First installation of an optical OBS, cabled offshore Les Saintes, Lesser Antilles

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Abstract

The detection, analysis and modeling of seismic processes worldwide very often requires the use of ocean bottom seismometer (OBS). Indeed, the largest earthquakes and transient slow slip events (SSEs) mostly occur offshore or near oceanic coasts, along the major plate boundaries, and in particular on the interplate thrust fault of subduction zones. However, most OBS deployments are done with stand-alone stations, with data recovery delayed by months or years. On the other hand, electrically cabled OBS, which allow for real-time monitoring, like in Japan (DONET), USA(Neptune), or France (EMSO Ligure), remain exceptional due to their very high cost of manufacturing, installation, and maintenance.

Here we present a new perspective for such cabled array of OBSs, using innovative, purely optical seismometers, plugged at the end of long fiber optic cables, aimed at reducing the cost of installation and maintenance for permanent observatories requesting real-time data. The optical seismometer has been developped in the last decade by ESEO, based on Fabry-Perot (FP) interferometer, tracking at high resolution (rms 30 pm) the displacement of the mobile mass of a 10 Hz, 3 component, purely mechanical geophone (no electronics nor feed-back). A prototype has been successfully installed at the top of La Soufrière volcano of Guadeloupe, in 2019, at the termination of a 1.5 km long fiber.

We replicated and marinized this sensor, and in June 2021 we installed it 5 km offshore the Les Saintes islands (Guadeloupe, Lesser Antilles), for better characterizing the intriguing swarm-type activity still persistent after the 2004, M6.3, Les Saintes destructive earthquake (Interreg Caraïbe PREST project). The cruise, FIBROSAINTES, was supported by the Flotte Oceanographique Française (FOF) with the N/O Antéa Research Vessel. A plow, designed by GEOAZUR, carried the reel with its cable, and was pulled on the sea floor by the vessel, burying the cable. The seismometer was installed by divers at the depth of 43 m. The landing cable in the harbour of Terre-de-Bas was connected to the interrogator, and the record are since telemetered in real-time to the Observatory of Guadeloupe (OVSG). The optical OBS has been qualified by comparison to the records of the M7.5 Haiti 2021 earthquake from a nearby land-based broad-band seismometer. A few local earthquake swarms have been recorded, allowing for a preliminary discussion of their mechanical origin. In 2024 the seismometer should be complemented by two other ocean bottom, innovative, high resolution instruments, a pressiometer and an hydrostatic tiltmeter, designed by ENS. This successfull installation opens promising perspectives for the seismic real-time monitoring in many other sites offshore, and more generally in any site, natural or industrial, presenting harsh environmental conditions, where commercial, electrical sensors are difficult and/or costly to install and to maintain, or simply cannot be operated.

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Supplemental Material

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Introduction

Most of active fault system worldwide, and in particular major subduction zones, are located along coastal regions. For better assessing their ongoing and future seismic activity, land-based monitoring seismological and geodetic arrays should be complemented with offshore instruments. Their aim is to better record and characterize the ongoing seismic activity, for improving tomographic images of the crust and of the structure of the fault system, and the space-time distribution and evolution of the seismicity related to it; and in particular for improving the forecasting of major earthquakes with the search and characterization of locked or creeping fault segments. For this ambitious objective, autonomous ocean bottom seismometers have been used for decades, offering a large variety of frequency range (from short period to broad-band), and power autonomy (from weeks to a couple of years). To compensate somehow the absence of real-time records, OBSs are regularly lifted onboard a survey vessel for data downloading, and reinstalled; but this is usually costly, and the shift in the new location, although small, can make impossible advanced analysis such as repeater identification, or velocity changes through noise correlation. New systems with a supply of data messengers partially solve these problem, but do not solve the real-time issue required by monitoring. For achieving real-time, cabled offshore observatories are the only alternative. Starting decades ago, a few countries have developed such infrastructures, electrically powered, for scientific objectives. They are now operational in the Pacific ocean, in USA and Japan, with impressive scientific achievements (Kelley et al., 2014; Shin et al., 2020). In the Mediterranean, one French broadband seismic station is cabled offshore Toulon (`https://numerenv.in2p3.fr/`), using the facilities of the ocean bottom observatory ANTARES, dedicated to neutrino detection for astrophysical research (Bertin et al., 2015).

More recently, the fast progressing DAS technology (DAS stands for "Distributed Acoustic Sensor") has allowed to test the use of existing, available telecom offshore optical cables for seismic monitoring. These commercial instruments, initially developed by the oil industry almost two decades ago, are based on an optical interrogator which sends into the fiber sequences of laser pulses, the backscattering of which, from every small fiber segment, produce interferences with the neigbouring one (Jousset et al., 2018). The evolution of the phase shift of these local interferences produces an image of the strain rate between each target segment of the fiber, offering thousands of measurement points on fibers tens of km long. A drawback of this technique is a lesser resolution than standard geophones, in particular at long periods, as well as strong local site effects mostly related to the varying coupling of the fiber to the ground (Lindsey et al., 2017).

Before the present development of DAS systems, a few other types of optical seismometers have been designed and operated at sea. Using Michelson interferometry for measuring the displacement of the mobile mass, Chen et al. (1999) has built and demonstrated an optical accelerometer, temporarely installed offshore Japan. With a similar interferometric design, Zumberge et al. (2010) have qualified a high resolution, broad band optical seismometer in a small borehole a few hundreds of meters offshore. For offshore geo-industrial application, ASN has developped a Permanent Reservoir Monitoring solution (PRM, `https://web.asn.com/prm.html`) based on fully passive subsea optical architecture and optical sensors, operational on the North Sea gas fields (ASN, 2019). Their optical accelerometers, based on Bragg gratings interferometry, are however less performant than commercial geophones.

For offshore installations, the use of purely optical systems, like those quoted above, are very promising, as it is expected to reduce the cost of electrically powered sensors (lighter equipment and cable, easy landing with no need of electrodes), and to reduce the cost maintenance due to an expected lower rate of failure (no electronics, nor electrically induced corrosion of connectors).

In this context, we have developed an innovative optical ocean bottom observatory, whose first installation offshore, with a seismometer, is the topic of the present paper. The optical geophone is similar to the land-based one which we developed in the recent years, as described in (Bernard et al., 2019; Feron et al., 2020). It uses Fabry-Perot interferometry, with a dedicated opto-electronic interrogator designed by ESEO: at the termination of the fiber, the laser beam passes through a collimator, and reflects on a mirror fixed on the mobile mass of a 9 Hz geophone constructed by ESEO. Returning into the fiber, this beam interferes with the beam reflected on the collimator interface, allowing for resolving 30 pm relative displacement of the mass. A land-based prototype has been successfully installed at the very top of La Soufrière volcano of Guadeloupe, in 2019, at the termination of a 1.5 km long fiber, the interrogator being safely installed at the basis of the active dome, with telemetry and solar pannels. Two prototype optical instruments designed by ENS, an hydrostatic tiltmeter and a pressiometer, are now ready to be installed offshore, aside the ocean bottom seismometer, the land-based version of the optical tiltmeter being in operation for many years at LSSB (Herty et al., 2016) and at CERN (Lesparre et al., 2016).

In the following, we first present the tectonic context and the scientific interest of the selected offshore target in Guadeloupe. We then describe the planned ocean-bottom optical observatory and its instruments, and the operation at sea for the seismometer installation. Finally, we present the qualification results of the ocean-bottom seismometer, and report the first, preliminary scientific results brought by the offshore recordings.

Tectonic setting and design of the cabled observatory

Tectonic setting

The Lesser Antilles is a major subduction zone where the North-Atlantic plate, to the East, plunges beneath the eastward spreading Caribbean plate, at a slow velocity of 2 cm/yr (Saurel et al., 2022). Major historical earthquakes occurred in 1839 and 1843, with estimated magnitude 7.5 and 8.0-8.5, respectively (Bernard and Lambert, 1988; Beauducel and Feuillet, 2012). The former caused extensive damage in Martinique, and its source is believed to be deep in the subducting plate. The 1843 earthquake produced heavy destruction in Guadeloupe and Antigua, and despite its large magnitude and epicentral location east of Grande-Terre (Guadeloupe), its source as an interplate event is debated, owing to the absence of reported tsunami, and, more indirectly, to the low coupling of the interplate contact as indicated by GNSS (Symithe et al., 2015). Offshore investigations, 50 to 150 km east to the islands and closer to the trench are requested for better constraining the debated interplate coupling and assess the related hazard. IPGP being responsible for the monitoring of the seismic activity of the above French territories, this was the primary motivation to imagine the installation of an optical cable on the ocean floor, for connecting not only optical seismometers, but also the optical tiltmeter and pressiometers developped by ENS for testing innovative offshore geodesy.

However, we had to start with a much more modest project, to qualify in situ our instruments with less costly marine operations. The international PREST project (2018-2022), lead by IPGP, and supported by the E.U. Interreg Caraïbe program, provided us the necessary funding and administrative support. For PREST, we focussed on the Les Saintes archipelago, 15 km south to the main island of Basse-Terre (Guadeloupe). This area was indeed stroken by the M6.3, 2004 "Les Saintes" earthquake, which activated a NW-SE striking offshore normal fault, dipping to the NE and cutting through the Caribbean upper crust, rupturing a fault segment from 10 to 30 km south to the islands, and producing a small local tsunami at Terre-de-Bas (Feuillet et al., 2011; Bazin et al., 2010; Beauducel and Feuillet, 2012). Since then, the northern edge of the rupture shows the persistence of swarm-like seismic activity, suggesting the occurence of episodic aseismic deformation due to fluid an/or creep migration on the main or on secondary normal faults of this submarine rift. However, with only two land-based seismometers on the Les Saintes islands, no accurate location of the swarms could be provided. This impedes any attempt to assess the related time-dependent hazard, an uneasy situation owing to the frequent report of felt earthquakes by the local residents, which rises concerns among the public and the authorities about a potentially large earthquake, or about a volcanic eruption, as the Roseau rift is the line linking the two main volcanoes of Guadeloupe and Dominica, cutting the submarine edifices of the two old volcanoes, "Colibri" and "Roseau" , to the south of Les Saintes islands. The small magnitudes of the earthquakes (mostly in the 1.0-2.5 range, from the OVSG bulletin), and their sometimes strongly felt effects (Macroseismic Intensity up to IV) suggests that many of them occur in the very shallow crust, very near the islands. To provide a minimal location capability, an offshore, cabled seismometer was clearly needed. Furthermore, the likely occurrence of episodic aseismic strain episodes called for the installation of innovative optical geodesy offshore, using the tiltmeter and pressiometer from ENS.

Design of the offshore installation

As the preliminary swarm location extends from the islands to 10 km southward, we selected a site about 5 km south to Terre-de-Bas island, around 40-45 m deep, at the southern, slightly rising edge of the submerged coral platform supporting the archipelago. Further south, the sea floor deepens rapidly, forbidding the installation by divers which was requested for a better control of all steps of this pilot installation. According to published bathymetry maps (Deplus and Feuillet, 2010), the 5 km of the future path of the optical cable would pass through a gentle hollow, no more than 60 m deep, covered with sand and coral debris; this was later confirmed *in situ* by optical imagery, and a first dive in 2020 found a dominance of unconsolidated rodolithes (mostly a few mm to a few cm in diameter). The absence of large, hard coral blocks was *a priori* favourable for the planned installation of the cable with a plow designed by GEOAZUR (Hello, 2021). This plow is supported by skids at the front to secure the passage of obstacles on the sea floor. At the back, it is supported by the plowshare which can penetrate up to 20-30 cm in soft sediments. The plow supports a reel with the cable, which unrolls and gets buried through the plowshare in the sediments when the plow progresses, as being pulled on the sea floor by a vessel.

The choice of the GEOAZUR plow for the cable installation was dictated to minimize the cost and footprint of our observatory. The alternative was the use of a much larger plow operated by a cable ship, as commonly used by the offshore industries, but too expensive for our budget. The use of the GEOZAUR plow was very constraining for the selection of the optical cable, as its maximal allowed diameter was 8 mm in order to pass through the plowshare. We selected a 6 mm diameter, loose optical cable, armoured and fit for submarine applications, with 12 optical monomode fibers. This was delivered by the Swiss company SOLIFOS, which also designed some of the connection boxes and the optical penetrators. Both terminations of the main cable was plugged to watertight connection boxes, one linked to the landing cable, the other linked to separate cables for each sensor.

For the landing in the Terre-de-Bas harbour, at Anse des Mûriers (see Fig. 2, left), the immersed cable was protected by a 350 m long pipe made by paired half-shells of iron cast, produced by FMGC, connected to each other, and laid on the sea bed by divers. On the sensor side, 5 km offhsore, only the seismometer was ready for the installation planned for june 2021, at the end of a 150 m long optical cable. The latter allowed for dry, onboard manipulation and connection of the sensor on a vessel, and provides four fibers, three for the 3-component mechanical geophone, and one for a reference "zero displacement" sensor in the same watertight housing. We decided to use three similar 9 Hz mechanical geophones, with passive electromagnetic damping (quality factor of 3), as done for the previous installation in La Soufrière Feron et al. (2020). First, because such oscillators are robust, which would reduce the risk of failure during the transportation at sea and its immersion. And second, because they can operate in any direction of space, contrary to longer period oscillators (4.5 Hz and less) which have a very limited tilt range. This lack of sensitivity to tilt should allow to accommodate for instability of the coupling to the sea-floor, and, in the long term perspective of installations elsewhere, to remain in operation on any tilted seafloor bed.

The preparation of the installation requested to apply for the service of the Antéa Research Vessel from the French Oceanographic Fleet (FOF - IFREMER), a 35 m long catamaran operating on shallow water, well equipped and large enough for safely handling the loading and unloading of the plow (6 m long and weighing 500 kg). The FIBROSAINTES cruise project (P.I., Y. Hello) was finally accepted by the FOF early 2020. The nominal daily cost of the ANTEA is of the order of 20 ke/day. The installation requested a number of authorization from French regional and local administrations, for the temporary use of a submarine territory, for the protection of the local marine plants and fauna, and for the technical issues of the landing in the Anse des Mûriers harbour, in Terre-de-Bas island. The rather small environmental footprint of the installation, with a cable 6 mm in diameter buried at shallow depth in loose soil, and no electrical hazard, contributed to the positive and fast evaluation of our cruise and administrative applications.

Installation of the observatory

The installation, initially planned in June 2020, was postponed to June 2021, due to the COVID pandemia which annuled the 2020 FOF cruises. Although the pandemia further delayed the construction and delivery of part of our systems, in particular for the pressiometer and tiltmeter, the sea operation was nonetheless maintained for the seismometer installation, and successfully achieved in 3 weeks, from June 1rst to June 22nd, 2021.

The operation at sea had to face a number of difficulties. A first problem arose during the first attempts of a detailed bathymetry survey along the planned profile, as the wire of the sensor of the Multi Beam Side Scan Sonar pulled by the vessel was cut twice by cables linking fish traps to their undetected small floating buoys (plastic bottles). Despite our broadcasted request for clearing the operation area, not all fishing equipment was removed from it, as part of it was abandonned for years with no surface marks, and as a few fishermen could not be reached.

The two sounders were hopefully recovered by the divers, but we gave up this survey task, and the Antea vessel had to spend a few days to remove all the remaining fish trap cables and other materials, like lost fishing lines and chains, which would have put the plow operation at risk. The pre-installation survey had thus to rely on the videos provided by the cameras set on the cable-free plow during the pulling tests along the main track, first with the plow gliding 5 m above sea floor, then with the plow sliding on the sea floor.

A second difficulty arose from the rather choppy sea due to strong trade winds, unexpected at this time of the year, which made uneasy the many systematic training operations for downloading the various equipment to the sea floor from Antea's rear deck, in particular the heavy plow and the large polyester boxes used for keeping safe the extra cable lengths on the sea floor. Furthermore, the short swell and the breaking waves, with sometime up to 35 knts of wind, made hazardous the work of the diver team, which was operating from a motorized, 7.5 m long semi-rigid boat. On the sea floor, at the target position (point B: 61°38'04" W, 15°48'59" N; 61.634444W, 15.816389N), at about 42 m in depth, the divers could only work for about 10-15 minutes, and only once a day, requesting the involvement of two diver teams for keeping the schedule tight. Because of these unexpected bad sea weather conditions, and in order to save time, we reversed the direction of installation of the main cable, which was initially planned from land (A) to offshore (B). To reduce the installation time at B, we loaded all the equipment (connexions boxes, seismometer, extra length of cable) on the plow, before downloading the latter to the sea floor, leaving the divers liberate all these at the staring point (B) before the plow started moving and cutting the seabed toward point A.

During their last dives at point B, the divers orientated the seismometer, its main axis been set close to the direction of tracks of the plow (N28°E from the cruis logs) , and partially buried it by hand, 15 cm deep into the rodolithes. This sea floor station has been named TDBSM (for "Terre-de-Bas Sous-Marine").

The last main difficulty was the need to solder the main cable to the landing cable, on board of the Antea vessel, at its termination near the harbour (point A: 61°36'59.1", 15°51'06.2"). Indeed, as the ploughshare was too narrow to let pass any connector, the near-land termination of the wound cable on the reel had none. When freed from the plow, this end of the cable had to be lifted on board, together with the end of the landing cable, for the 12 fibers to be soldered. At the time when this operation had to be done onboard, only 60 m away from the coast line, the sea was agitated and strong winds were blowing (however less than at point B). Thanks to a cautious control of the ship position subject to a slow drift despite its two anchors, the soldering operations could be achieved in a couple of hours, under the uncomfortable roll of the ship (the Antea catamaran is well known for its amazing rolling capability), and the splicing was subsequently enclosed in waterproof boxes.

Onshore, the landing cable enters a wooden creole house on the harbour jetty, let by the local authorities, and is plugged to the "LOKI" interrogator built by ESEO. The latter has a power of 6W provided by batteries plugged onto the mains. It interrogates the optical path at 50 MHz on each channels, and produces the displacement of the geophone masses of the remote ocean bottom seismometer, presently sampled at 200 Hz. It generates a mseed record, telemetered through mobile phone in real-time to the Volcanological and Seismological Observatory of Guadeloupe (OVSG-IPGP), where it is routinely integrated to the monitoring of the local and regional seismicity. Next to the LOKI interrogator, a commercial DAS interrogator was temporarily in operation, from the 18th to the 26th of June, connected to one of the free, 5.5 km long fibers reaching point B.

Instrumental and scientific results

Qualification of optical seismometer and of the installation site

The result of the burying operation of the main cable was checked by the divers near points A and B. For the first 60 m after point A (at about 10 to 15 m in depth), the burying process failed as a result of the thinness (less than 20 cm) of the sand layer overlaying the hard carbonate platform, which prevented to maintain the cable in the very shallow trench. This exposed cable segment has been since protected by additional cast shells, in January 2022. Near point B, a few segments of the cable, some meters long, emerged on the sea floor, likely to be related to irregularity of the plowing speed, and to the heterogeneity of the rodolithe cohesion and size. On all the rest of the cable, inaccessible to the divers, the buried status is revealed by the analysis of the background noise of the DAS records: clear high amplitude eigen-mode vibration appear on several long segments of the cable, revealing their decoupling from the soil. These vibrations strongly reduces the capabilities of the DAS system, but fortunately has no impact on the quality of the optical seismic records of TDBSM, unperturbed by the strain variations along the fiber. They however point out places were the outcropping cable may be more at threat from sea animals or anthropic activities like fish trap, nets and anchors. In total, roughly 90% of the cable is estimated to be properly buried. Repeated DAS interrogation of the cable will allow to track the time evolution of the buried condition of the cable.

To finalize the data processing at OVSG, the displacement record of the mobile masses of the geophones, extracted by the processing of the optical signals, is corrected for the instrumental response of the three geophones, to produce the ground motion. Optimizing the correlation of the three components with the records of the nearby TDBA broadband seismometer (a

CMG3 located 4 km to the North, on Terre-de-Bas island) allowed to accurately determine its orientation, $N12.5 \pm 1°$. Figure 5 presents one day of the displacement spectra for the vertical and horizontal components. Despite the low resolution at long periods caused by the high frequency resonance of the geophones (the instrumental noise of simple oscillators increases as the square of this resonance frequency, at lower frequencies), the oceanic microseismic noise is still resolved at periods up to 10 s. The secondary microseismic peak (around 0.2 Hz) at TDBSM matches well the one recorded on land at TDBA. We also note a strong peak around 0.1 Hz, unrecorded at TDBA, very likely related to the direct effect of the swell above the seismometer, favoured by the shallow depth of the sea floor. The intrinsic resolution of this seismometer is therefore very well adapted to these submarine environmental conditions.

Since the first day of operations, local, regional, and world seismicity is well recorded. A first illustration of the performance at low frequency of the geophones is provided in Fig. 6, with the low-pass records, at 0.03 Hz, of the M8.3, 2021 Alaska event. The records for the M7.0, 2021 Haiti event is presented in appendix (Fig. A1). The comparison with the TDBA station shows a difference of less than a few percent, a level expected by the combination of the calibration uncertainties of both seismometers, and ground motion differences due to the distance between the stations.

The record of regional and local events allowed to qualify the optical sensors at higher frequencies, although no colocated OBS has yet been operated. Figure 7 shows the velocity record and spectrum of a M5.0 event at 100 km distance, compared to that at TDBA, in the 0.1-10 Hz domain, providing very similar results. A last example, in a higher frequency domain (1-30 Hz), is presented in Appendix, Fig. A2, with the 3 component record of a local M2.1 event, about 5 km distant from both stations. The land and ocean bottom seismograms show similar clear P-wave and S-wave onsets, and present a very similar spectral level, except near 20 Hz, possibly due to the resonance of the thin, incohesive sedimentary layer (sand and rodolithes) covering the coral platform at TDBSM.

The anthropic noise is found to be very low, due to the scarcity of the navigation in this southern part of the archipelago, and to the modest size of the fishermen's boats. However, a prominent, impulsive noise, lasting less than 1 second, is very frequently recorded, several times a day, sometimes as a succession of tens of events in a few minutes. They have very variable amplitudes, up to a few micrometers, the largest one been often accompanied by a displacement step of a few tens of nanometers. Their absence on the "zero displacement" control channel shows that it is not related to opto-electronic disturbance. The absence of coda calls for a very close mechanical source, and excludes the effect of a standard seismic source. It does not show any diurnal nor semi-diurnal effect, so it is unlikely produced by an animal either. This intriguing signal may come from slow, micro-release of tension of the rather rigid optical cable plugged into the buried seismometer shelter, to very local gravity instabilities of the sediments of the submerged coral reef, or, less likely, to micro slip events on nearby fractures or faults. Hopefully, planned studies in 2023 with an additional, standard OBS should allow to identify its source.

Preliminary analysis of a local seismic cluster

Since the end of June 2021, the local seismicity rate remained low, apart from a few, small seismic swarms, the two largest one occurring in November 2021 and April 2022, with 10 and 12 events located by OVSG, respectively. We focussed on the 5-18 April sequence, which had 30 detected events, among which 20 could be classified in 6 multiplets, i.e., families with highly correlated waveforms (correlation coefficient higher than 0.85). Records of these events are presented in Figure 9. Among the 20 earthquakes which belong to the 6 multiplets, only 8 of them can be located (marked with a star in figure 9).

The use of station TDBSM significantly improved the location of these events, as it fills the large azimuthal gap of the land-based OVSG stations to the south of the epicenters (fig. A3). We use the NonLinLoc software (Lomax et al., 2000, 2009), to relocate the events using their differential P and S picking and found that some events of the same families were located 2 km apart. As the true distance within events of the same multiplet is most probably much less than 0.5 km according to their high waveform correlation level and to their small distance to the closest stations, one can estimate the absolute OVSG epicentral location uncertainty of 1 to 5 km. The NNL depths are found between 4 and 8 km, to which one may associate an uncertainty similar to that of the epicenter.

Considering only the 3 stations located in Les Saintes (TDBA, THMA and TDBSM), and using the NonLinLoc software, we relocated the 8 events. Hypocenters are now highly concentrated as expected for multiplets (Figs 10 and A4). The NNL depths are now ranging between 3.5 and 6 km. The multiplets families are thus located just south to the Terre-de-Bas southern shoreline. As the Roseau fault, dipping NE, is outcropping about 5 km SW from this cluster of epicenters (see cross-section 1 in Fig. 10), at least part of the families may well be associated to seismic slip on this fault. In this context, the high waveform correlation within multiplets might be further interpreted as the signature of repeaters (i.e., sources from the repeated rupture of single asperities), which the requires the occurrence of slow slip around the fault surface surrounding them. This leads us to suggests that the April cluster might have been triggered by a transient slow slip spreading on the shallow Roseau fault plane, or on neighbouring minor faults. As the cluster is located a few km north from the northern end of the 2004 rupture, this may be related to velocity strengthening properties of the faults at this latitude. One may speculate that the latter could be enhanced by high pore pressure related to deep hydrothermal activity, so that pore pressure migration might accompany or trigger these microseismic swarms.

Conclusion and perspective

We have presented the successful installation, in June 2021, of a permanent, innovative optical ocean bottom seismometer, at the termination of a 5 km optical cable offshore Les Saintes islands (Guadeloupe, Lesser Antilles). This experiment fulfilled two main objectives, technological and scientific. A technological objective, to qualify and demonstrate the marinized optical geophone constructed by ESEO, to qualify the use of the GEOAZUR plow for burying the optical cable in heterogeneous sea floor sediments, and validate the design of the cabled network and of the related operations at sea and for landing -

incidentally, the installation allowed to test the performance of the DAS system along this cable. And a scientific objective, to provide real-time, continuous records to be integrated to the OVSG monitoring routine, and to document the persistent swarm-like seismicity of the northern Roseau fault system, just south to Les Saintes, triggered by the 2004 M6.3 earthquake.

Concerning the geophones, their 9 Hz resonance was selected for benefitting from omnidirectional sensors, securing the installation, but leading to an increase of their noise level at the longest periods; the instruments however still retrieves good quality signal from large regional and worldwide earthquakes worldwide up to 30 s period, and its low frequency noise appears to remain well adjusted to the local, rather high microseismic noise.

Other innovative optical sensors designed at ENS and based on the same FP interferometry are been tested in Britany, for ocean bottom installations: One hydrostatic tiltmeter (short term noise 1 nanorad), and one pressiometer (short term noise 1 Pa, equivalent 0.1 mm of vertical sea bottom displacement). Both will be installed and qualified along side with the seismometer offshore Les Saintes, hopefully in 2024, for their *in situ* qualification, and for resolving transient deformation possibly accompanying the local seismic swarms.

Future optical ocean bottom observatories, like the one in development in Les Saintes, have appealing advantages over classical ones requiring electrical power. First, there is an expected global reduction of cost for the installation, thanks to an easier landing (no electrodes to install and maintain, no security issues on power), and a light cable to install or manipulate under water, manageable by a moderate size vessel pulling a plow. Second, but essential, there is a very low risk of failure at the sensors, at they bear no electronics and as the connectors cannot suffer from electrically induced corrosion, which saves the cost of maintenance - a big issue for permanent, cabled observatories.

The perspectives of technical evolution of such optical observatories are promising. Recently, laboratory experiments conducted by ESEO have demonstrated the operation of a such a seismometer at the termination of a 50 km long fiber without reduction of the record quality. Offshore targets between 50 to 150 km can thus be envisioned, using more stable and powerful laser diods, and less attenuating fibers. GEOAZUR is now working on a larger plow able to carry a reel with a 50 to 60 km long optical cable, manageable with a moderate size ship. Improving the low frequency resolution is another objective: this can be easily achieved using 1 or 2 Hz resonant geophones, as demonstrated in 2018 by our team during a 9 months experiment offshore (Bernard et al. (2019)). Finally, in addition to the pressiometer and the tiltmeter, we have successfully tested a prototype of high resolution fiber strainmeter, which could complement the set of our optical sensors (Bernard et al., 2023).

Many interesting scientific target could benefit from such optical observatories. Our optical seismometer and pressiometer have been integrated in the design of the future Mayotte ocean bottom, electro-optic observatory, with an installation planned in 2026, to contribute to the real-time monitoring of the seismo-volcanic activity triggered by the birth and growth of a new volcanic edifice, in 2019 (Feuillet et al. (2021), MARMOR (2021)). In the Lesser Antilles, our successful installation may open the way to more ambitious targets such as the coupling of the interplate contact of the subduction, 50 to 150 km offshore Guadeloupe and Martinique, and the activity of the hazardous Kick-em-Jenny submarine volcano, offshore Grenada island.

To conclude, our optical instruments, seismometers and future tiltmeters, pressiometers, and strainmeters - the list is not closed -, could be useful to design new offshore observatories, and to complement and reinforce existing offshore as well as land-based observatories, thank to their simplicity and robustness. They may also find fruitful applications in the geo-industry, in particular for high pressure and hot temperature boreholes, deep mines, and large underground infrastructures.

Data and Resources

The seismological records from land-based station TDBA of Les Saintes and of TDSBM are freely available from the IPGP Data Center. See the GL network in http://volobsis.ipgp.fr/data/geophysical-data-availability.

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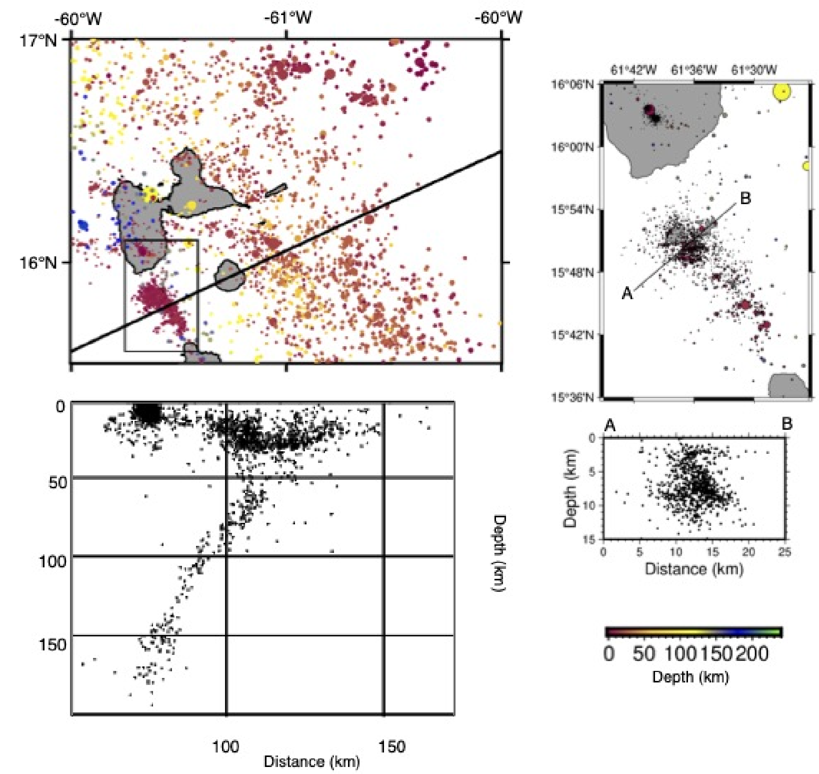

Figure 1. Seismicity around Guadeloupe and Les Saintes ilsands. Left: seismicity 05/17/2011 to 05/15/2012, from OVSG-IPGP website, including a cluster between Guadeloupe and Dominica. Right: zoom of the seismicity in Les Saintes surroundings (08/18/2021-08/16/2022), presenting large uncertainties in the OVSG epicentral location (several km) due to limited stations coverage.

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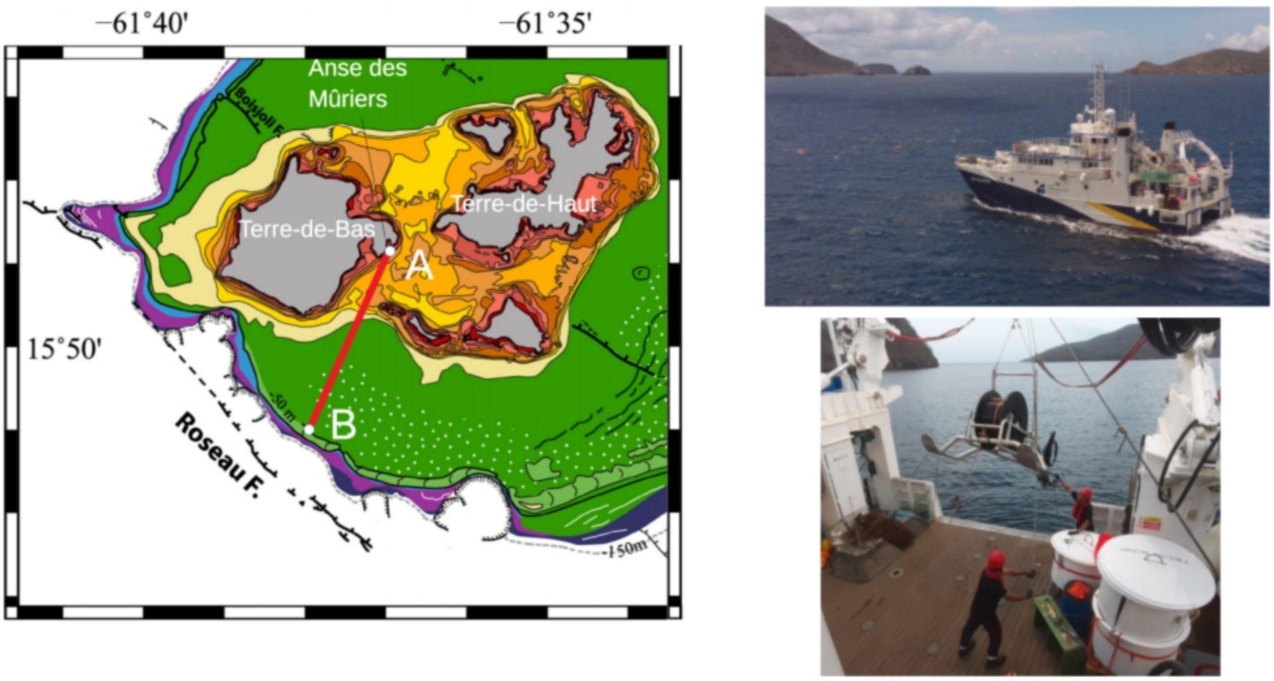

Figure 2. Installation of the optical cable. Left: cable path (red line) on the bathymetric map (modified from Leclerc et al. (2014). The seismometer is located at the southern termination of the cable (point B), on the edge of the deep submerged coral platform (green area), 1.5 km from the Roseau normal fault . Right, top: Antea vessel (FOF) cruising close to the installation site. Right, bottom: from Antea, launching trial of the plow carrying the reel with the 5 km optic cable.

Figure 3. Landing of the cable at Anse des Mûriers harbour, Terre-de-Bas. Top: google map view of the harbour. dotted line: path of the cable protected by cast shells. Bottom: submarine view of the chain of cast shells protecting the cable.

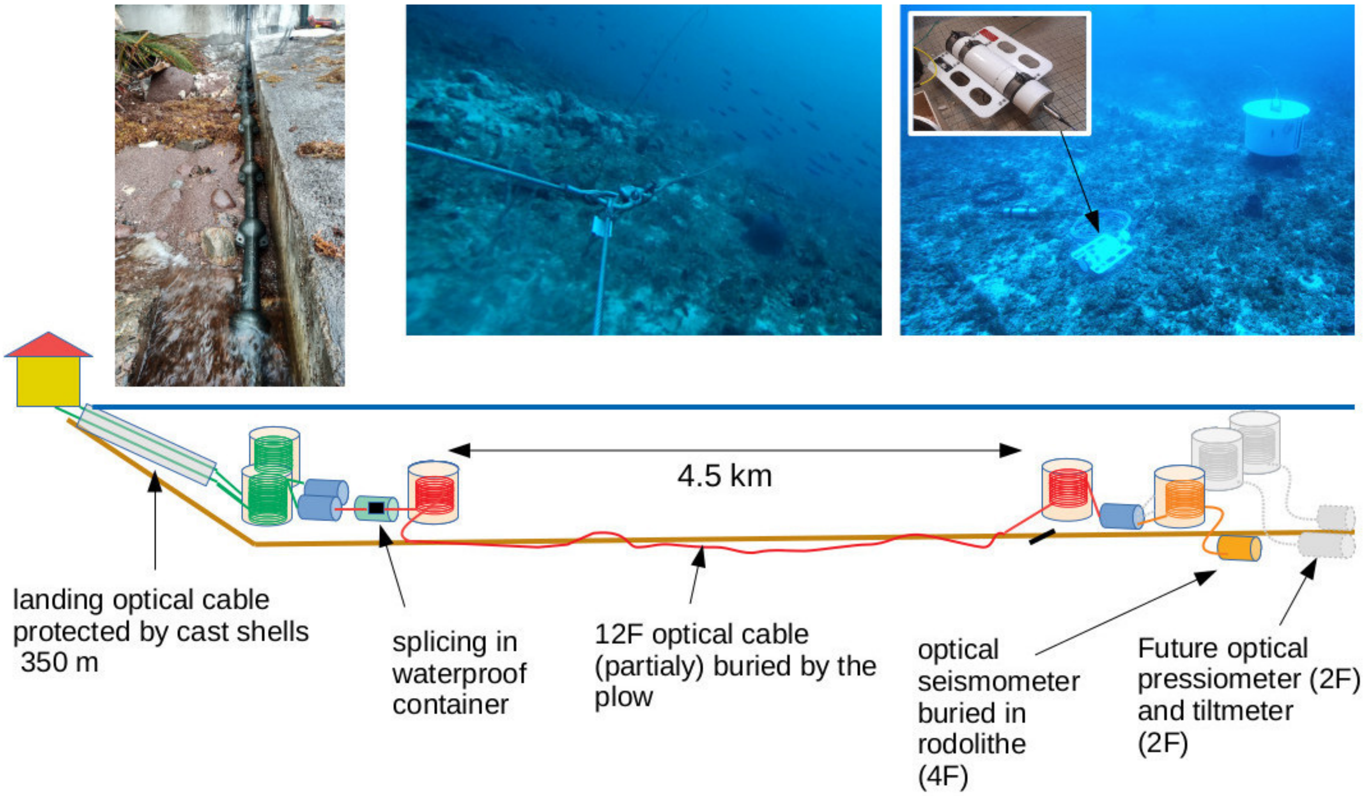

Figure 4. Scheme and sea floor pictures of the final installation. Top left: picture of the chain of cast shells protecting the cable, at low tide. Top center: picture of the sea floor ahead of the plow during the pulling operation by Antea. Top right: picture of the sea floor at the installation site, with the optic seismometer at the bottom center, before its burying in the rodolithe. insert: the seismometer before its installation. Bottom: scheme of the installation.The large cylinders are containers for protecting the extra cable left for operations at the surface.

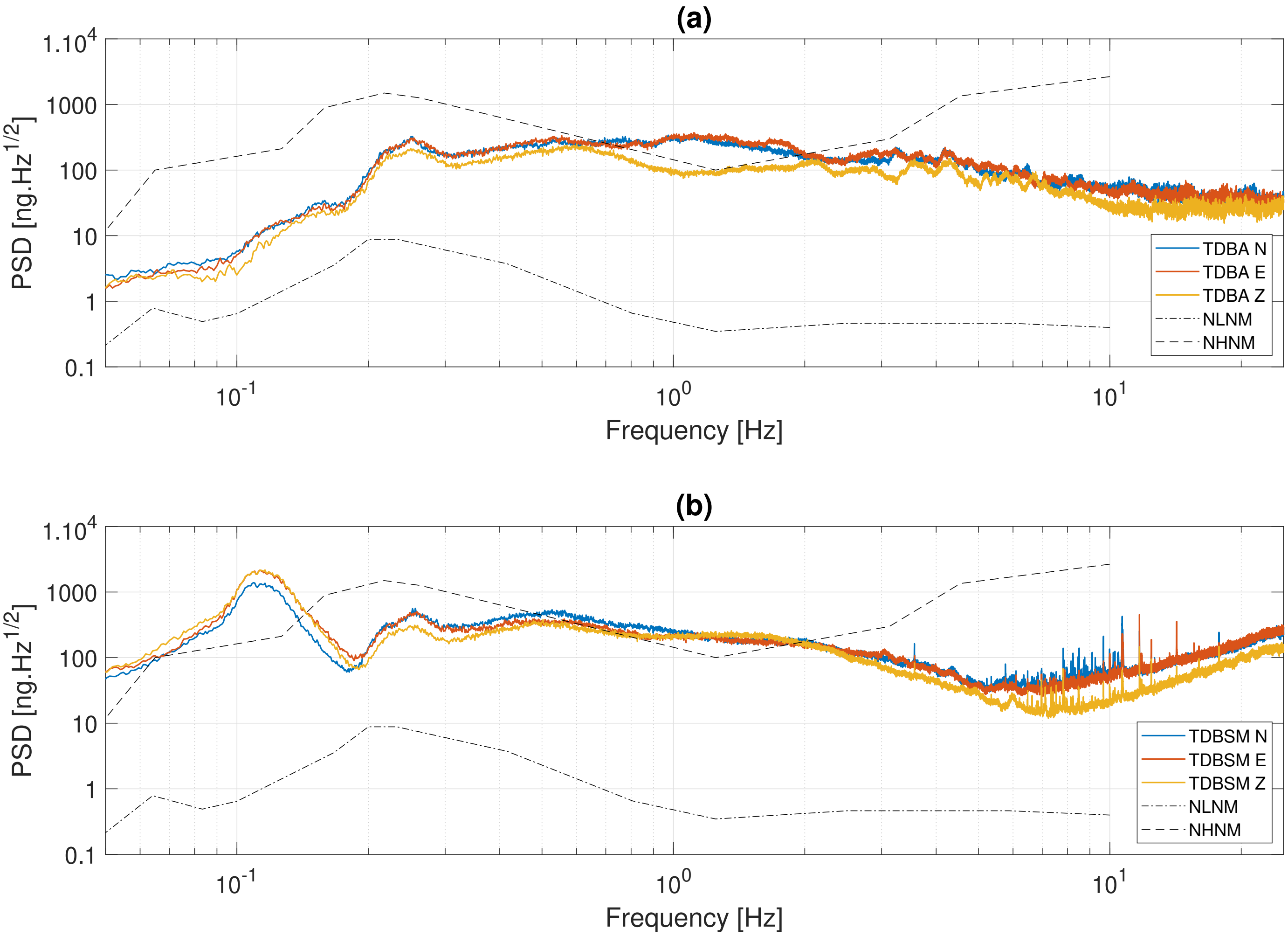

Figure 5. PSD of the ground acceleration (3 components), for 24 hours record: top, TDBA (onland, Trilium 120); bottom, TDBSM (offhshore, optic geophone). Note the similar microseismic peak arounf 5 s period, and the large peak at 10 s at TDBSM only, related to the local swell.

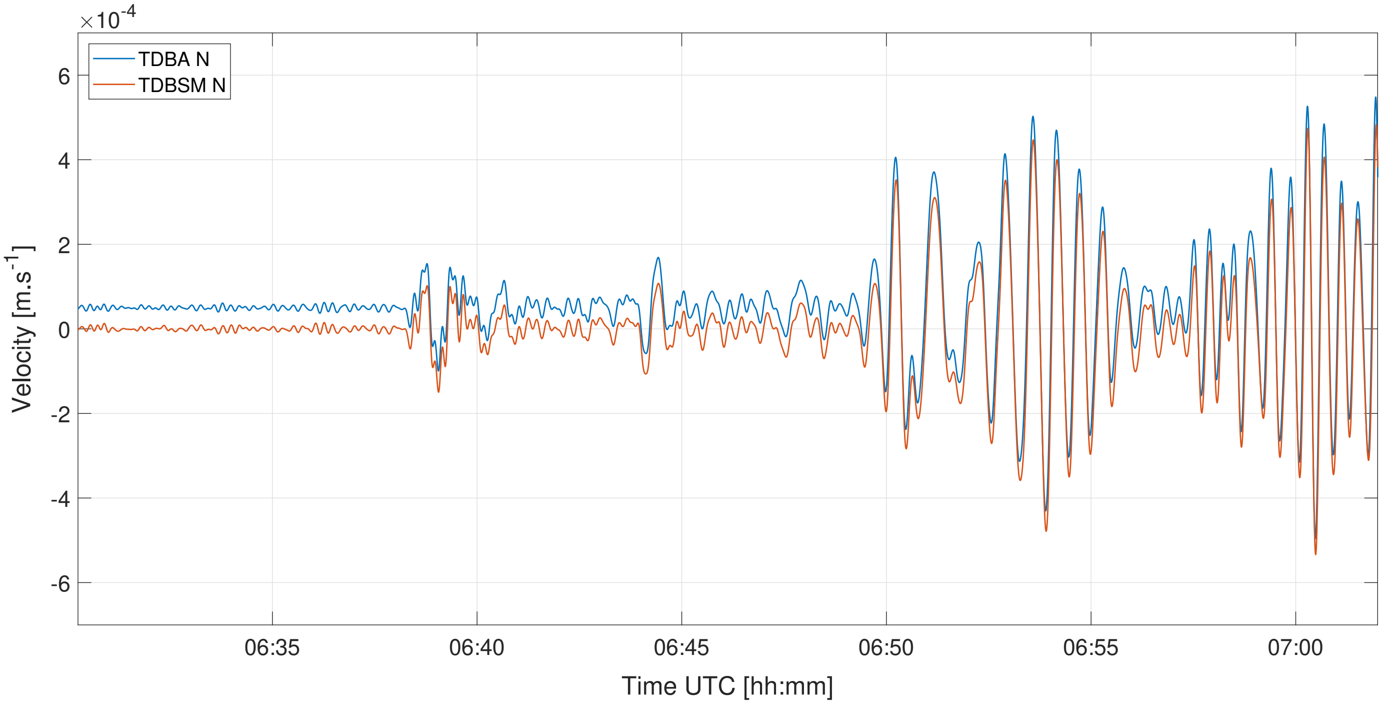

Figure 6. velocity record (East component) of the 2021, M8.3 Alaska earthquake. Red: TDBSM (offshore optic), and blue, TDBA (onland, Trilium 120). The TDBA record is shifted vertically for easier comparison.

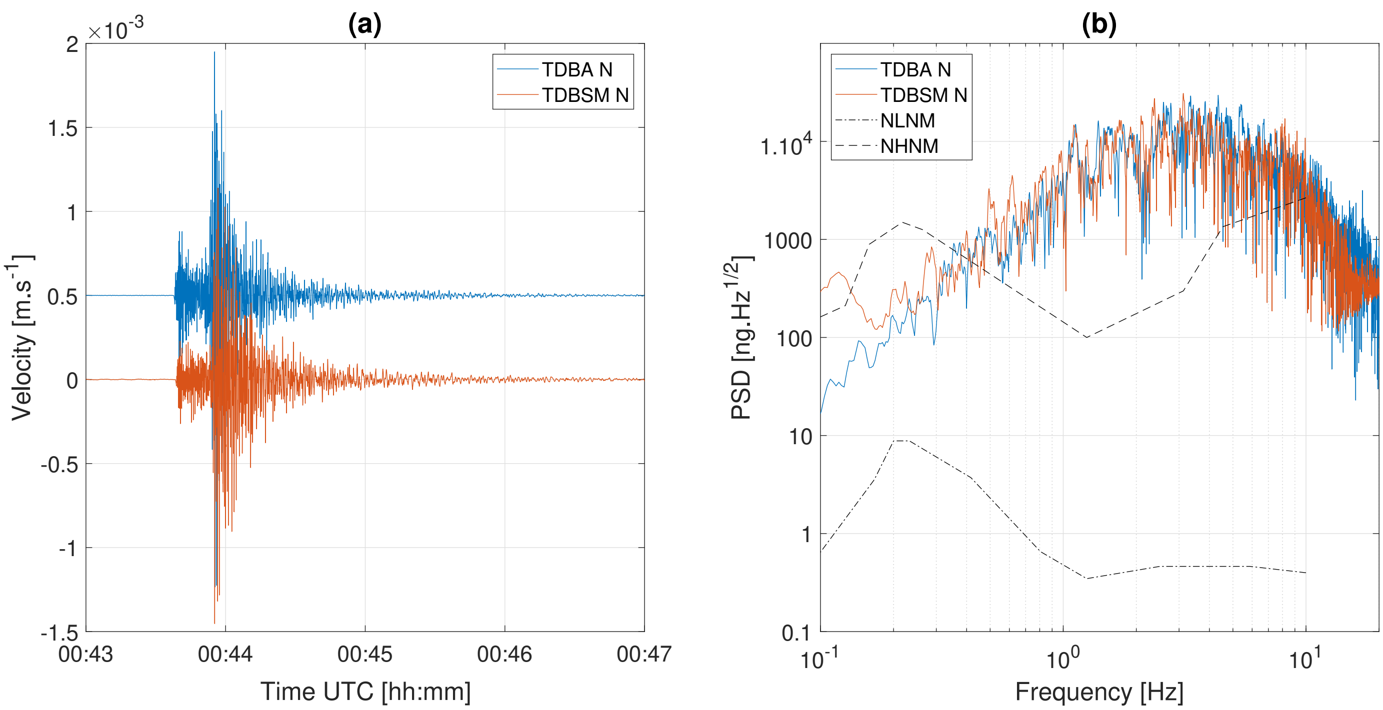

Figure 7. Records (North component) of a regional M5 earthquake (10/09/2021). Red: TDBSM (offshore optic); blue: TDBA (land, Trilium 120). left: velocity record, TDBA shifted vertically for easier comparison. right: PSD of acceleration, with the standard references for low and high noise models (dotted lines).

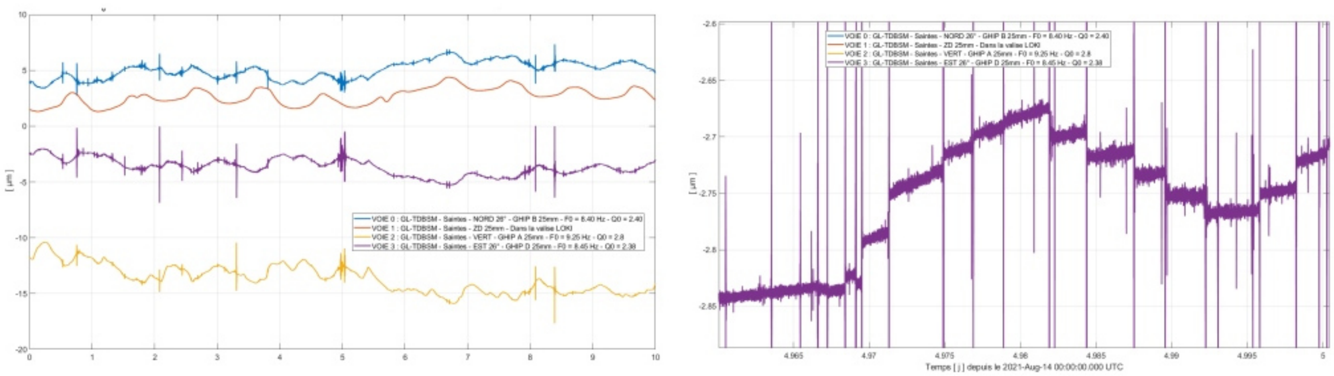

Figure 8. Record of impulsive signals at TDBSM. left: 10 days of 3-component displacement records (14 to 24/08/2021). right: zoom on the strong activity of day 19/08, showing micro-steps on the E (transverse) component, possibly associated to tilt from rotation of the instrument around its main axis.

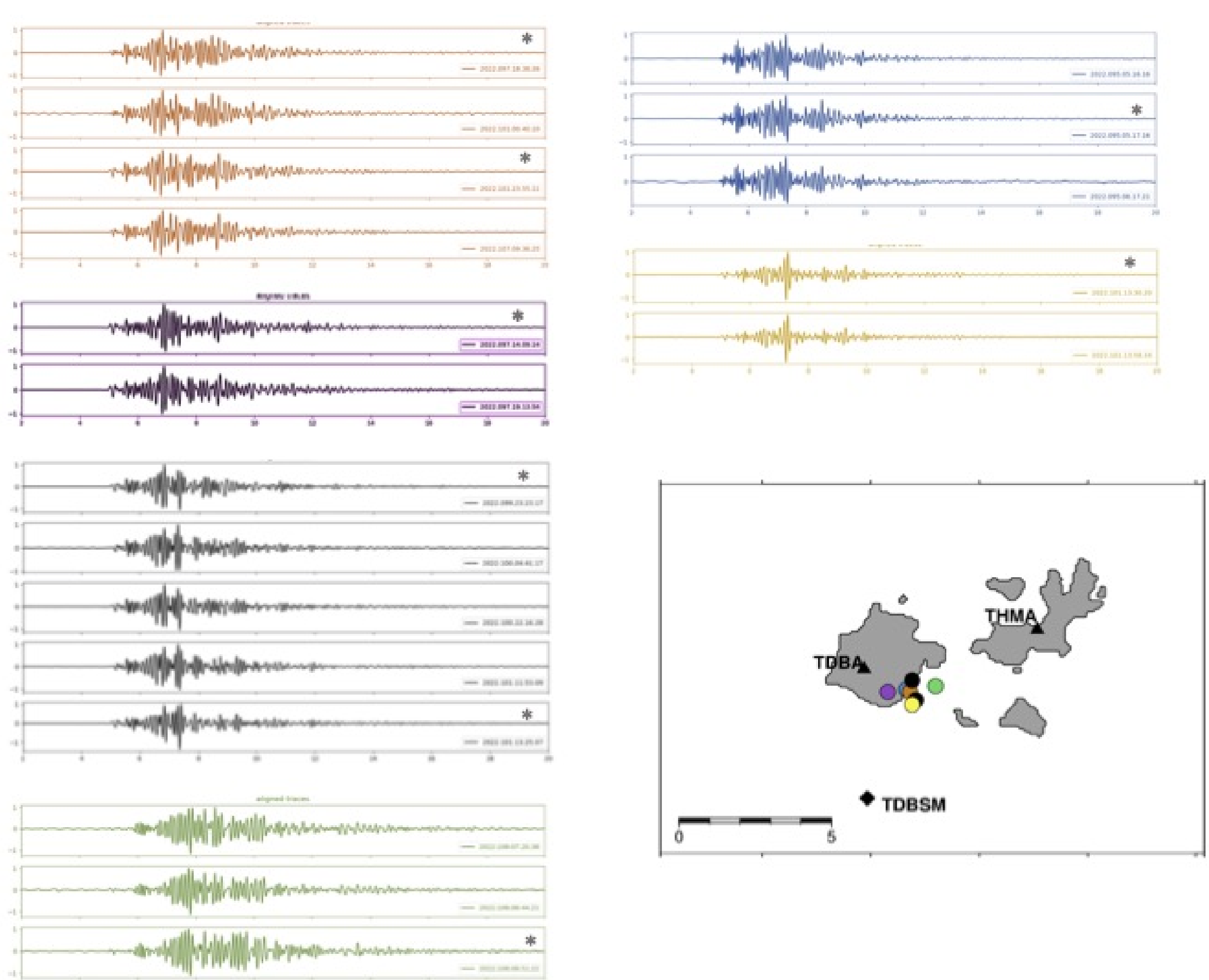

Figure 9. Multiplet records of the April 2022 swarm. Localized earthquakes are marked with a star. The colors correspond to the different multiplet families represented in figure 10.

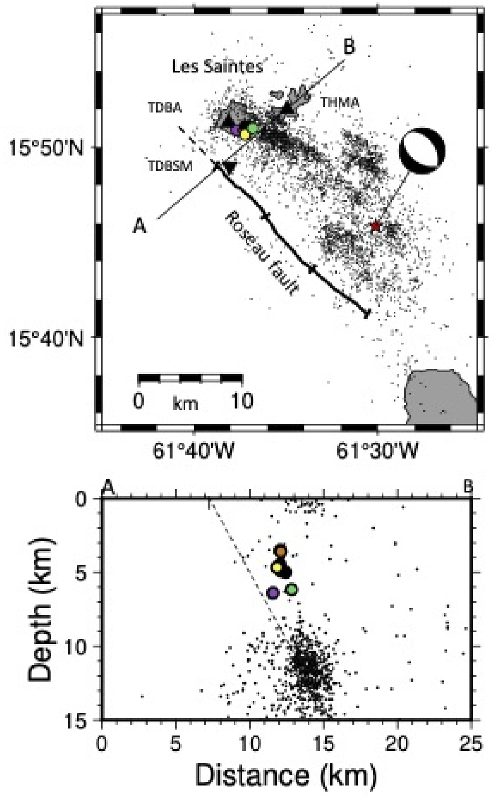

Figure 10. Locations of the multiplets (colored circles) in plan and section in the seismo-tectonic context of the November 11, 2004 earthquake. The locations of the aftershocks are in black (Bazin et al., 2010). The focal mechanism and the location of the mainshock (red star) are from (Feuillet et al., 2011).