ENERGETIC AND SHORT WATER-BORN SIGNALS FROM MID-OCEANIC RIDGES

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Abstract: *The OHASISBIO network of autonomous hydrophones moored in the SOFAR channel of the southern Indian Ocean detected many short-duration and energetic acoustic events originating at mid-oceanic spreading ridge axes. Their average duration of 10 to 15s makes them "impulsive" relative to the 80 to 200s-long T-waves generated by submarine earthquakes. Their frequency goes up to 50-60 Hz and their source level ranges from 200 to 233 dB. Most of them are detected as far as 3700 km away from their source where received levels can reach up to 108 dB. They are associated with seismic swarms located on ridge axes where new seafloor is produced. Along the Southwest Indian Ridge (ultra-slow spreading rate at 14 mm/yr), such impulsive events (IMP) were found near Novara transform fault (58˚20'E), with 69 IMP among 1109 seismic events, near Melville transform fault (61˚00'E), with 118 IMP among 27624 events, and at 67˚45'E, with 58 IMP among 4880 events. Along the Central Indian Ridge (slow spreading rate at 40 mm/yr), 711 IMP among 2015 seismic events were found near an active hydrothermal field at 23˚52'S, 69˚30'E. The short duration, high energy and frequency content of IMP suggest that their source is punctual and generates water-borne waves, thus not resulting from the conversion of seismic waves on the seafloor. IMP sources are often located at the foot or slopes of bathymetric highs and occur in clusters after large-magnitude earthquakes nearby. All these clues point to a volcanic origin, perhaps to hot lava and seawater interactions during magmatic eruptions, after dike-intrusion triggered earthquakes. This hypothesis calls for in-situ inspections with a submarine vehicle to be confirmed. Except for their locations, these events could be mistaken for man-made underwater explosions. These narrow and energetic events could also provide useful sources to investigate the effects of long-distance propagation of acoustic waves in the ocean or to monitor sound-speed or temperature anomalies at long range.*

Keywords: *Impulsive events, Hydroacoustics, Mid-ocean Ridges, Indian Ocean, Volcanic activity*

1. INTRODUCTION

The majority of volcanic activity on Earth is concentrated along mid-oceanic spreading ridges (MOR), where new seafloor is created. Despite this prevalence, however, understanding the mechanisms that drive submarine volcanic eruptions remains limited due to their often-unnoticed nature. Their detection and characterization pose significant challenges due to remoteness from terrestrial seismic networks. To address this issue, passive acoustic monitoring has emerged as a valuable approach for identifying and analyzing such eruptions [e.g. 1] and provided critical insights into the dynamics of these volcanic phenomena, thereby contributing to a better understanding of geological processes that shape the Earth.

MORs are divergent plate boundaries in the plate tectonic realm. The southern Indian Ocean is home to three MORs where its seafloor is created. The Southwest Indian Ridge (SWIR) separates the African and Antarctic plates, while the Central Indian Ridge (CIR) separates the African and Indo-Australian plates, and the Southeast Indian Ridge (SEIR) separates the Indo-Australian and Antarctic plates (Fig. 1). These three ridges meet at a point called Rodrigues Triple Junction (RTJ). Their spreading rates span from ultraslow at about 14 mm/yr along the SWIR, to slow at about 40 mm/yr along the CIR, and intermediate at about 60 mm/yr along the SEIR. The spreading rates determine the MOR morphology and the preponderance between tectonic and volcanic processes.

As divergent plate boundaries, these MORs are characterized by a complex interplay of volcanic and tectonic processes where molten rock rises to the seafloor or where the young crust undergoes extension as a result of the separation of plates, both processes generating numerous earthquakes. However, detecting the low-level seismicity associated with these processes is challenging with conventional land-based seismic networks due to the remote locations of these ridges and the rapid attenuation of seismic waves over distance. Nonetheless, earthquakes generate low-frequency T-waves in the water column. Such T-waves (or tertiary waves) result from the seismoacoustic conversion of seismic waves at the seafloor, and travel at the water sound-speed, thus much slower than seismic primary (P) and secondary (S) waves. They also travel over much longer distances due to a minimal attenuation through the oceanic acoustic waveguide [2]. To detect the low-level seismicity associated with the three Indian MORs, a network of autonomous underwater hydrophones of the Hydroacoustic Observatory of Seismicity and Biodiversity in the Indian Ocean (OHASISBIO), has been deployed between 2010 and 2023. It was also set up to monitor the cryogenic and biological activity in the southern Indian Ocean [3]. In this study, we present peculiar acoustic events occurring in clusters at several swarms of events detected between 2016 and 2020 along the SWIR and CIR axes.

2. DATA AND METHODS

The occurrence of a sound fixing and ranging (SOFAR) channel in most of the world ocean allows sound waves to travel with little dissipation compared to seismic waves in the Earth, making hydroacoustic data particularly useful for detecting underwater events over long distances. In this study, the hydroacoustic data was recorded continuously at a sampling rate of 240 Hz by 3 to 9 hydrophones moored at depths between 1000 m and 1300 m, in the SOFAR channel. The arrival times of hydroacoustic events in the data were picked on the highest energy arrival in T-wave spectrograms; their location and time of origin were then estimated using a non-linear least square minimization of these arrival times [2]. The travel times were converted into distances using oceanic sound velocities based on the three-dimensional (3D) Global Digital Environment Model [4]. The Source Level (SL) of hydroacoustic events was inferred from the Received Levels (RL) at each hydrophone, after accounting for cylindrical and spherical transmission losses between an event and a hydrophone. The RL is a decibel measurement with respect to 1 micro-Pascal at 1 m (hereinafter simply noted as dB) of an average power spectral density in a 10s-time window centered on the energy peak of the acoustic signal, in the 5-60 Hz frequency range.

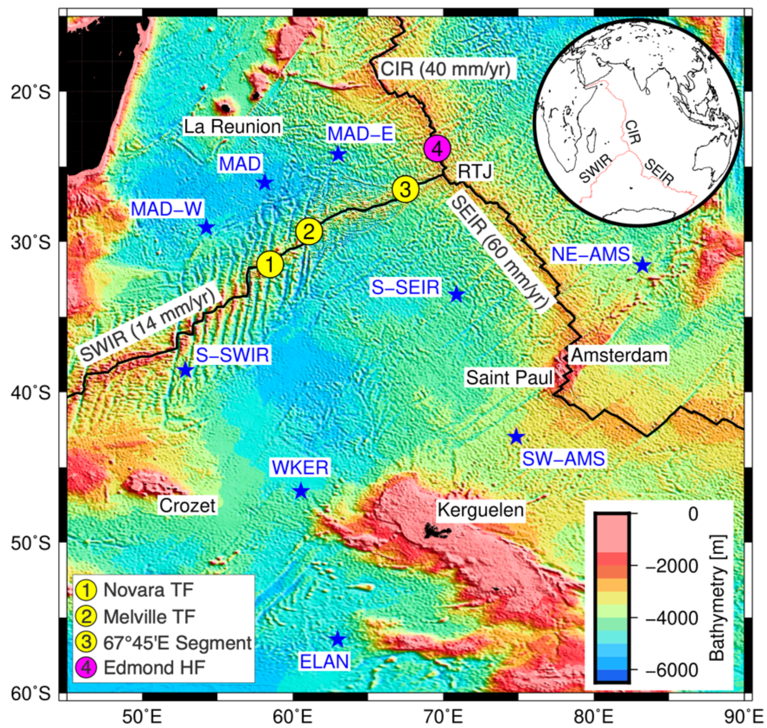

Fig. 1 - *Bathymetric map of the southern Indian Ocean with mid-ocean ridges (black lines) and locations of the OHASISBIO stations (blue stars). Yellow and purple circles mark the study regions along the SWIR and CIR, respectively.*

3. RESULTS

In this study, we investigated hydroacoustic T-waves from four distinct swarms, located along the SWIR (yellow circles in Fig. 1), and CIR (purple circle). To locate these swarms, we first looked for seismic clusters in the catalog from the International Seismological Centre (ISC; Table 1; [5]). In the first swarm, situated near Novara transform fault (TF; 58°20'E), the ISC catalog reported a total of 231 seismic events over a 13-day period in July 2018, whereas we were able to detect 1109 hydroacoustic events [6]. The TF is a seismically active boundary that offsets two MOR segments and where tectonic plates slide past each other horizontally in opposite directions. In the second swarm near Melville TF (61°00'E), 258 ISC seismic events were reported over a period of 298 days from June 2016 to March 2017; we found that it was the most intense seismic swarm along the SWIR, with 27624 hydroacoustic events [7]. In the third swarm, located near a segment at 67°45’E along the SWIR (~200 km from RTJ), we detected 4880 hydroacoustic events compared to the 92 ISC events reported over a 33-day period in September to October 2018. Lastly, near the Edmond hydrothermal field (HF) along the CIR (at 69°30’E), we detected a swarm of 2015 hydroacoustic events over a period of 142 days from April to September 2020, while the ISC catalog reported only 68 events in the same time period. The Edmond HF is an active vent field, discovered in the late eighties [8], where geothermally heated water discharges near the ridge axis. In the four areas, all events were localized with small uncertainties less than 0.3 s in their origin time and 400 m in location, compared to that of 10-20 km reported in the ISC catalog. The SL of completeness, which is the minimum SL above which all hydroacoustic events are reliably recorded, was 212, 206, 209 and 210 dB based on all the events from each of the four respective regions, respectively. The findings confirm that hydroacoustic monitoring is an accurate and sensitive method for detecting seismic activity in remote regions of the ocean.

	Swarm 1	**Swarm 2**	**Swarm 3**	**Swarm 4**
Spreading ridge	SWIR	SWIR	SWIR	CIR
Region	Novara TF	Melville TF	Segment at 67°45’E	Edmond HF
Longitude	58°20’E	61°00’E	67°45’E	69°30’E
Dates span (dd/mm/yy)	06/07/18 - 18/07/18	01/06/16 - 25/03/17	27/09/18 - 27/10/18	16/04/20 - 04/09/20
Duration (days)	13	298	33	142
Number of ISC events	231	258	92	68
Number of OHA events	1109	27624	4880	2015
Number of IMP events	69	118	58	711
SL of OHA events (dB)	201 - 236	186 - 228	196 - 240	199 - 246
SL of IMP events (dB)	206 - 233	200 - 225	209 - 230	205 - 224
SL of completeness (dB)	212	206	209	210

Table 1 - *Detection summary of four seismic swarms in the southern Indian Ocean. OHA are the hydroacoustic events recorded by the OHASISBIO network and IMP are impulsive events.*

Among all the hydroacoustic events, a number of peculiar events, short and energetic up to 60 Hz were observed: 69 near the Novara TF, 118 near the Melville TF, 58 near the segment at 67°45’E and 711 on the CIR (Fig. 2). Their SL values ranged between 200 and 233 dB with a most frequent value at 211 dB (Fig. 2e). Out of these 952 events, 576 (60 %) have SLs above this value. So, compared to T-waves from high magnitude earthquakes reported in the ISC catalog, these events combine a high SL, a high frequency content (up to 50-60 Hz) and a much shorter duration (10-15s) versus 80 to 200s for regular T-waves. Unlike typical T-wave events, their rise time is also very sharp. From all these characteristics, they can be qualified as impulsive events (IMP). As an example, the spectrogram in Fig. 2f shows an IMP event, originating near the Edmond HF and detected at the ELAN site, 3757 km away with a RL of 109 dB. Their short duration and high frequency content suggest that these signals are water-borne H-waves, meaning that the energy is directly released into the water and does not originate from waves having traveled into the solid crust, like regular T-waves. Finally, aside from being associated with seismic swarms on spreading ridge axes, IMP sources are mostly located at the foot or slopes of bathymetric highs and generally occur in clusters after large-magnitude earthquakes nearby, as if triggered by them [6,7].

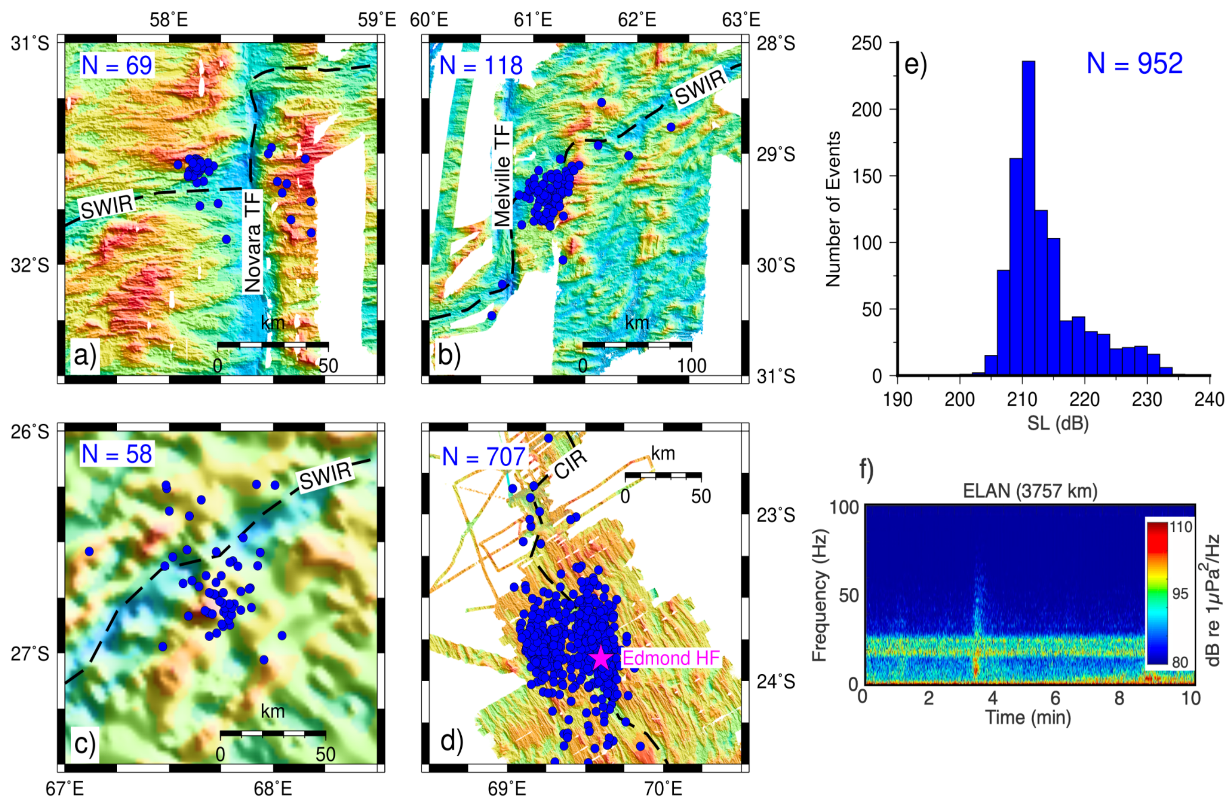

***Fig. 2** - Locations of IMP events (blue dots) along the SWIR: a) near Novara TF; b) near Melville TF; c) near segment at 67°45'E, and the CIR; d) near Edmond HF, bathymetry is from [9]. e) SL histogram of the 952 impulsive events shown in a)-d). f) Spectrogram of an IMP event originating near the Edmond HF and recorded 3757 km away (ELAN site, Fig. 1).*

4. DISCUSSION

Hydroacoustic IMP events have been observed on several spreading ridges as well as during underwater volcanic eruptions [e.g. 1,10]. In this study, the absence of precursory P and S seismic arrivals, as well as the short duration and frequency range of IMP events, suggest that they are not produced by shallow earthquakes, which would generate broader waveforms. Instead, as demonstrated in other studies, IMP events showing similar signatures as ours likely result from hot lava and seawater interactions at the seafloor. For example, during a recent volcanic eruption off Mayotte Island [11,12], similar events originated from a location with direct evidence of active lava flows, within a 50 km range of the hydrophones. During the Axial seamount eruption on the Juan de Fuca Ridge in 2015 [13], similar events with SLs ranging from 130 to 190 dB, recorded at a closer range (< 20 km), were interpreted as hot lava and seawater interactions.

Natural IMP events along MORs may have different source mechanisms. One possibility is that they are associated with the steaming of cold (~2-4 °C) seawater in contact with hot lava at the seafloor. Another mechanism could be the implosions of rising magmatic gas (sudden inward bubble collapse). Additionally, "bomb-like" lava fragmentations could produce high frequency compressional acoustic waves [14]. Moreover, they could also arise from the cracking of rapidly cooling lava or lava quenching on the seafloor.

Natural IMP events have similar signatures as that of signals generated by underwater controlled source experiments. Fig. 3 compares the spectrogram of an IMP event generated near the Edmond HF on CIR, recorded at WKER site (2737 km away) with that of an explosion of a 102 kg of TNT offshore Argentina (45°40'S, 59°25'W) on 1st December 2017 [15]. This man-made signal has been recorded at a distance of 8195 km at the WKER site near Kerguelen Island. This experiment was carried out by the International Monitoring System of Comprehensive Nuclear Test-Ban-Treaty Organization in an attempt to characterize an unknown signal originating from a submarine of the Argentina Navy that went missing on 15 November 2017. This comparison shows that IMP events, here interpreted as hot lava and seawater interactions, can be mistaken for man-made underwater explosions. However, natural IMP events occur in long-lasting clusters (weeks or months) centered on spreading-ridges or underwater volcanoes, and generally nearby high-magnitude earthquakes.

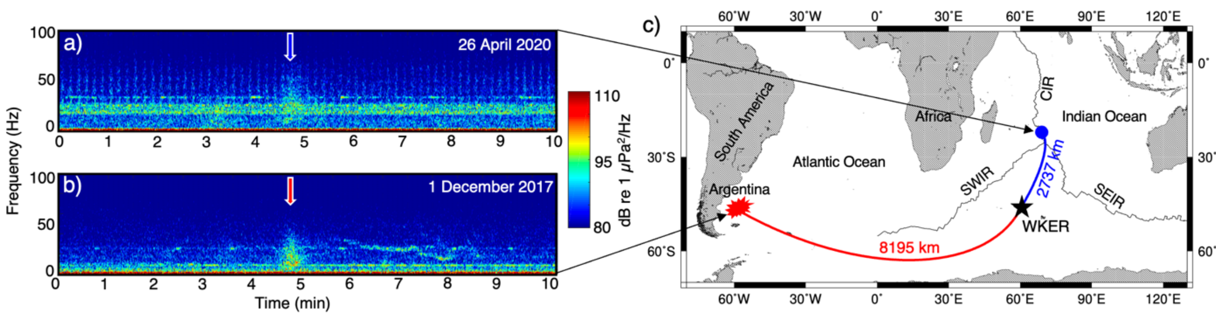

Fig. 3 - Spectrograms of impulsive signals recorded at WKER site (black star) and resulting from a) lava-water interaction on the CIR (blue) vs. b) controlled source explosion offshore Argentina (red).

5. CONCLUSIONS AND PROSPECTIVES

This seismoacoustic study of swarms along the SWIR and CIR in the Indian Ocean evidence many energetic and short duration impulsive events which can be recorded as far as ~3800 km away from their source. Their relative abundance on the CIR with respect to the SWIR may reflect different interplay of volcanic and tectonic processes. Impulsive events are interpreted as water-borne H-waves resulting from hot lava and seawater interactions on the seafloor. They cluster near or on the ridge axis, at the foot or slopes of bathymetric highs, and occur after large-magnitude earthquakes nearby, possibly caused by dike intrusions. Despite their very similar signatures, such events of volcanic origin should not be misinterpreted as acoustic impulse responses generated by man-made explosions. Machine learning algorithms may be able to discriminate them from more specific characteristics [16].

This study also calls for *in-situ* oceanic campaigns to better understand the origin of these impulsive events. Although it is a challenge to monitor such events in real-time, there would be several ways to study them apart from collecting hydroacoustic data. For example, by repeating high-resolution multibeam bathymetric surveys to detect changes in seafloor morphology, side-scan sonar surveys to highlight freshly formed lava from the backscattered energy, and/or deep-sea camera surveys from autonomous underwater vehicles.

As shown in Fig. 2a-2d, impulsive events mostly originate from the same location over extended periods of several weeks to months. They generate water-borne signals with a high acoustic-energy (> 200 dB) directly released into the water column, which, through the SOFAR channel, can travel long distances (e.g. > 1000s km as in Fig. 2e and 3). On distant receivers, their narrow signature makes their arrivals more easily discernible on spectrograms than the long cigar-shaped T-wave signals, resulting from the complex conversion of seismic to acoustic energy at the seafloor. With their impulsive nature, these events may, thus, provide useful natural sources for analyzing the effects of long-range propagation of acoustic waves [e.g. 17], as well as for monitoring the sound-speed and thermography of the ocean at long range [e.g. 18].

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