from arrival-times detected on at least 3 hydrophones. T-wave sources do not necessarily match epicenters but seafloor acoustic radiators of unknown size. However, in the context of spreading ridges where diking and faulting events are shallow, they provide a very useful and precise indication on where active processes take place (Fig. 1). T-waves commonly last several minutes (Fig. 2a), but hydroacoustic data also display short and energetic impulsive signals (5-15s), indicating that their energy (up to 100 Hz) is released directly into the water (H-waves, Fig. 2b) and has not travelled into the solid crust. We attribute these impulsive events to interactions between lava and seawater that can be used to track submarine eruption.

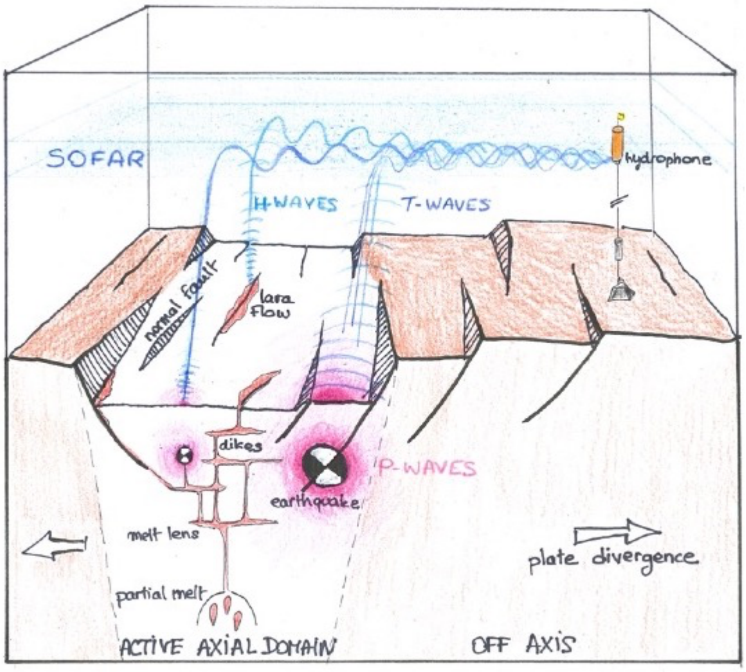

Fig.1: Mid-ocean ridges acoustic waves that can be captured by moored hydrophones.

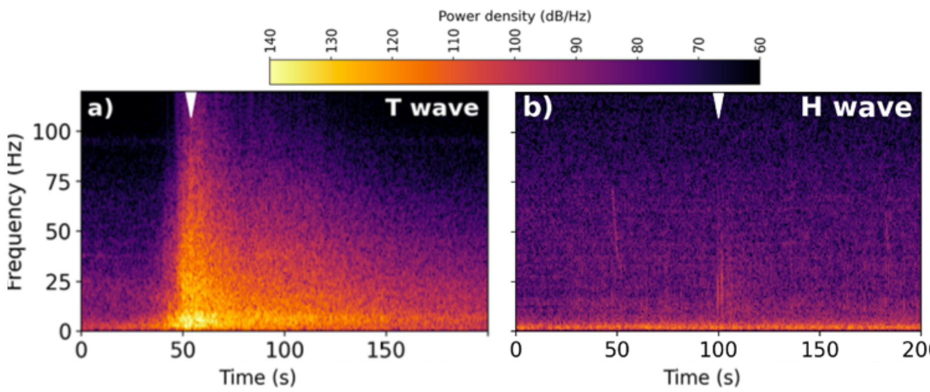

Fig.2: Spectrograms of a T- and a H-wave detected at mid-ocean ridges, after [3].

2. INSIGHTS FROM LONG-TERM MONITORING OF MID-OCEANS RIDGES

Mid-ocean ridges create and shape the ocean floor through a complex interplay of volcanic and tectonic processes, which remain difficult to unravel when the low-level seismicity is lacking. Investigating seismic clusters by T-wave monitoring helps fill this gap. For instance, along the 3 Indian mid-oceanic ridges, we identified 94 seismic clusters in the 2010 to 2020 land-based catalogue from the International Seismological Center (ISC; Fig. 3). Among them, we selected the 15 biggest clusters, spanning over the 3 contrasting ridges (ultra-slow, slow and intermediate spreading rates). The analysis of these large seismic clusters with continuous hydroacoustic data, recorded from 2012 to 2020 by the large-scale OHA-SISBIO network, yielded a catalogue of 38,910 hydroacoustic events [2], 50 times larger than the ISC catalogue, and with an average location accuracy in the order of 400 m. The spatio-temporal distribution of events within each swarm reflects its origin, either magmatic, tectonic, or a complex interplay of both. Five out of the 15 selected swarms included clusters of impulsive events, interpreted as submarine eruptions. However, they lack in situ evidence to confirm them.

T-wave sources can also be characterized by their Source Level (SL), which measures their acoustic level in dB re 1 µPa @1m. It is estimated from the sound levels recorded at the receivers (RL) corrected for the transmission loss (TL) along the acoustic paths. Comparisons of SLs with seismic magnitudes yield empirical relationships between these parameters (for example SL = 6.25 mb + 186 along the Southwest Indian Ridge [2]).

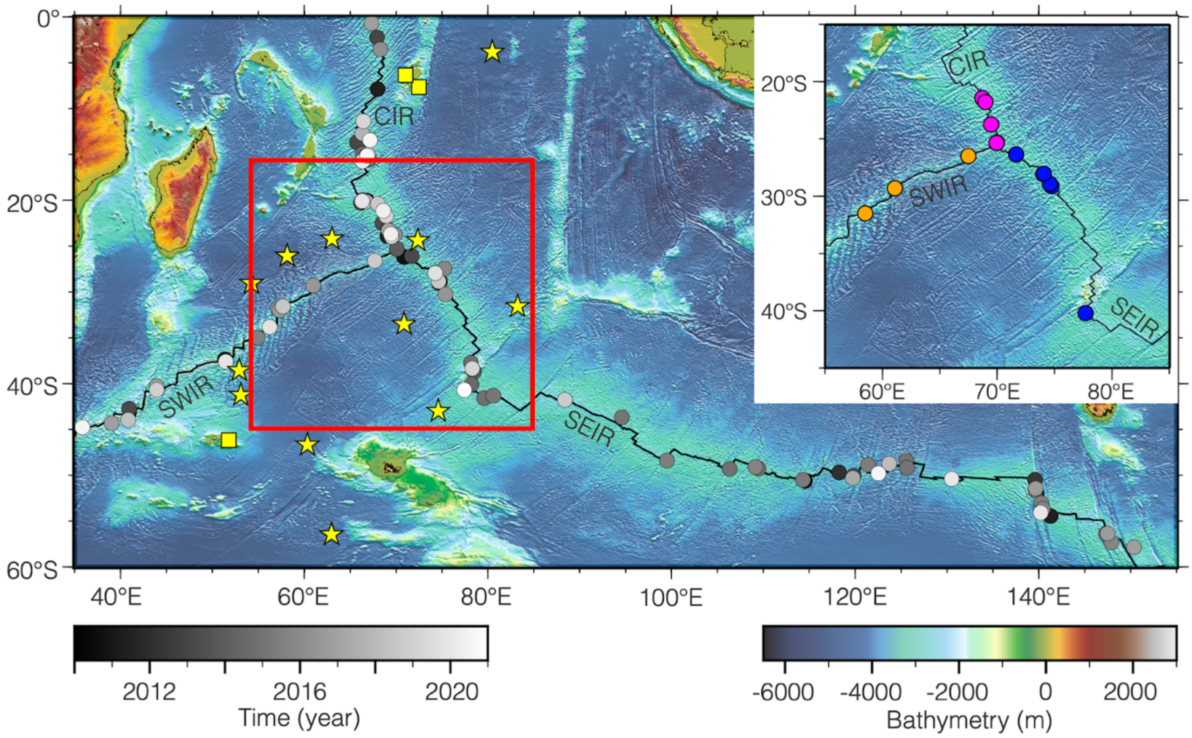

Fig.3: 2010-2020 ISC clusters along the 3 Indian ridges shaded with respect to time. Among them, 15 clusters (inset) along the ultra-slow Southwest (orange), slow Central (pink), and intermediate Southeast (blue) Indian ridges were analyzed using the OHA-SISBIO (yellow stars) and IMS (yellow squares) hydrophone networks [2].

3. INSIGHTS FROM SMALL-SCALE ACOUSTIC MONITORING OF AN UNDERWATER VOLCANO

In 2019, a new volcano was discovered at 3500 m depth, 50 km east of Mayotte Island in the Mozambique Channel. The intense seismicity associated with this event is monitored by the REVOSIMA (MAyotte VOlcano and Seismic Monitoring) network. Since 2020, it includes the MAHY (MAyotte HYdroaoustic) array with 4 hydrophones moored in the SOFAR channel for monitoring sounds generated by the volcanic activity. It indeed detected several clusters of impulsive signals that we interpret as lava flow emplacements, confirmed by a towed-camera transect over glossy lava fields (Fig. 4). The events occurred in swarms of 4 to 7 days, and stopped after December 4, 2020, which would end the eruption [4]. Based on the lava thickness derived from successive ship-borne multibeam bathymetric surveys and the duration of the lava flow events, the average effusion rate can be estimated to 14 m^3/s, compatible with that derived from land-GPS data and deflation rate over time. Within the northern cluster, events migrated towards the Northeast at a velocity of ~3 m/h, probably representative of the end of the eruptive phase. In addition, a 40 s-long and low-amplitude signal recorded by all 4 hydrophones on October 25, 2020 is interpreted as a submarine landslide, moving down-slope at a speed of ~26 m/s from the top of a lava pile over a distance of nearly 1 km.

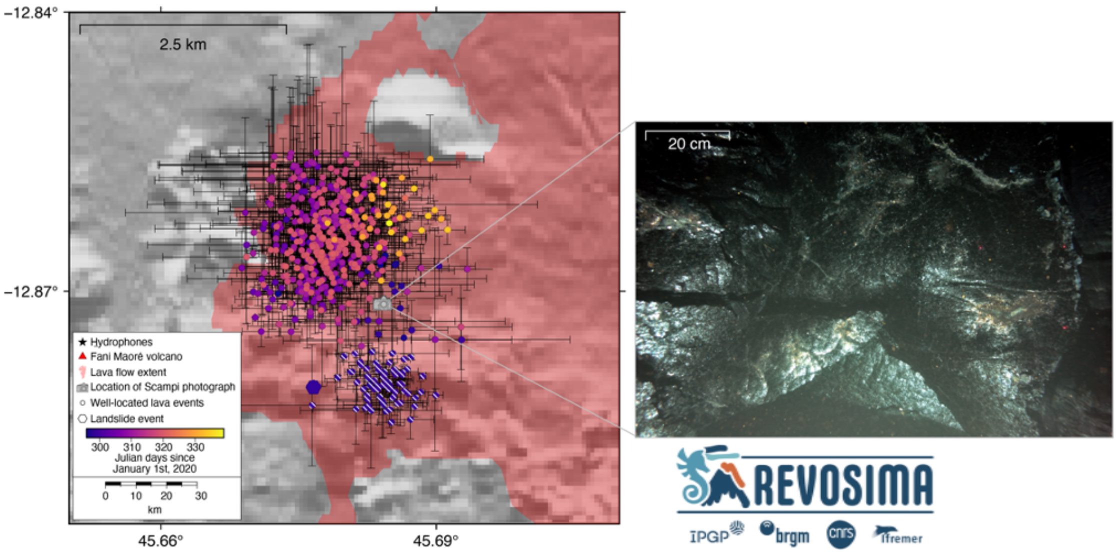

Fig.4: Spatio-temporal evolution of the impulsive events near the Fani Maoré volcano. An underwater photo reveals fresh lava flows associated with ~5-cm wide cracks, from [4].

4. NEW TOOLS FOR PASSIVE ACOUSTIC MONITORING

To optimize the hydroacoustic data analysis, we implemented automated algorithms based on machine learning to detect and identify T- and H- phases in hydrophone spectrograms. This Time Spectrogram Segmentation Network (TiSSNet) model is designed to process spectrograms of arbitrary duration with 128 bins of frequency as inputs and provides a probability of an event occurring at each time step as output [3]. Along with the TiSSNet modules and notebooks, available on GitHub, a common benchmarking framework for the community is also provided to evaluate and compare performances of other hydroacoustic detection tools. This annotated data set will be further improved and updated. Future developments include automatic trilateration using various hydrophone network geometries.

In addition, we are implementing an automatic categorization tool by type of source for the 6 real-time IMS stations (Fig. 6, [7]). Major volcanic events could thus be detected in near real-time, facilitating rapid intervention studies on active undersea volcanoes and enabling new scientific discoveries in the field of volcanology.

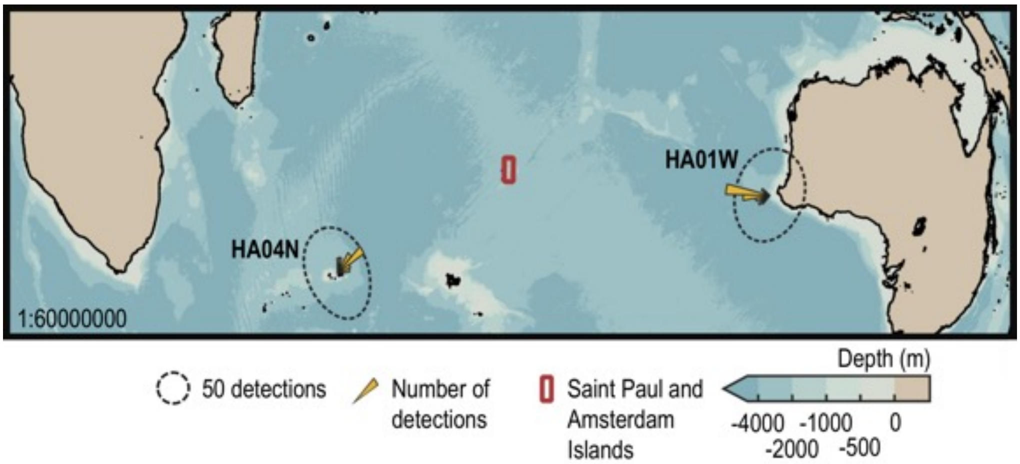

Fig.6: Real-time detection of major in April 2024 by IMS triplets at Cape Leewin and Crozet Isl. We since confirmed a submarine eruption along the Southeast Indian ridge.

Data recorded by the French pool of moored hydrophones will soon be distributed, using standardized FDSN Web Services, through the open database of the European Plate Observing System. Specific metadata regarding the data format and units, and internal clock drift are now implemented in the Obsinfo toolbox (in GitHub) in the hope that it will foster hydroacoustic data sharing among a broader scientific community [5].

Finally, to facilitate access to data recorded by autonomous hydrophones, should a major event of interest occur during a monitoring period, we developed a new hydrophone equipped with releasable glass spheres to allow data retrieval from any type of boat (Fig. 5, [6]). Three of them are currently deployed off Mayotte Island.

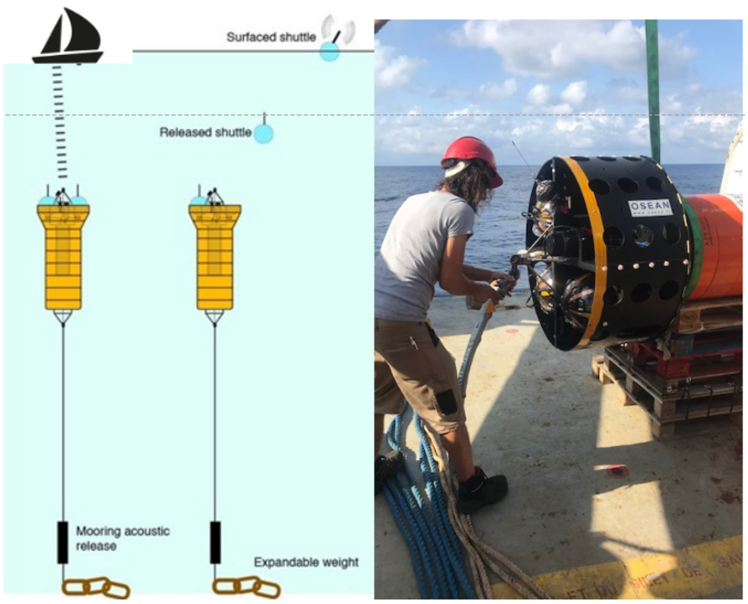

Fig.5: Autonomous HYDROBS mooring equipped with data messengers.

5. QUANTIFICATION OF THERMAL CRACKING IN LAVA

The lava events have an average SL of ~190 dB, similar to the energy released by a 300 in^3 seismic air-gun at 140 bar (~50 kJ, [4]). Several mechanisms have been proposed to explain such impulsive events observed during underwater eruptions [8]: collapse of lava tubes, steam bursts, or lava quenching. In Fig. 4, the photographed lava surface is glossy, without any fragmented pieces that an explosion would produce. There are no bubble effects in the spectrograms and the seafloor is below gas critical-depth which excludes the formation and implosion of bubbles. We therefore favor thermal cracking while fresh lava quenches. The elastic strain energy density released by a thermal crack can be estimated with Young's modulus (E~100 GPa), the maximum tensile strength (σ_T ~10 MPa), and Poisson ratio (ν) in basalt: $U=\sigma_T^2/E(1-\nu)$ ~1 kJ/m^3. A lava volume of ~50 m^3 undergoing thermal cracking could then generate an impulsive event releasing 50 kJ of acoustic energy. This rough estimate is consistent with in situ observations.

6. ACKNOWLEDGEMENTS

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