Introduction

Introduction/objective

The majority of the Earth's surface (70%) is covered by water and therefore earthquakes and tectonic activity in that domain are difficult to monitor with modern networks of geophysical instruments (broadband seismological stations, accelerometers, tiltmeters). The use of submarine fiber optic cables to detect seismic waves and to monitor deformation on the seafloor offers the potential for a revolution in natural hazard assessment and early warning capacity related to earthquakes below the sea and active faults on the seafloor. These are the objectives of the **ERC Advanced Grant project FOCUS, funded from Oct. 2018 - Sep. 2023.** The **FocusX1 expedition 6 - 21 Oct. 2020 onboard R/V PourquoiPas?, (Toulon – Toulon)**, is the first part of the work planned in the ERC project (site survey, deployment of a 6-km long fiber optic strain cable using an ROV and deployment of 8 seafloor geodetic stations)**.** The main goal of the ERC project FOCUS is to demonstrate for the first time, the use of **BOTDR laser reflectometry**, to measure **small (1 - 2 cm) displacements across faults on the seafloor** by continuous measurements in real-time, using fiber optic cables and to **calibrate these measurements through other seafloor observations.** The ERC project has three main parteners Laboratoire Géosciences Océan (LGO – CNRS/ Univ. Brest), Ifremer (Unités Géosciences Marines, RDT et Systèmes sous-marins La Seyne sur Mer) and IDIL (a small to medium sized company specialized in fiber optics, located in Lannion). The project is a large scale international collaboration with teams from the physics institute INFN-LNS Catania, providing access to their cabled seafloor observatory infrastructure (Test Site South) 25 km offshore Catania, Univ. Catania, INGV Rome, Geomar, Kiel, Germany (who in Sept. 2020 deployed a network of 6 seafloor geodetic stations using the R/V Sonne to better quantify displacement along the target fault offshore E Sicily). Additional marine expeditions are planned over the next 3 - 4 years, to recover seafloor instruments and to download data at regular (roughly yearly) intervals, in cooperation with these international partners (Italian, German), who are also performing marine operations in the area. The **FocusX2 expedition**, (submitted in Sept. 2019 and ranked first priority P1) may be scheduled for early 2022. The work performed by the FocusX1 cruise together with future marine expeditions in the area are expected to shed new light on the fault behavior of the North Alfeo Fault, a mere 20 - 30 km from Catania, an urban center of 1 million people and thereby help constrain plate tectonic movements, local and past seismicity and seismic hazard of the study region.

Seismicity

The vast majority (90%) of **earthquakes** occur in subduction zones immediately **adjacent to the coasts** of continents and island chains, which are commonly heavily populated. Other active faults (strike-slip faults) may have on-land and **offshore** portions **near major urban centers**. Prominent examples include the San Andreas Fault (San Francisco, Los Angeles) or the North Anatolian Fault (Istanbul). In all of these cases, most of our knowledge regarding the offshore faults is obtained by onshore networks of instruments, supplemented by marine geophysical surveys. In particular, combined geodetic and seismological networks have been key to increasing our fundamental understanding of the different types of slipping mechanisms that a fault uses to relieve stress (tremor, low frequency events, etc.). In some exceptional cases, temporary networks of offshore instruments (e.g. Marsite project in the Marmara Sea), usually deployed for limited periods of time (a few months to at most a few years) can provide additional data. In recent years permanent networks of instruments have been established offshore densely populated, high-risk regions of industrialized countries (DONET - Eastern Japan offshore cable tsunami early warning network, NEPTUNE - observatory offshore the Pacific NW of the USA and Vancouver Island Canada). Although, offshore, cabled observatories provide important observations (including seismological data in real time) and improve early warning capabilities, they are very costly and cannot be deployed in all geo-hazard zones around the world.

Mediterranean

The densely populated Mediterranean region straddles the plate boundary between Africa and Eurasia, which produces moderate to strong seismicity in many countries (Fig. 1). There have also been numerous deadly and **catastrophic earthquakes (>20,000 victims)** throughout this region over the past several centuries. Four of the six deadliest of these (Catania Italy 1693, Algiers Algeria 1716, Lisbon Portugal 1755, Messina Italy 1908) triggered strong tsunamis (≥5-10 m) and almost certainly ruptured a major fault offshore (Fig. 1). To this day the exact **locations of the faults** that produced these 4 catastrophic earthquakes are still **unknown** or hotly debated. Furthermore, the **displacement rates and the nature of movement (aseismic slip, slow slip events, earthquake)** along the candidate faults remain **uncertain**.

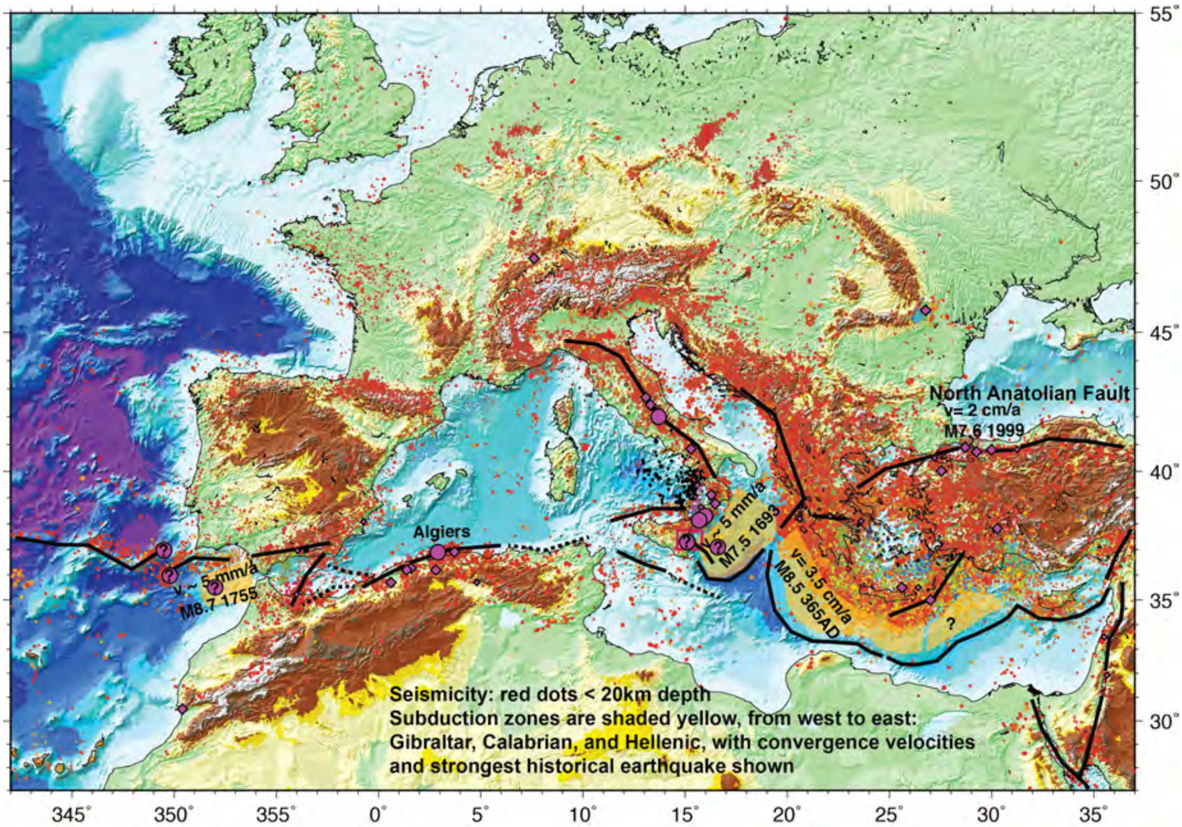


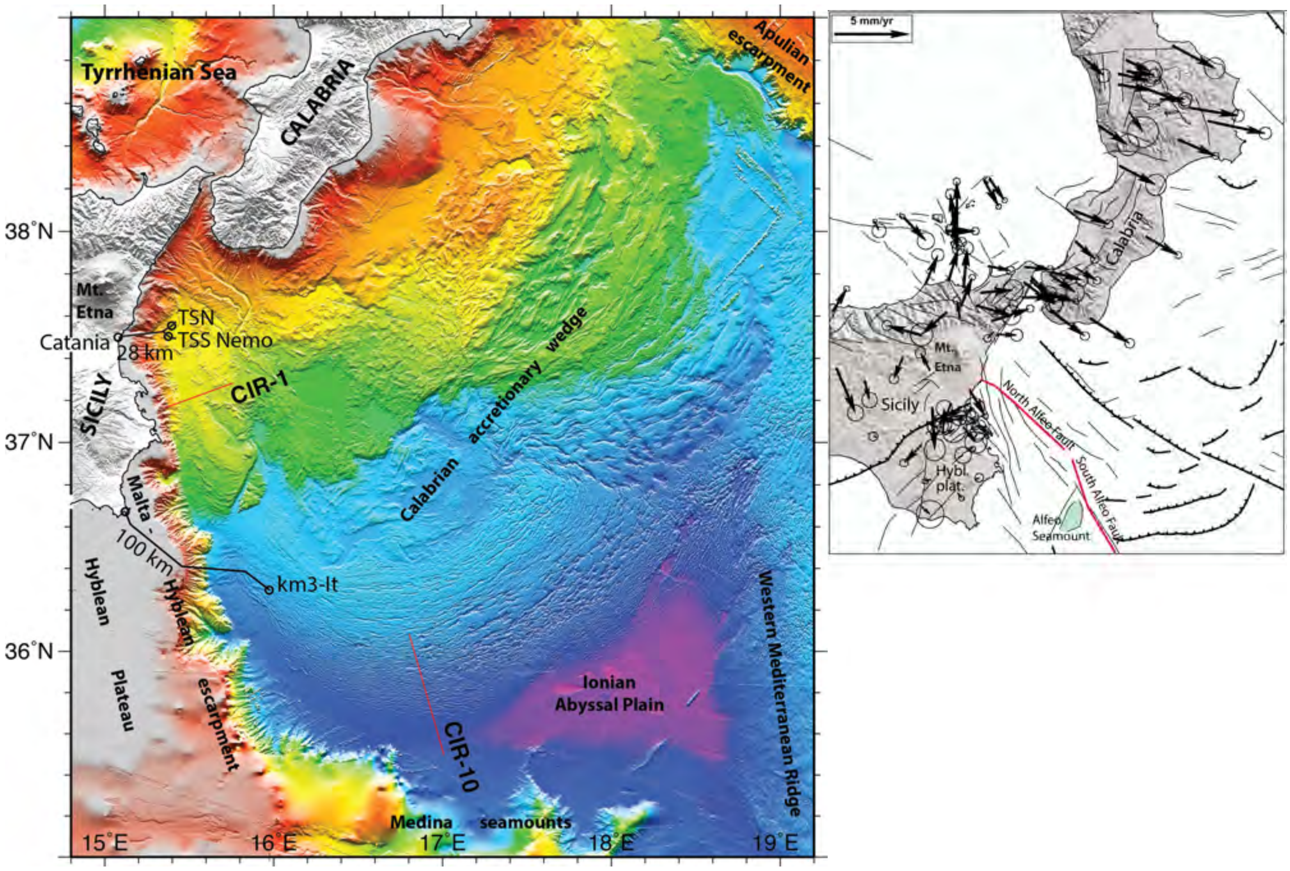
Figure 1: Europe - Mediterranean region with seismicity from 1973 - 2016 (M 2.5 - 7). Small and medium sized purple diamonds are deadly historical earthquakes with >100 and >1000 victims, respectively. Large purple circles show catastrophic historical earthquakes (>20,000 victims). The major segments of the Africa - Eurasia plate boundary are shown as black lines (dashed where uncertain).

The **deadliest region in the Mediterranean is Eastern Sicily - Calabria** (southern Italy), with 200,000 victims in the past 500 years. On a small scale it is representative for most of the Mediterranean since it is characterized by a complex tectonic setting, with several independently moving micro-plates or blocks interacting, and a network of faults in the nearby offshore zone, whose exact kinematics (direction and speed) remain very poorly constrained (Fig. 2B). It also presents the great advantage that **two fiber optic cables are already deployed here on the seafloor** connecting Seafloor Observatories managed by INFN-LNS (physics institute in Catania) (Fig. 2A). East Sicily is therefore the **ideal study area for the FOCUS project expeditions to develop and test a novel approach to monitor active submarine faults**.

Primary target area offshore East Sicily: State of the art and results of previous cruises

Over the past decade, there has been a major international research effort to better understand the tectonic activity of the Calabria subduction zone, its relation to **crustal faults along the East Sicily margin** and the possible connection to the **strong historical earthquakes** that have devastated the region in the past centuries. Numerous studies used GPS stations on land to better understand the active tectonics of the region and the relative displacement rates between the different blocks (d'Agostino et al., 2011; Devoti et al., 2011; Palano et al., 2012). The results indicate slow but significant displacement (3-5 mm/yr) of the Calabrian block towards the south-east, in a local reference frame (Apulia and Hyblea fixed) as well as N-S convergence (a few mm/yr) in eastern Sicily (Palano et al., 2012) (Fig. 2B). Unfortunately, the absence of GPS data offshore, means that submarine faults accommodating this motion cannot be located (Fig. 2B). This hampers tsunami hazard analysis, since land based GPS networks are generally unable to quantify fault coupling for trench zones in marine environments, e.g. Japan Trench (Loveless and Meade, 2011).

Figure 2: (next page) (A - left) Eastern Sicily - Calabria region (Ionian Sea), onshore (white and gray) and offshore in color. Bathymetry is from a recent regional compilation (Gutscher et al., 2017). The positions of the two submarine fiber optic cables are shown (Catania - Nemo and SE Sicily km3-It). The location of two CIRCEE seismic lines is shown (red lines). (B - right) GPS vectors (on land) from a recent study (Palano et al., 2012), (with the Alfeo faults shown). A 3-5 mm/yr movement of the Calabrian block to the SE is observed with respect to the Hyblean plateau (SE Sicily). 3-4 mm/yr of convergence also occur between SE and NE Sicily. In both cases it is unknown how these relative motions continue offshore.



Seismic imaging, bathymetric mapping and sediment coring

Several studies presented the results of deep-penetration multi-channel seismic reflection profiles, which through modern processing techniques have revealed more about the geometry and lithology of the units involved in the Calabrian subduction. These seismic profiles imaged the sedimentary succession in the Ionian abyssal plain (i.e. - old, Tethys age, oceanic northern portion of the African plate) as it is compressed, deformed and tectonically thickened to produce one of the world's thickest and widest accretionary wedges (about 250 km down-dip width, and up to 15-20 km thick) (Minelli and Faccenna, 2010; Polonia et al., 2011; Gallais et al., 2011; 2012; Gutscher et al., 2016; 2017; Maesano et al., 2018) (Fig. 3).

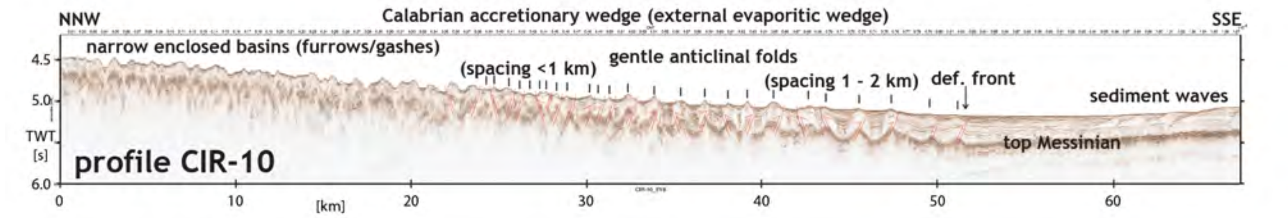


Figure 3: Seismic profile CIR-10 showing folding and thrusting in the external (post-Messinian) portion of the Calabrian accretionary wedge indicating ongoing shortening (Gutscher et al., 2017) (Location Fig. 2a)

Major discontinuites revealed near the western boundary of the accretionary wedge and close to the East Sicily margin are thought to be the expression of crustal scale faults (Hirn et al., 1997; Nicolich et al., 2000; Argnani and Bonazzi, 2005; Polonia et al., 2011; Gallais et al., 2013). Several new marine geophysical surveys were conducted in the following years in order to further investigate these crustal faults and search for the expression of an expected lateral slab edge tear fault. Among these surveys was the CIRCEE expedition (R/V Suroit Oct. 2013, PI Gutscher - see Figs. 3 and 4). Results from these **recent surveys document a network of major strike-slip faults** expressed in the morphology and **bathymetry of the seafloor** (Gross et al., 2016; Gutscher et al., 2016; 2017) (Fig. 2A, Fig. 5A), as well as in **high-resolution seismic profiles revealing strongly focused deformation** of the sedimentary layers below and adjacent to these faults (Fig. 4, Fig. 5B,C). These profiles, crossing the North Alfeo Fault in the target study area, image a **single, distinct vertical fault trace (**with no subsidiary fault splays), which **offers the perfect target for geodetic and strain measurements on the seafloor (**Fig. 5B,C).

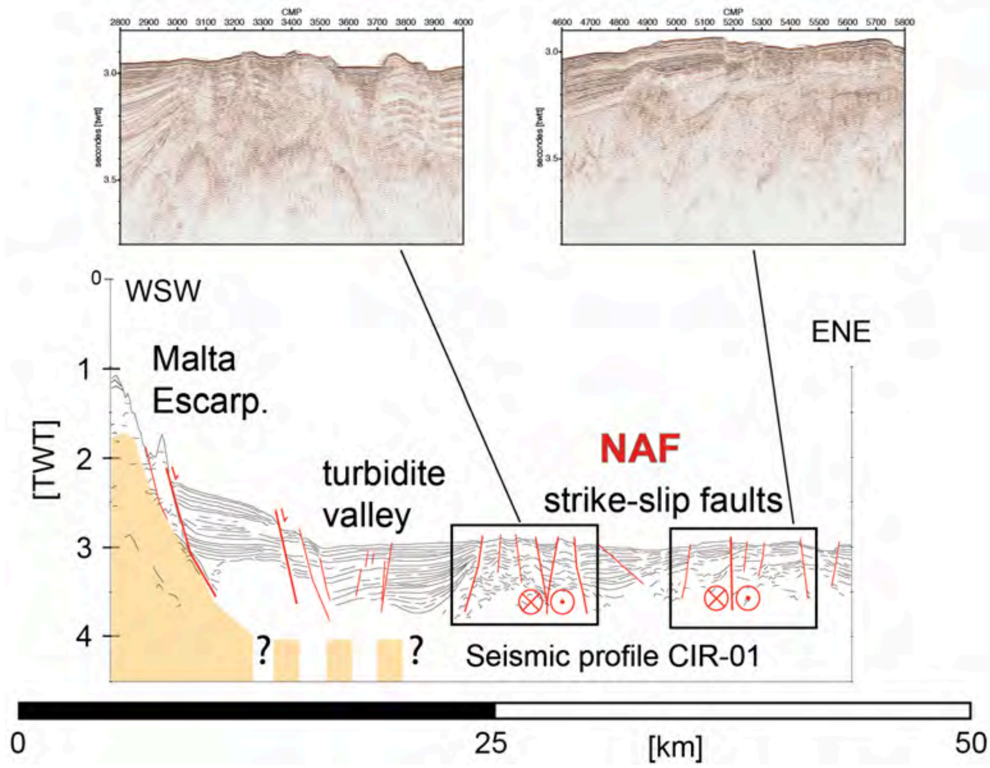


Figure 4: Seismic profile CIR-1, with a line drawing (below) and close-up of zones cross-cut by strike-slip faults (Gutscher et al., 2016). NAF = North Alfeo Fault. For location see Fig. 2A.

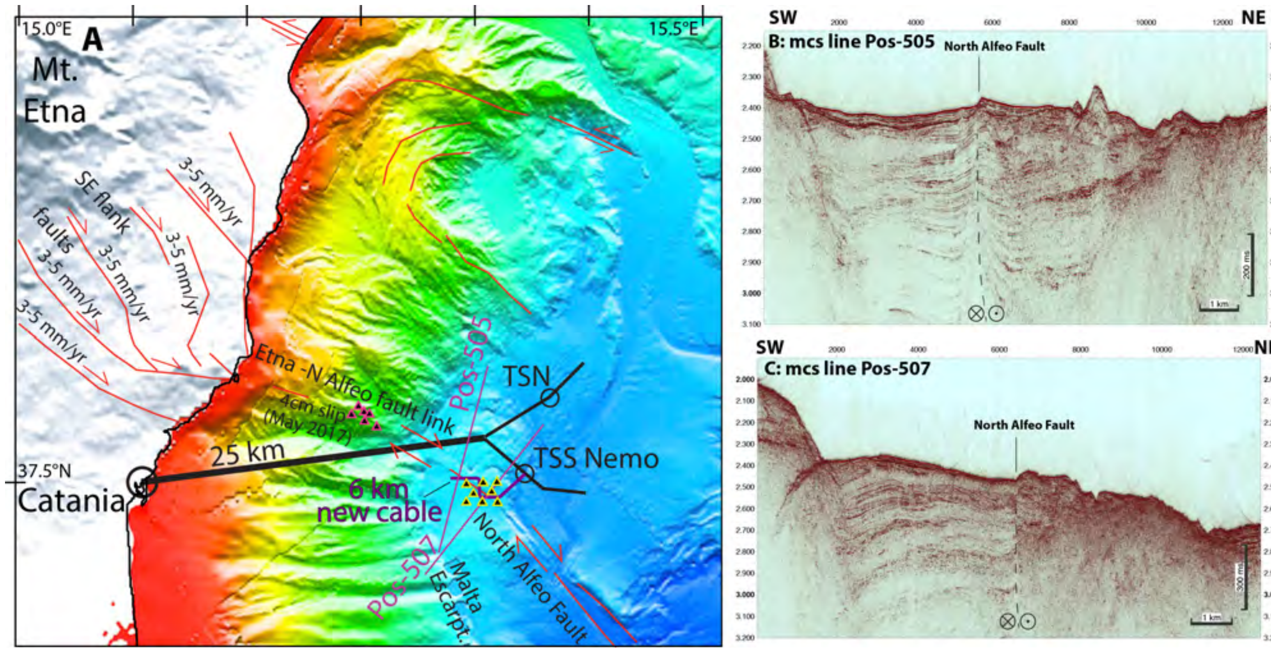


Figure 5: A: Relief map of the Catania - Etna region (NE Sicily), onshore (in gray) and offshore (in color) (Gutscher et al., 2017) showing the position of the Catania EMSO cable, connected to seafloor stations TSN and TSS Nemo (Neutrino observatory). The faults on the SE flank of Mt. Etna connect offshore with the North Alfeo Fault. Small magenta/black triangles show the German (Geomar) network of seafloor geodetic stations deployed 2016 - 2017 (Urlaub et al., 2018). This network was redeployed in Sept. 2020. Small yellow/black triangles show network of 8 geodetic stations purchased by the ERC FOCUS project and planned to be deployed during the FocusX1 expedition. The initially planned track of the 6-km-long fiber optic strain-cable (shown in purple) crosses the North Alfeo Fault at three positions. B: Multi-channel seismic profiles Pos-505, C: Pos-507 from the Ionian Sea, image the single, vertical fault trace at the junction with the planned strain cable, unpublished data from Poseidon 496 survey, (Krastel et al., 2016).

In 2014, a joint German-French-Italian marine geophysical survey (DIONYSUS), used ocean-bottom seismometers and land-based seismological stations to determine the **deep crustal structure of the East Sicily** margin using wide-angle seismic profiles. The **recently published results (Dellong et al., 2018)** confirm that there is a **major crustal scale discontinuity offshore E Sicily** corresponding to the surface expression of a strike-slip fault system (the Alfeo fault Fig. 2B). The coastal geophysical survey (CRACK - Aug/Sept 2016) investigated the connection between a network of faults on the SE flank of Mount Etna volcano observed by GPS and InSAR (Bonforte et al., 2011; Chiocci et al., 2011; Palano et al., 2016; Murray et al., 2018; De Guidi et al., 2018) and the crustal scale North Alfeo fault located further offshore (Figs. 5A, 6A). From 2016 - 2017, **5 seafloor geodetic stations recorded slip along this fault link** (Urlaub et al., 2018) (Fig. 5) and these results are described below. On 26 Dec. 2018 a shallow M4.8 earthquake occurred on the Findaca fault on the SE flank of Mt. Etna, part of the onshore prolongation of the North Alfeo Fault system, with ~30 cm of dextral strike-slip motion (De Novellis et al., 2019).

Results of seafloor geodetic study

An array of five seafloor geodetic instruments, was deployed by Geomar and the Univ. of Kiel with the R/V Poseidon along the offshore continuation of strike-slip and normal faults accomodating a gradual eastward gravitational collapse of the SE flank of Mt. Etna (Fig. 5A, Fig. 6A) (Urlaub et al., 2018). This network was deployed in April 2016 in water depths of 900 - 1200 m and data recovered in July 2017. Analysis of baseline length changes during this 15-month period indicates **a dextral strike-slip movement of 4 cm** (Fig. 5B) along the fault trace (Urlaub et al., 2018), with nearly all the movement having occurred during a **slow slip event in May 2017**. The cumulative motion of the Etna flank faults (Fig. 5A) is about 2 cm/yr (Bonforte et al., 2011). The slip observed by the seafloor geodetic network indicates **an active submarine fault ~20 km to the east of Catania, an urban area of 1 million people**, and crossed by the Catania submarine cable (Fig. 5A). The seismic hazard posed by this major fault and its deep offshore continuation, with a total length of ~80 km (Fig. 2B) (Gutscher et al., 2016; 2017), unknown prior to 2010, has yet to be properly estimated. The FOCUS project can provide a major contribution to this seismic hazard assessment by measuring the spatial variation in coupling (i.e. the degree to which the two sides of the fault are locked/sliding) along the fault and by quantifying current slip rates.

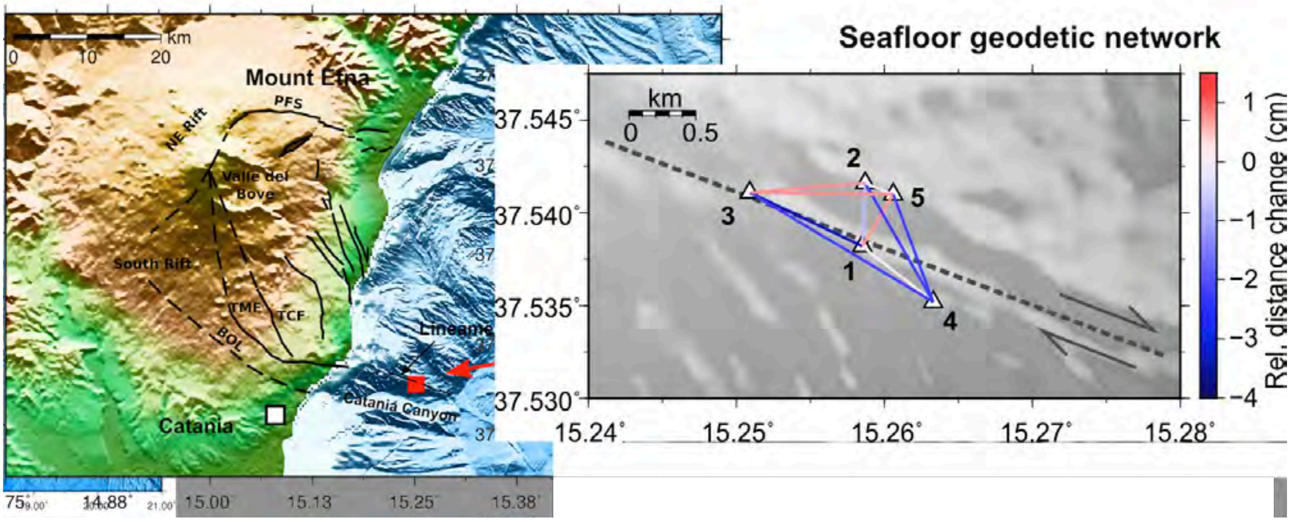


Figure 6: A left): Regional map showing position (red square) of seafloor geodetic network deployed offshore Catania / Mt. Etna (Apr. 2016 - Aug. 2018) by Geomar and Univ. Kiel (Urlaub et al., 2018).
Figure 6: B (right): change in base-line lengths over 15-months (Apr 2016 - Jul 2017) with 4 cm of dextral strike-slip movement detected between the NE stations (2 and 5) and the SW stations (3, 1 and 4), and interpreted to have occurred during a 5-8 day slow slip event in May 2017 (Urlaub et al., 2018).

Fiber optic cables and monitoring technology

Laser reflectometry techniques permit the use of fiber optic cables to measure fluctuations in temperature and in strain. These techniques are widely used for structural health monitoring of large-scale infrastructure (bridges, hydro-electric dams, tunnels, cooling towers of nuclear power plants, wind turbines, pipelines, skyscrapers, train tracks, etc.) (Fig. 7A). There have also been some studies regarding specific geo-hazards on land, e.g. monitoring slow creep of a landslide (Sun et al., 2016) or collapse of roadways over karst (sink-holes in limestone) (Jiang et al., 2016). One study has successfully applied this technique to monitor a submarine power cable connecting two Chinese islands (Zhao et al., 2014). An earlier study tried measuring seafloor displacement across an incipient submarine landslide offshore Santa Barbara California using a strain sensor cable (operating as a Michelson interferometer) but proved “unsuccessful in several attempts” due to “broken fiber cable” during deployment (Blum et al., 2008). Thus, to this day, there are no documented examples regarding the use of laser reflectometry for monitoring of submarine faults.

Recently, DAS (distributed acoustic sensing) using on-land fiber optic cables and Rayleigh laser reflectometry has been demonstrated for earthquake detection and recording (Lindsey et al., 2017; Jousset et al., 2018). Similarly, ultra-precise metrology using laser interferometry on both onshore and offshore fiber optic cables, has for the first time, successfully observed earthquakes (Marra et al., 2018).

BOTDR (Brillouin Optical Time Domain Reflectometry) is performed by firing a laser pulse from one end into an optical fiber (Fig. 7B). As laser light diffracts off microscopic imperfections in the fiber it produces several characteristic peaks (Rayleigh, Brillouin and Raman) (Fig. 7C). The Rayleigh peak is sensitive to short period strain (vibrations), the Raman peak varies with temperature, and the Brillouin peak varies with both strain and temperature. If the fiber has been subjected to strain, the Brillouin spectrum will vary between successive measurements (Fig. 7C) at the distance along the fiber corresponding to the position where this change occurred. Under optimal conditions, **strains of 50 µm/m, (1/3rd the thickness of a human hair), can be measured at distances of several tens of km, and located to within 1 m** (Maraval et al., 2017). These detection limits are **2 orders of magnitude better than typical land-based GPS techniques**. Testing BOTDR in a deep-sea offshore environment is a great technological challenge and requires an elaborate seafloor experiment as performed during the FocusX1 expedition. A demonstration of this method could revolutionize the study of submarine faults, plate tectonics and earthquake hazard, and help improve early warning capability.

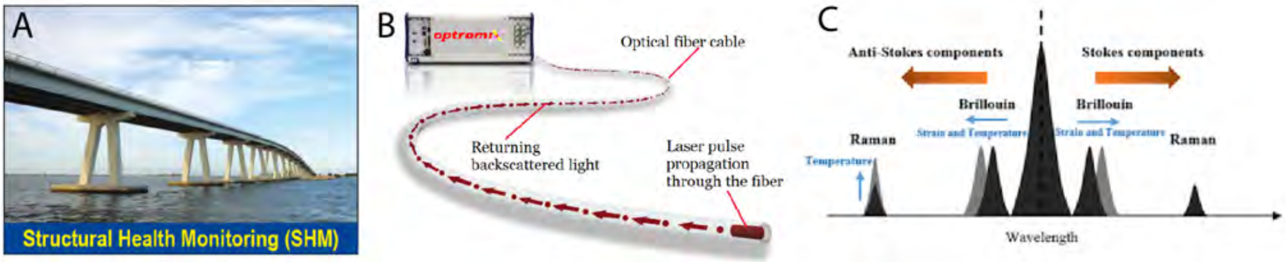


Figure 7: Large-scale infrastructures and BOTDR monitoring, A: SHM - example of bridge, B: Principle of backscattering and BOTDR, C: Types of backscattering during laser reflectometry (Rayleigh - central peak, Brillouin and Raman). The Brillouin spectrum of a given fiber shifts as a function of temperature and strain.

The main goal of the FOCUS project is to measure small displacements/strain across the North Alfeo fault using laser interferometry on fiber optic cables. Further instrumentation is required to validate that any observed variations in strain are due to tectonic processes, to classify them correctly and to quantify (calibrate) them. A variety of instrumentation ranging from geodetic (slow slip, afterslip, aseismic slip) to seismic (earthquake, slow slip events) will be required to best capture different slipping modes (Fig. 9). The primary objectives of the FocusX1 cruise (6-21 October 2020) were to deploy a prototype fiber-optic strain cable and 8 seafloor geodetic stations across an active submarine fault.

The FocusX1 expedition

Overview of planned operations

The R/V PourquoiPas arrived in the study area around 0:00 (local time) on 10 October 2020. The preliminary plan of operations was as follows:

1 - 2 hrs of hull-mounted swath-bathymetric mapping of the regional study area (covering the Etna - North Alfeo Fault system);

2 - 2-days of micro-bathymetric mapping of the local study area (seafloor observatory, planned cable track and 3-km long segment of the North Alfeo fault) using the ROV Victor6000 Reson system;

3 - 0.5 days video-camera survey of the seafloor along the potential track of the cable and along and across the submarine fault;

4 - Deployment and connection of a Y-splice junction box (Y-JB), to the cabled seafloor observatory Catania Test Site South (TSS) station in 2060 m water depth;

5 - Deployment of the Deep Sea Net plow (version 2020) and the cable end-module (CEM) including the 6.2 km length of fiber-optic strain cable on the drum (reel) to the seafloor and connection of the CEM to the Y-JB;

6 - Plowing operations using the ROV Victor6000 to deploy the cable along the selected track and bury the cable 20cm below the seafloor in the soft sediments;

7 - Deployment of a network of 8 seafloor geodetic stations (Canopus acoustic beacons, iXblue) mounted on tripods;

8 - visual inspection (with ROV Victor6000) of the orientation of the tripods.

This series of operations was originally scheduled for 8 working days on site. This was considered a dense, ambitious program, but thought to be feasible if all operations went smoothly and if weather and sea conditions were favorable.

Indeed steps 1-5 all went according to plan (despite a few minor technical delays, and some trouble with one of the ODI wetmate connectors). Survey operations were completed by the morning of 13 October. (More details on these surveys are provided below in the sections on bathymetric and micro-bathymetric mapping below.) The first connection of the FOCUS cable via the CEM was complete by 20:30 the same day. However, step 6, the plowing operations proved to be the most challenging.

Difficulties encountered during plowing operations 13-14 Oct. 2020
A short test expedition had been performed with the PourquoiPas and ROV Victor6000 (2-4 March 2020) offshore Toulon in order to perform a run-through of steps 5 and 6, and which included unfolding a "dummy" (replica) CEM, and plowing/burying 500m of cable in soft sediments in 680m water depth (Fig. 8). These tests in early-March ran smoothly. Cable burial was easy at typical speeds of 0.1 to 0.2 m/s (ROV and plow velocity wrt the seafloor). The cable was successfully buried along the entire 500m length, with the sole exception being, when the plow was lifted by the ROV in "obstacle avoidance mode" and instead lain down upon the seafloor as intended. The PI and the ROV team were thus confident plowing operations would run smoothly.

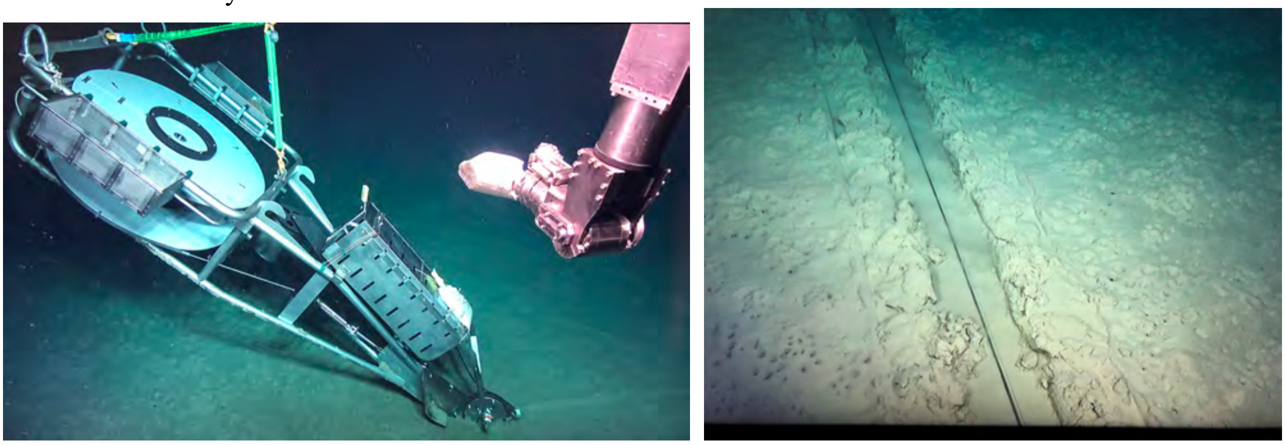


Figure 8: (left) Deep-sea net plow (version 2020) on seafloor during tests on 3 March 2020 offshore Toulon in 680m water depth, with dummy cable-end module (CEM) and ROV arm; (right) plow track with groove (mini-trench) showing successful burial of cable (a test length of 500m was deployed and buried)

Unfortunately, mid-October 2020 in 2000m water depth offshore Sicily, plowing operations turned out to be unexpectedly difficult. To begin with it was much more complicated trying to establish the ideal (proper) buoyancy for the ROV Victor6000 and the plow/drum system holding 6200m of 9-mm cable. The weight of the plow in water is about 400kg and the weight of the cable in water is 37 kg/km, which means that the combined weight in water was about 630kg. In order to compensate the weight of the deployed cable length coming off the drum (reel) it was necessary to add 50kg of ballast (small metal beads in 25kg bags - weight in water) about every 1.5km. Naturally, all of this had been calculated beforehand. However, something did not add up properly and the plow-ROV system proved to be much too heavy at the beginning and unable to move forward. So 4 x 25kg bags had to be removed before the plow could be moved by the ROV. In general the physical properties of the sediments in 2000m water depth in the Ionian Sea appear to be far more sticky and cohesive than those offshore Toulon and it was exceedingly difficult to advance. We were at the maximum energy capacity of the ROV and barely able to get the plow to move forward. But there were soon far more serious problems to be encountered…

Brake system malfunction
The brake-system on the plow-reel, which is activated by a spring on a small tension cylinder, malfunctioned and fell off the edge of the reel (we discovered this later) (see Fig. 9). There were several reasons for this (which we also discovered later) among them : 1 - the stickiness of the sediments and the excessive weight of the entire plow-cable system led to a jerky (start and stop) type of motion when advancing, and the spring mounted cylinder would swing widely and wildly back and forth (this system was connected directly to the thin metal band which is the brake mechanism), 2 - two additional guide pins (metallic pins the length and thickness of human fingers) which were in use during the tests in March 2020 were rendered non-operational

by the large weight of the 6.2km of cable on the fiber-carbon reel, which caused it to deflect (bend) by 1.5cm downward (onto these metal guide pins). The metal guide pins (now obstructing the reel) had to be removed, which freed (and greatly destabilized) the thin metal band - the brake itself. (This modification had occurred onshore, weeks before when mounting the reel, fully loaded with the 6.2km of cable and was unknown to the ROV operators and to the PI.) Shortly after midnight during the night from 13-14 October, after deployment and burial of 500m of cable (and almost certainly after initial damage had occurred to the brake system) the plow-reel system which had been significantly lightened in order to facilitate plowing operations passed over some rugged terrain. The ROV Victor6000 became detached from the plow. Normally this is not a problem (the plow is designed for this - to be disconnected and reconnected at will). This time, however, the plow was too light and the brake system had failed and therefore there was no restraining tension. So the plow simply "took off" and started rising from the seafloor, with the cable unspooling smoothly (and uncontrollably) behind - a bit like when a child loses his helium balloon at a fair or amusement park. The plow "flew" up to about 20 - 30 m above the seafloor at which point several coils (about 5 - 6) from the drum had come off the drum and a few had gotten stuck below the drum, getting wedged against a square metal plate near the axis of the drum (see Fig. 9). This is probably what stopped the plow from rising even further. Soon thereafter ROV Victor6000 was able to transfer two or three additional ballast bags (25 kg each) to the baskets on the plow. The plow/drum system was now once again heavier (than water) and it sank back to the seafloor. There followed a series of desperate (but futile) attempts to try to replace the fallen coils back onto the drum using the ROV's manipulator arms. We observed and finally understood the severe damage and total incapacity of the brake system (Fig. 9) and realized the implications of the small coils wedged under the square plate near the reel axis. We thus decided that the only hope was to attempt to disconnect the CEM and to salvage the plow, the 5.7 km of cable still on the plow, and the 500 m of deployed cable, and to raise all of this equipment from the seafloor back onto the deck of the PourquoiPas. And that is exactly what happened next.

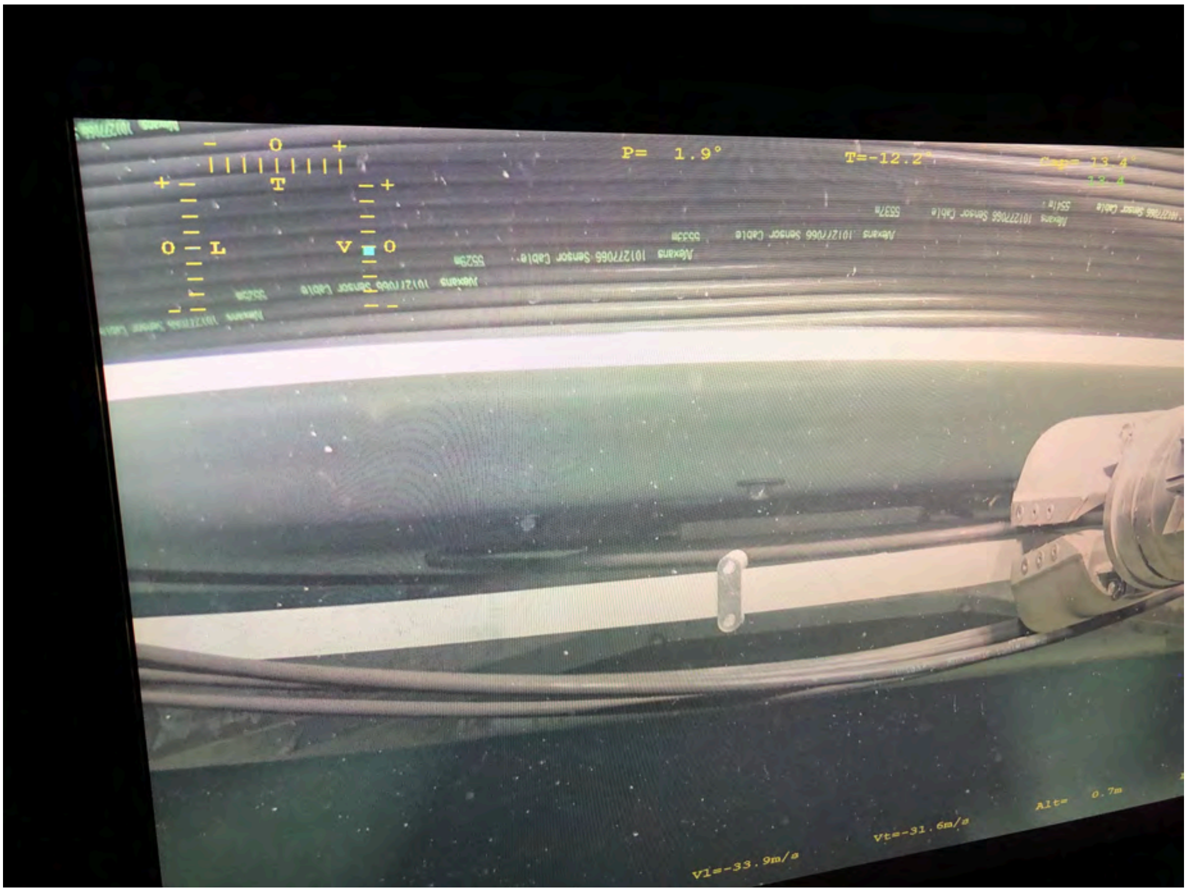


Figure 9: Disaster strikes - the incapacitated plow/drum system with 5-6 coils fallen off and the brake mechanism fallen off as well. (It is the thin curved metal band being held by the ROV arm-grip and is supposed to be in place on the lower circular edge of the reel, about 15-20 cm higher). One or two smaller coils can also be seen wedged into the square metallic plate at the axis of the reel.

It is far simpler to write these words and to describe these actions, than it is to undertake such delicate and complex seafloor operations in 2000 m water depth. It is a testimony to the ROV team and the deck crew of the PourquoiPas, that using the tools, cords, and wraps available to the ROV (sent down from the surface first of course) that they were able to secure the cable drum (so it would not spin and lose even more cable) and secure the 5m umbilical cable (between the CEM and the ODI wetmate connector) and raise it all from the seafloor and get it on deck safely. In particular I have to point out with astonishment (and great relief at the time) that they were able to hoist the 500 m of already deployed cable to the surface, and then to coil it smoothly (at first in very long loops and later in roughly 5 m long coils) without the cable getting uncontrollably tangled. So while we started planning repair operations we proceeded to step 7 - the deployment of the network of 8 geodetic stations.

Network of geodetic stations

The network of 8 geodetic stations, Canopus acoustic beacons mounted on tripods, were deployed next (Fig. 10, left). A separate section below describes the geodetic network and the deployment operations in more detail. Suffice it to say here that the 2.5 - 3.0 m high tripods were lowered by winch to the seafloor and released gently, one by one, at the target locations which had been identified following the micro-bathymetric mapping (Fig. 10, right).

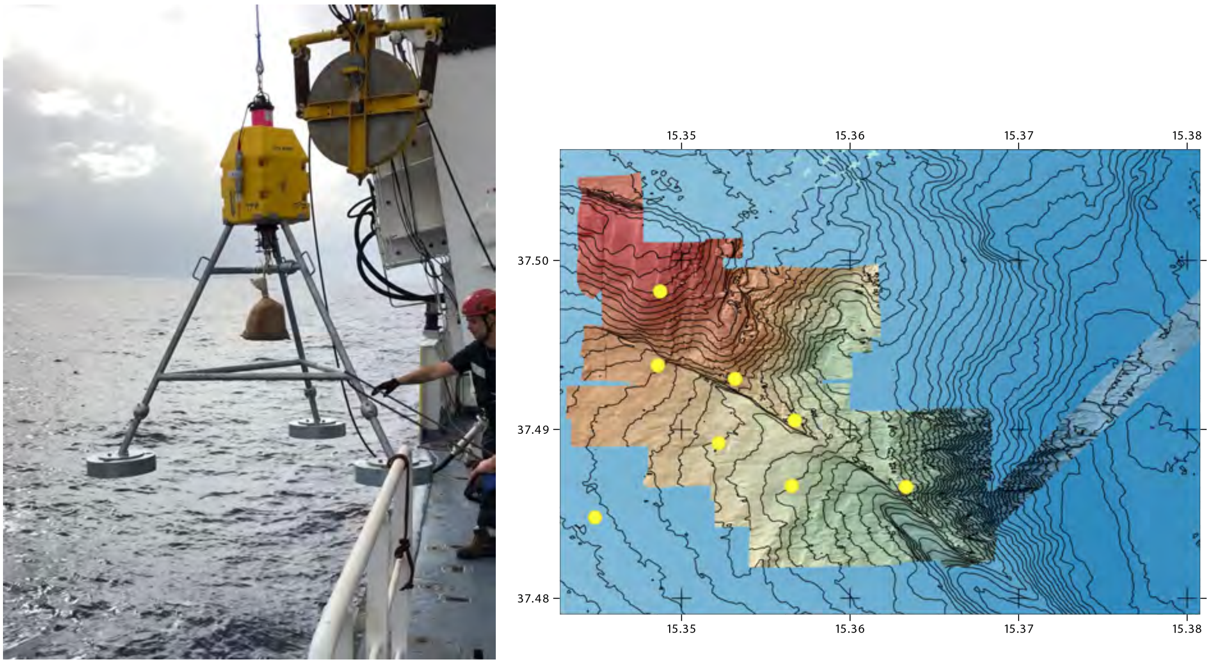


Figure 10: (left) deployment of a sea-floor geodetic station, with Canopus acoustic beacon (the pink cylinder visible at the top), buoyancy (yellow polyhedral cover) and the metallic tripod; (right) map of study area, with the micro-bathymetric data (ROV Victor6000) and showing the location of the 8 seafloor geodetic stations deployed (yellow circles), 4 to the north of the fault, and 4 to the south.

Cable connection and deployment - a second chance

Significant improvements were made (by the ROV team and the onboard crew) to the Deep Sea Net plow (2020 model), which included adding two PVC cylinders just below the edge of the carbon-fiber reel, designed to keep the brake (metal band) in place, adding a restraining bar to limit the angular range of the spring attached to the reel and to the brake, which had been swinging by up to nearly 90°, and adding two 15cm high PVC pins (about 1cm in diameter) at the interior (vertically), yet outermost edge (radially) of the reel in order to capture (hold/restrain) any potential coils that might slip off and fall down from the stack on the reel. Finally a smooth, flat PVC plate was added covering the entire lower surface of the "ski-runners" on either side of the plow blade (in order to try to reduce the friction with the sticky sediments). The 500 m of loose coils were respooled onto the reel (by hand, by a team of about 10 people) and we were now ready to make a second attempt at deploying the 6.2 km long cable. The plow and CEM were deployed safely to the seafloor, the cable-end module was unfolded, the ODI wetmate connector was successfully inserted/connected to port C (Fig. 11) and a good optical connection was established. While plowing operations once again proved difficult (finding the right buoyancy, getting the plow to move forward, stockpiling and retrieving the ballast bags in order to compensate the unreeled/deployed cable) overall the cable deployment progressed for the most part as planned.

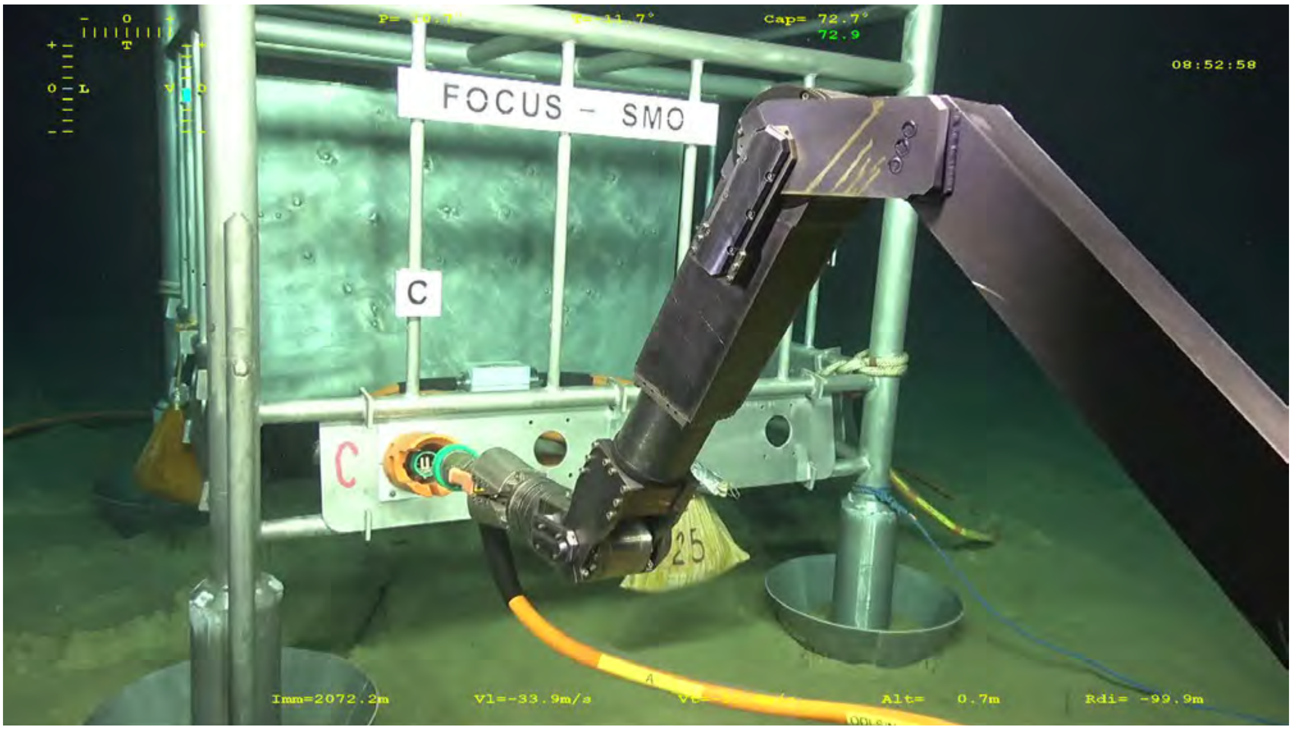


Figure 11: connection of the umbilical from the cable-end module, via the ODI wetmate connector to the Y-junction box using ROV Victor6000 (manipulator arm Maestro).

Figure 12: Deep Sea Net plow (model 2020) on the seafloor. Most of the 6.2 km long fiber-optic cable can be seen, spooled on the reel (drum).

One of the major challenges was attempting to bury the cable in the soft, unconsolidated seafloor sediments, using the plow, particularly when passing through rough terrain. There is a rugged east facing slope rising from about 2050 m to 1900 m and incised by E-W oriented gulleys (Fig. 10, right). This slope has an average incline of 15-20°, with numerous rounded blocks, escarpments and locally vertical cliffs. The same is true for the fault scarp associated with the strike-slip fault (the North Alfeo Fault) our target structure. This 10-20m high linear feature is systematically marked by rugged terrain and slopes of 15-30°. It was impossible to bury the cable when crossing the fault and as a result we deployed the cable in "obstacle avoidance mode" laying it down across the top of the rugged seafloor.

Figure 13: (left) blade of the plow in rough terrain (obstacle avoidance mode); (right) plow track in soft, flat sediments, after successful burial of the 9mm diameter fiber optic cable (note small fish at right).

BOTDR (Brillouin Optical Time Domain) laser reflectometer experiments:

Two BOTDR interrogators purchased for the FOCUS project were used during the course of the cable deployment operations and thereafter. The VIAVI BOTDR interrogator was first connected (in late January 2020) to the existing 29 km-long fiber optic cable operated by the physics institute LNS, linking the seafloor observatory Test Site South (TSS) to the laboratory facility at Catania port. Since May 2020 the VIAVI BOTDR interrogator has been performing uninterrupted monitoring of this 29 km long submarine cable. The VIAVI BOTDR was in continuous operation during the cable deployment (mid-October 2020) during the FocusX1 expedition to monitor the quality of the optical connection as well as the progress of the cable deployment. A few examples of BOTDR data acquired during October 2020 are shown below.

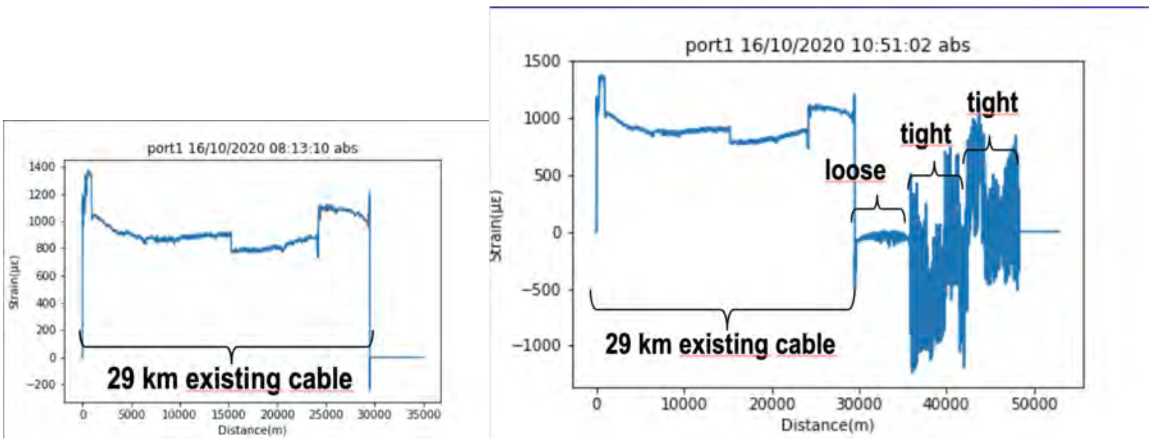


Fig. 14: (left) BOTDR absolute baseline (acquired on 16 Oct. 2020 at 8:13 local time) of the existing 29km long cable extending from the the Catania port laboratory to the seafloor observatory TSS; (right) BOTDR absolute baseline (acquired on 16 Oct. 2020 at 10:51 local time, just after connection of the FOCUS optical chain) of the existing 29km long cable and the three-part loop of fibers in the 6.2km long FOCUS cable, first a loosely bound fiber (in the external armoring tube), then a tight fiber (in the core) and lastly another tight fiber in the core. The complete optical path is thus ~48 km.

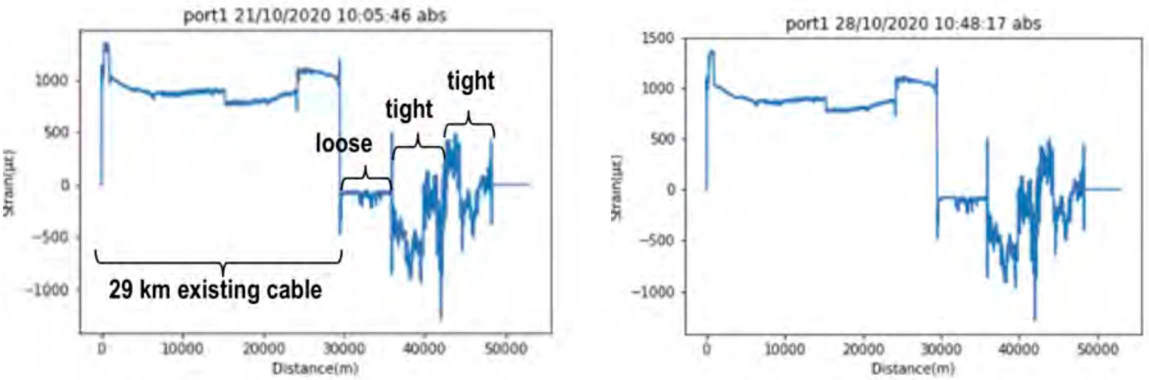


Fig. 15: (left) BOTDR absolute baseline (acquired on 21 Oct. 2020, 3 days after cable deployment); (right) BOTDR absolute baseline (acquired on 28 Oct. 2020 after installing new software on VIAVI interrogator), There is no discernible difference between the two measurements.

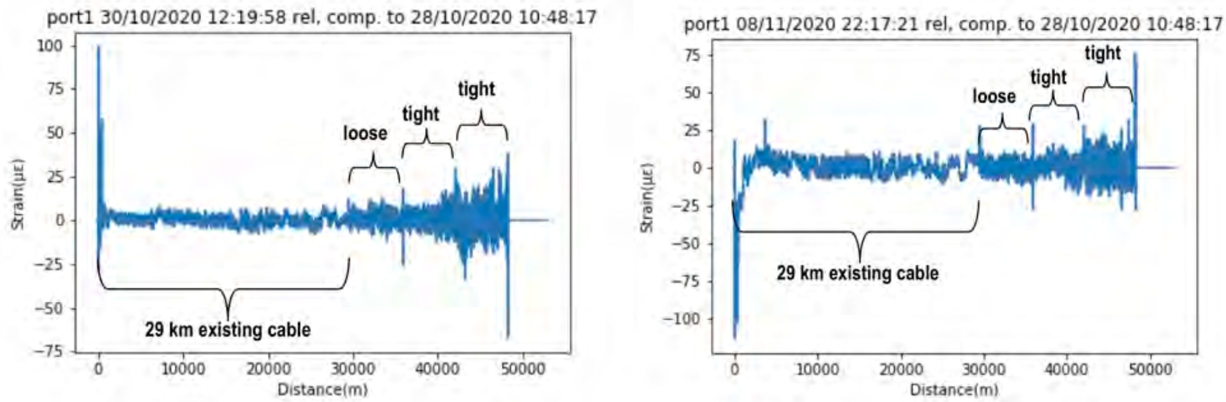


Fig. 16: (left) BOTDR relative strain measured on 30 Oct. (compared to 28 Oct. baseline) along the entire 48 km optical path; (right) BOTDR relative strain measured on 8 Nov. (compared to 28 Oct. baseline) along the entire 48 km optical path. The noise level is about ±5-10 microdefs for the loose fiber, and about ±10-20 microdefs for the tightly bound fibers, increasing progressively beyond 40km distance.

DAS (Distributed Acoustic Sensing) laser reflectometer experiments during FocusX1 expedition:

Together with Philippe Jousset (GFZ Potsdam) and INFN-LNS Catania port laboratory of the INFN-LNS a new laser reflectometry experiment (not mentioned in the original shiptime proposal FocusX1 submitted Sept. 2018, but involving no days of additional shiptime) was performed using the DAS (distributed acoustic sensing) technique on the existing 29 km submarine cable in early October 2020. During the FocusX1 expedition and the subsequent connection of our new 6-km long cable, the entire length was also interrogated by the DAS technique. DAS is based on continuously measuring the Rayleigh backscatter (Fig. 7C) and enables a fiber-optic cable to be used a long string of seismometers. It is used by oil industry to perform VSP (vertical seismic profiles) in oil wells and has recently been demonstrated to be capable of recording earthquakes and other acoustic sources (Lindsey et al. 2017; Jousset et al., 2018).

The DAS interrogator was connected to the Catania submarine cable during cable deployment operations. On the one hand this allowed us to confirm the distance (along the cable) out to the plow and provided an independent measure of the amount of cable already deployed (Fig. 17). The DAS data also exhibit strong reverberations / oscillations in certain positions (Fig. 17 and 18), where rugged terrain made cable burial impossible and where the cable is exposed above the seafloor, dangling between two highpoints and thus exposed to seabottom currents causing the cable to swing back and forth. Overall the intensity of oscillations seems to have diminished between the dates 17 Oct. and 21 Oct. suggesting the cable had settled and stabilized somewhat.

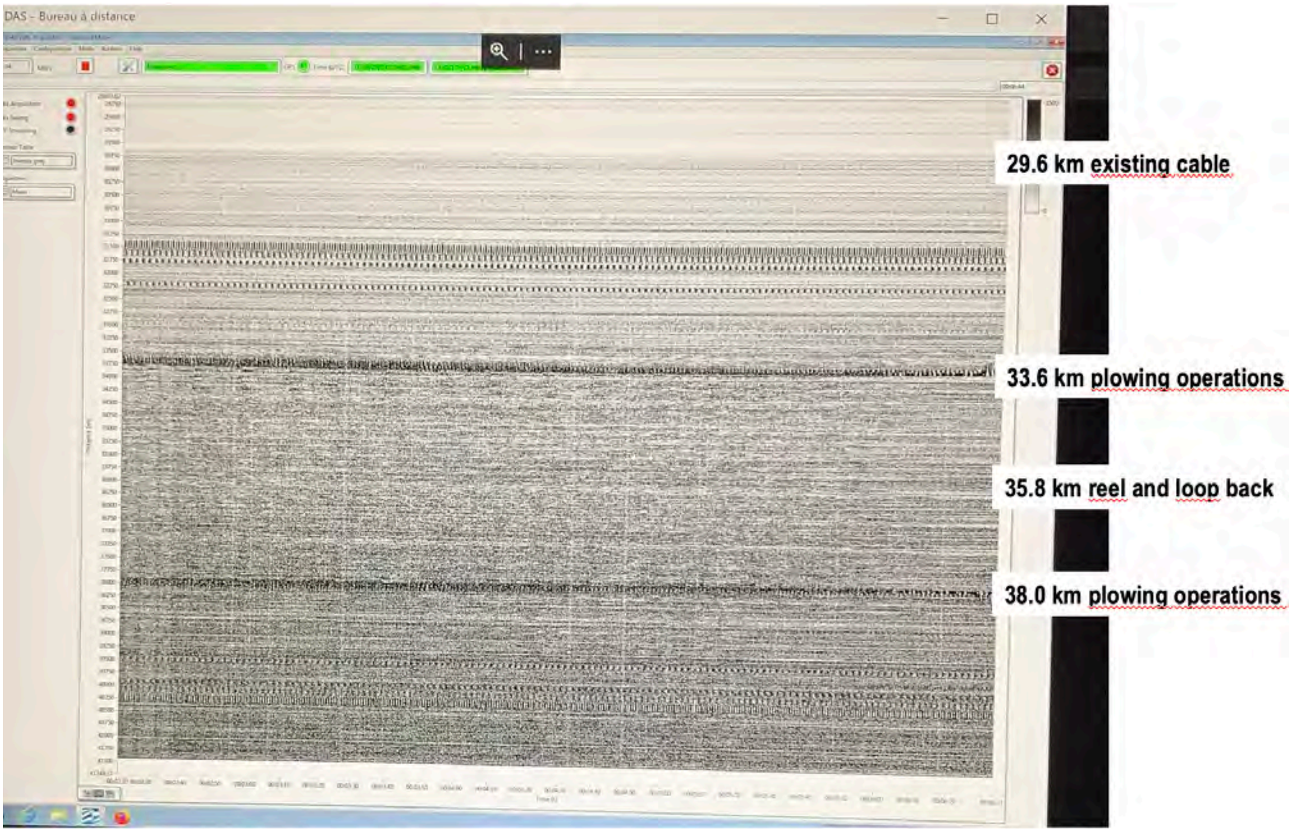


Fig 17: DAS acquisition during FocusX1 cable deployment operations on 17 Oct. 2020. 4 km of cable have been deployed and 2.2 km are still on the reel / drum. Strong oscillations are observed between km 31 and 32 (and the same are observed on the return loop around km 40 to 42).

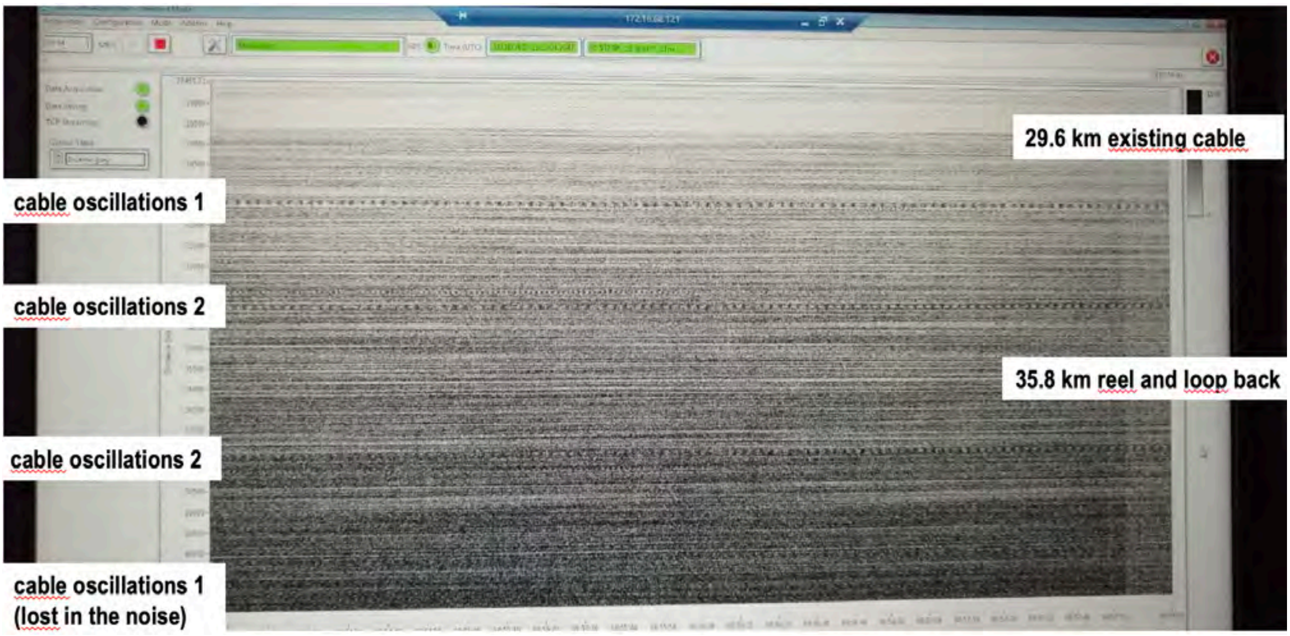


Fig 18: DAS acquisition from 21 Oct. 2020, 3 days after FocusX1 cable deployment operations were completed (on 18 Oct.). Note the symmetric oscillations due to the fiber path out to and back from the plow drum (located at 35.8 km distance from the port laboratory of INFN-LNS in Catania. Noise levels increase significantly beyond 40 km distance.

Bathymetry report (English version)
NB - a more detailed French version describing the processing is included as an annex at the end

The RESON Seabat7150 multi-beam echo-sounder of the Pourquoi Pas.

The Pourquoi Pas? Is equipped with two multi-beam echo-sounders : a RESON Seabat7111 for shallow water and a RESON Seabat7150 for middle and deep water depths (Figure B1). The latter has two frequencies and can be used in 24kHz for middle depths (up to 2500m) and 12kHz for deep water (up to 8000m). During the FOCUSX1 cruise the RESON Seabat7150 was used in the 24kHz constellation.

Figure B1: The RESON Seabat7150 multi-beam echo-sounder at the Pourquoi Pas.

The main features of the SeaBat 7150 are summarised below.
• **Swath coverage.** The system forms up to 855 receiver beams (mode dependent) to cover a total receive sector of 150o.
• **High resolution.** The high-resolution SeaBat 7150 provides beamwidths of 0.5° x 0.5° at 24kHz and 1° x 1° at 12kHz.
• **Beamforming.** The SeaBat Sonar Processor Unit (SPU) performs initial signal processing, time delay beamforming, FM matched filter processing and bottom detection. The sidelobe suppression is better than –25dB, using a modified Chebyshev weighting function.
• **Bottom detection.** The special bottom detection algorithm uses a combination of centre-of-energy and phase-zero-crossing algorithms to be able to detect the bottom in each individual beam with the highest possible accuracy.
• **Transmit focussing.** The SeaBat 7150 utilises focussed transmission to maintain narrow beamwidths when operating in shallow water.
• **Receive focussing.** To offset the nearfield effect, the SeaBat 7150 employs dynamically focused beamforming in a number of pre-determined focal planes. The operator has no control over this process.
• **Multiple pings.** The SeaBat 7150 employs a multi-ping approach to perform motion compensation, transmit focusing and ensuring adequate bottom coverage.
• **FM processing.** Linear FM transmissions are used to improve range performance
• **Pitch stabilization.** The pitch stabilization incorporates transmit beam steering, up to ±10° from vertical to maintain full bottom coverage. This function is essential for achieving full bottom coverage in shallower water.

• **Roll stabilisation.** A roll stabilised bottom detect output may be selected, providing stabilisation to ±15° of roll.
• **Real-time QC display.** The 7150 generates a real-time display with an intensity image on 20” LCD monitor. Overlaid on this intensity image is the bottom detect display giving an excellent QC tool for the operator.
• **Built-in-Test Equipment (BITE)** is an integral part of the SeaBat processor unit, monitoring status of internal sub-systems as well as that of the transceiver and acoustic arrays.

Depth ranges and coverage of the Seabat7150 multi-beam echo-sounder :
The resolution of the Seabat7111 is 2°x2° for the is seabat7150 in 12kHz mode and 1.9°x1.5° in 24 kHz mode. The vertical resolution for deep sounding echosounders is generally about 0.05% of the water depth. It can reach several meters and up to 10m in large water depth for the external beams, decreasing resolution in the outer parts of the swaths (Figure B2).

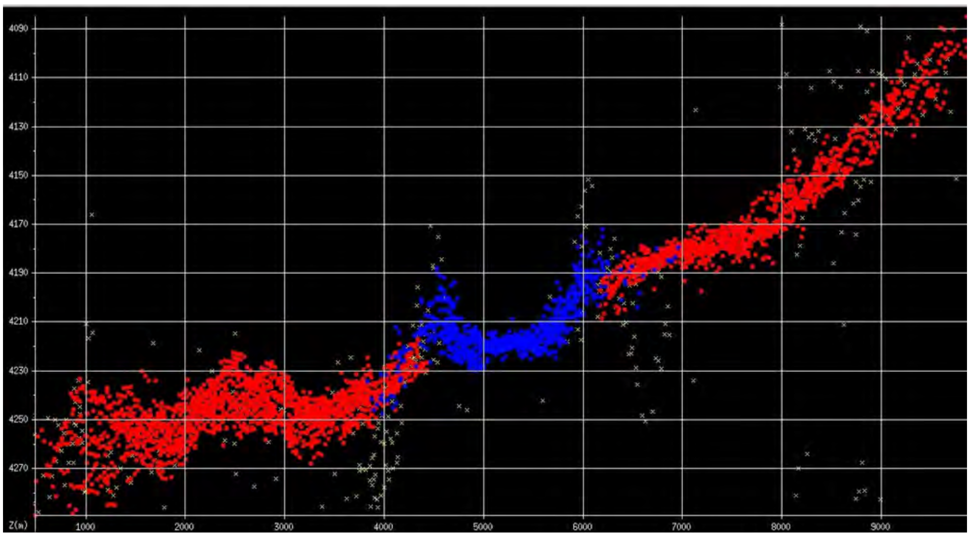


Figure B2: Profile of all beams from one signal perpendicular to the ships route. Gray points are outliers which are automatically excluded during the acquisition. The difference between blue echos (amplitude detection) and red echos (zero-phase detection) is cleaned manually. The larger variability of the outer echos is due to the decreased resolution of the outer beams.

The resolution along the profile depends on the ping rate and the velocity of the ship. The ping rate varies between 15 pings/s at depth between 5-35m and 0.047 at a depth of 15000 depth. The rate is about 0.35/s at a depth of 2000m corresponding to our study area. The coverage of a bathymetric survey can be imaged as a density plot (e. g. Figure B3).

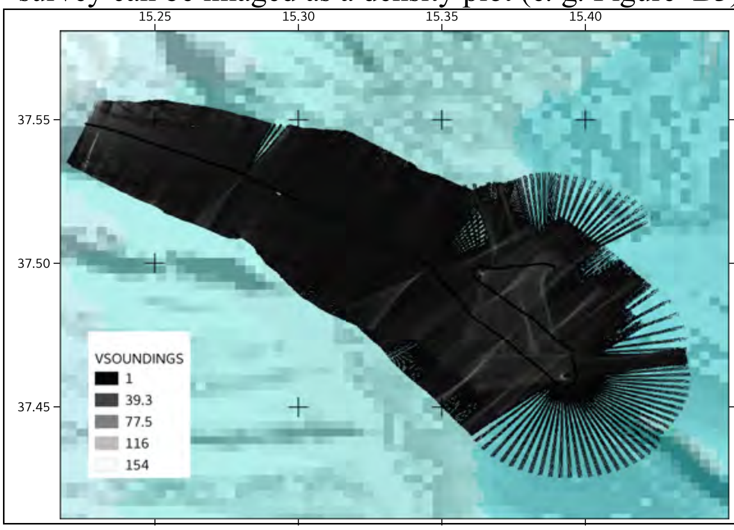


Figure B3: Depth sounding density for the ship-hull survey.

	High resolution system	Wide coverage system
Depth range	200 – 6000 m	200-7000m
Coverage (Bottom –30dB)	5xdepth from 200 to 1000 m 5000 m @ 6000 m	5 x depth from 200 to 4000 m 20 km @ 7000 m

Processing of the ship-hull bathymetric data
Data were processed using the Globe software (Figure B4; Figure B5). For more details please refer to the French version in Annex.

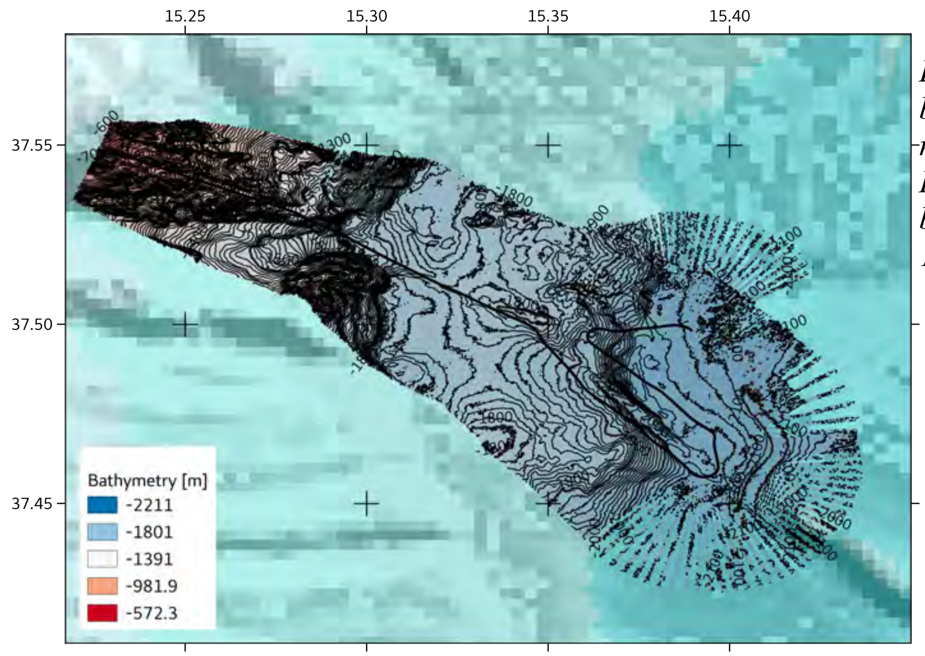
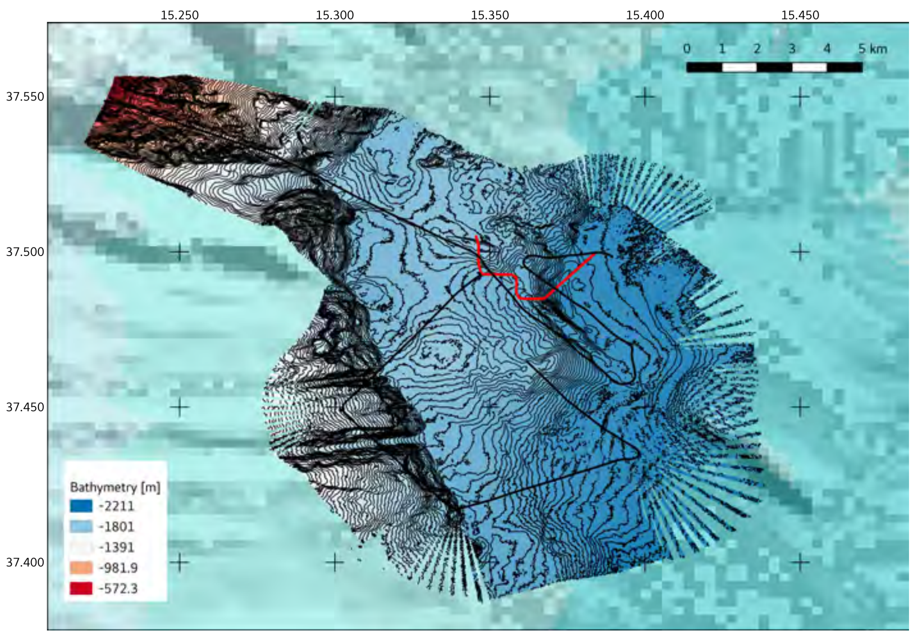


Figure B4: Seafloor bathymetry of the study region from the hull mounted RESON Seabat7150 multi-beam echo-sounder in survey 1..

Figure B5: Seafloor bathymetry of the study region from the hull mounted RESON Seabat7150 multi-beam echo-sounder in survey 1 and 2.



Microbathymety data acquired with the ROV Victor 6000
In order to perform detailed bathymetric mapping of the study region before deployment of the cable, the Module de Mesures en Route (MMR) of the ROV Victor6000 was used (Figure B6). It can cover surfaces of up to 1.5 km^2 per day using a RESON 7125 multi-beam echo sounder.

The SeaBat 7125 multi-beam echo-sounder system operates at 400 kHz and offers up to 120° swath coverage to an altitude of at least 100 meters with a maximum slant range in excess of 200m. The maximum depth is 6000m. 256 equally spaced, fully corrected bathymetry soundings are generated per ping and broadcast from the 7P processor over a standard 10/100 using UDP protocol. Each sounding may be corrected for: refraction, mechanical offsets between the projector and hydrophone, sensor offsets, attitude, heading, depth and tide.

Figure B6: ROV victor at deployment during the cruise.

Characteristics of the RESON 7125 multi-beam echo-sounder
Frequency : 400 kHz
Measurement : bathymetry/backscatter/water column
Pressure max : 600 bars
Height over seabottom : 100m
Survey velocity : 0.3 m/s
Number of soundings : 612
Width of soundings = 1°x0.5°
Repartitioning of soundings : équidistant
Cmpensated for the ROV movement
Possibility for narrowing the width of soundings keeping the number to 256.
Autopilote mode possible

Performance

Bathymetric precision	0.2% of altitude
Swath	128° (4*altitude) width max # 300 m altitude max = 100 m
Resolution	1 à 2% of the altitude

Processing of the Victor6000 bathymetric data
The Globe software was used for the processing of the Victor6000 data (Figures B7 and B8).

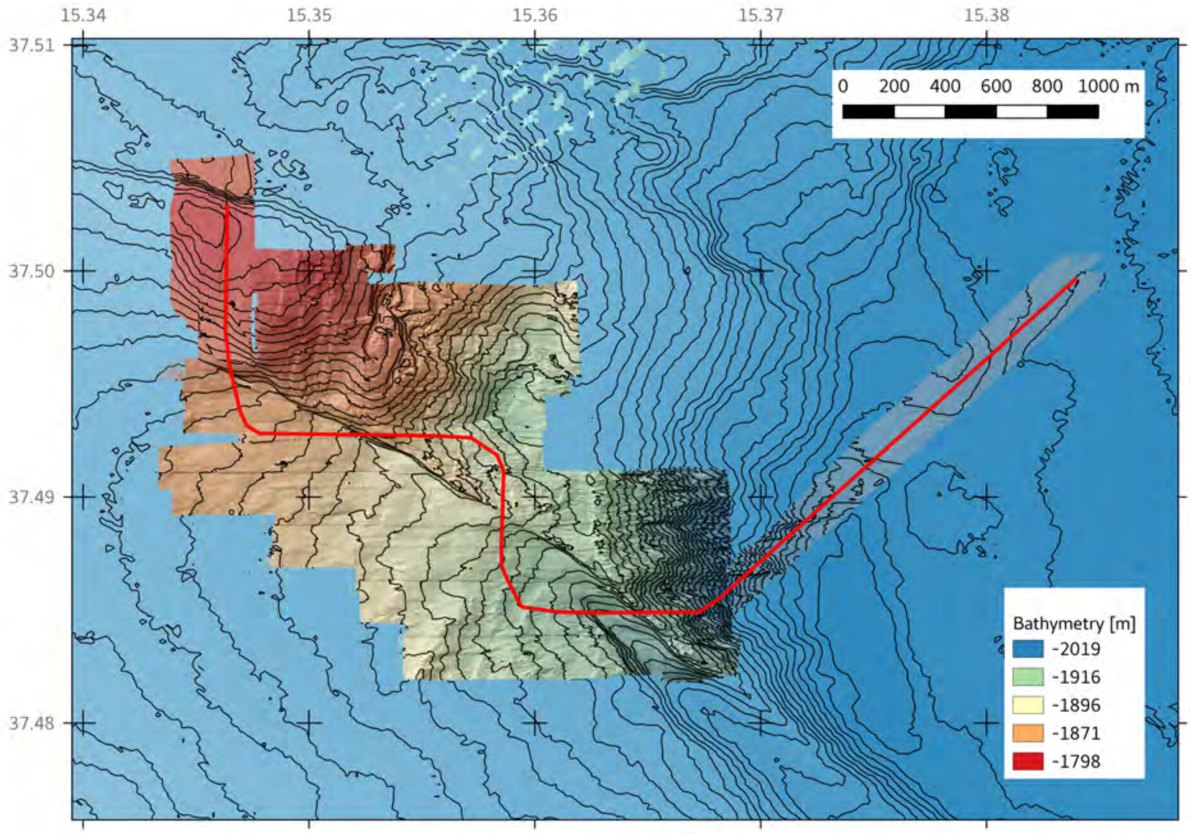


Figure B7: Seafloor microbathymetry from the ROV dives. Resolution of the grid is 2m and contouring every 5m. Red line depicts the provisional cable location.

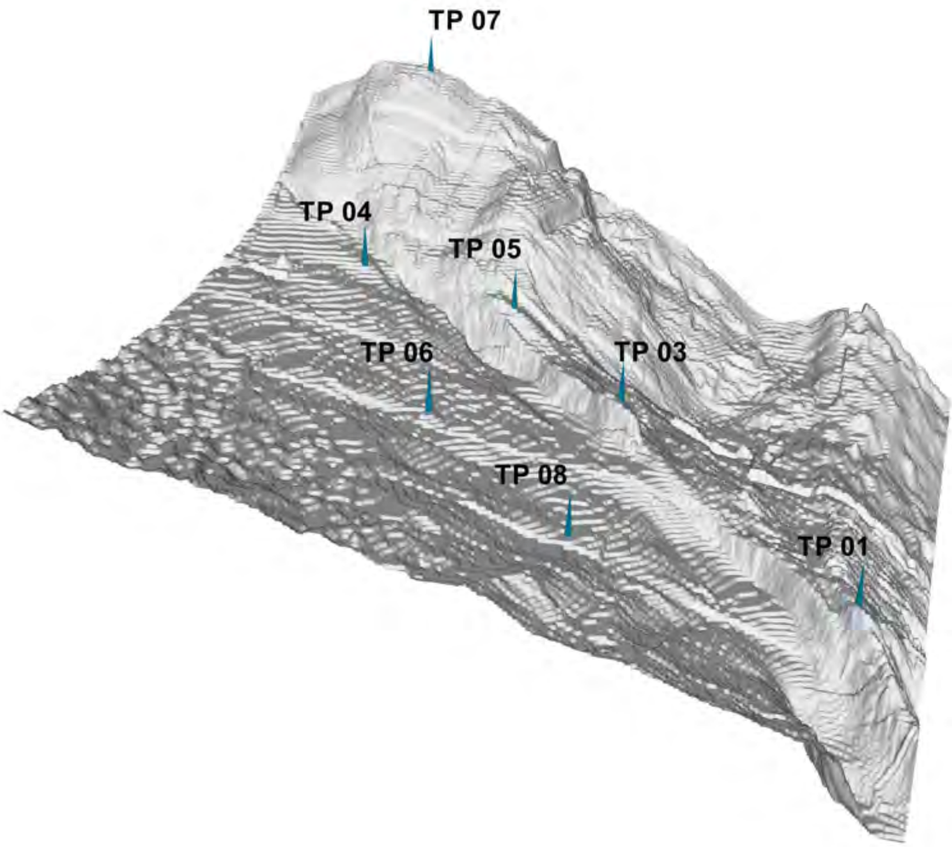


Figure 8: Seafloor micro-bathymetry (3-D view) from the ROV dives with the location of the geodetic stations.

Seafloor geodesy report

FOCUS geodetic experiment

Experiment principle:

A network of eight acoustic beacons have been deployed on either side of the North Alfeo fault to measure its displacement. Four times per day (i.e. every 6h), each beacon will emit an acoustic signal towards each of the surrounding beacons, which each will reply, and store the measured two-way-travel times (TWTTs). Knowing the sound-speed, these times can be converted into distances between pairs of beacons. This continuous monitoring will thus allow to detect and measure precisely any displacement between beacons induced by the activity of the North Alfeo fault.

In addition to TWTTs, each beacon is acquiring measurements from temperature, pressure and sound-velocity sensors. These data are crucial to monitor any changes in the sound-speed. In addition, each beacon is equipped with inclinometers to monitor their stability on the seafloor.

Data stored by the beacons (TWTTs and auxiliary data) can be downloaded using an acoustic modem from a surface ship. So, the beacons are not displaced and continue to measure the same baselines during the whole duration of the experiment (3 to 4 years). The expected displacement to be measured is in the order of 2cm/yr; to this effect, TWTTs are measured with an accuracy of few microseconds (~2-3mm).

Network layout:

Four acoustic beacons have been deployed south of the North Alfeo fault (even numbers), and four beacons north of the fault (odd numbers; Table 1 and Figure 1). Baselines on the same side of the fault should not change with time, whereas baselines crossing the fault should either lengthen or shorten depending on the orientation of the baseline relative to the fault. Four of the latter baselines are parallel to the fiber-optic cable and will be used to calibrate the displacements measured by BOTDR (red lines in Figure G1).

Acoustic beacons are mounted on 2.5m- tor 3.0m-high tripod above the seafloor, so that they can communicate with one another (Figures G2 and G3).

All beacons have been tested after deployment and were operating as expected. In particular, they are all able to communicate with one another. The longest baseline is 1819m-long (Figure 1).

Table 1: Geodetic beacons location and depth

Beacon	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8
Latitude	37˚29.19'N	37˚29.08'N	37˚29.43'N	37 ˚29.62'N	37˚29.57'N	37˚29.35'N	37˚29.88'N	37˚29.19'N
Longitude	015˚21.79'E	015˚20.69'E	015˚21.40'E	015˚20.91'E	015˚21.19'E	015˚21.13'E	015˚20.92'E	015˚21.39'E
Depth	1908 m	1859 m	1880 m	1863 m	1867 m	1884 m	1805 m	1900 m

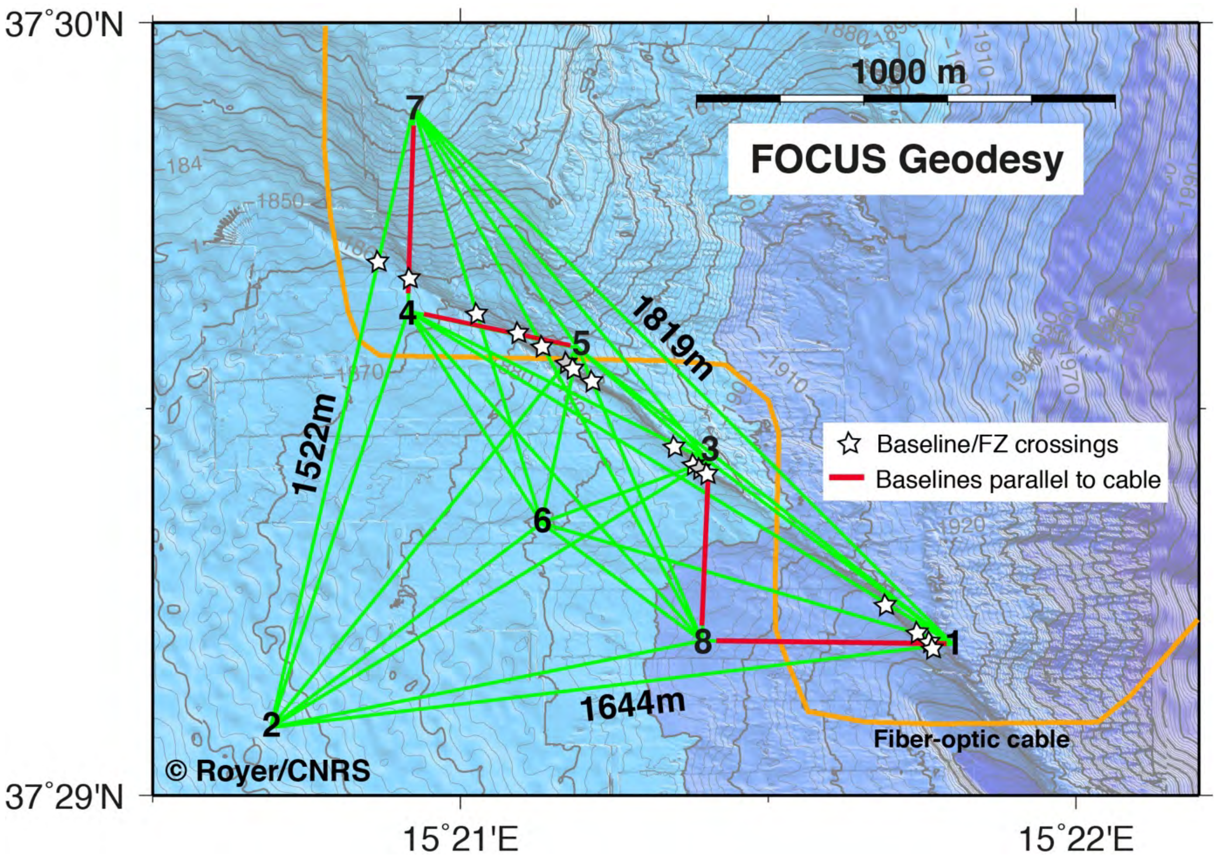


Figure G1: Geodetic beacons (numbers) and baselines (green lines). Stars show the crossings between the North Alfeo fault and the baselines. Red lines show the baselines parallel to the fiber-optic cable, which will be used to calibrate the displacements measured by BOTDR.

Figure G2: Geodetic beacon setup: each acoustic beacon is mounted on a 2.5m- or 3.0m-high tripod above the seafloor (Figure 3). The beacons are equipped with an external temperature sensor (fixed on the yellow floats).

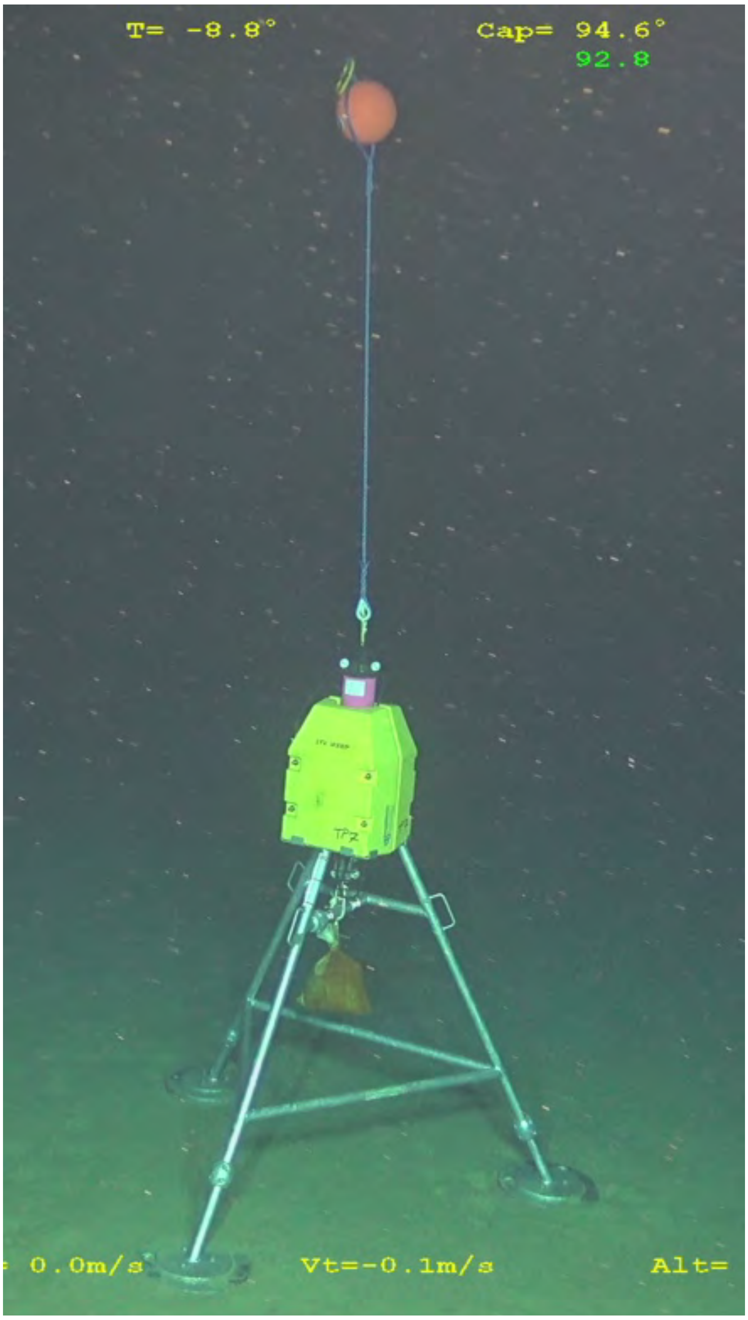
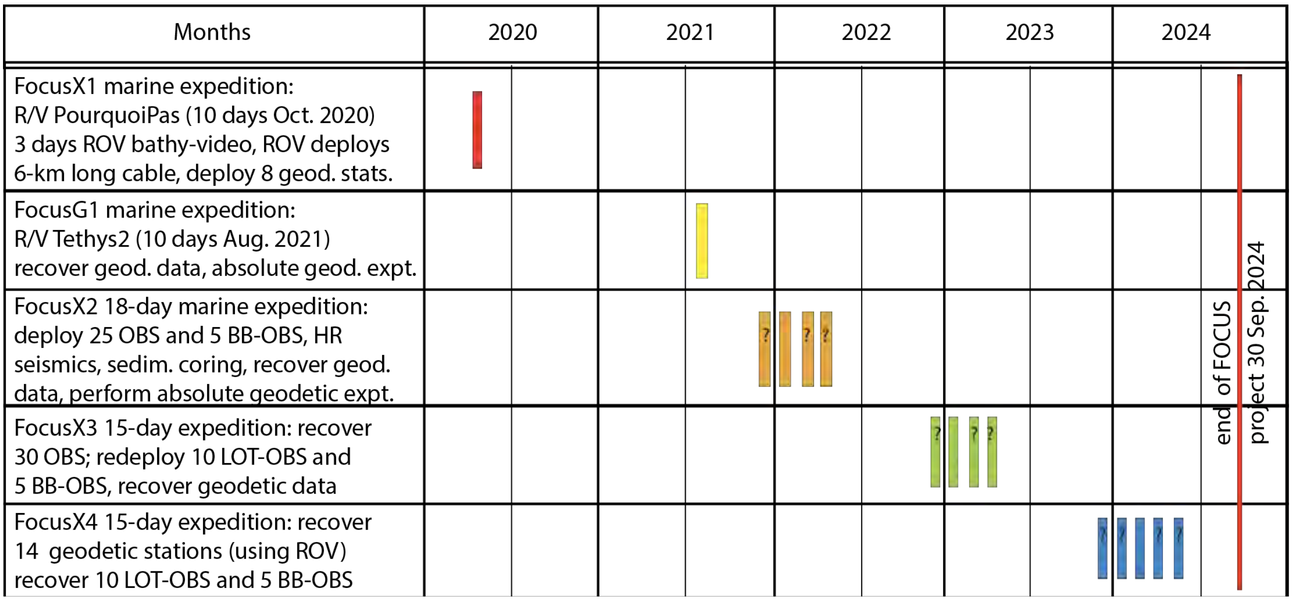


Figure G3: One of the beacons laid on the seafloor, inspected by ROV Victor. Sites with smooth bathymetry were selected.

Outlook - future expeditions:
The 10-day FocusX1 is the first and most crucial in a series of expeditions. A 10 day expedition (title Focus-G1) with a coastal vessel (R/V Tethys2) is scheduled for Summer 2021 (3 working days on site) to download the first 8 months of data from the network of 8 seafloor geodetic stations. The 18-day FocusX2 marine expeditions is ranked high priority (P1) and may be scheduled in early 2022. Its objectives are to monitor the regional seismicity using an onshore - offshore network of seismological stations. Onshore the permanent network of seismological stations operated by INGV will be supplemented by 15 temporary land stations and a marine expedition will deploy a network of 25 Ocean Bottom Seismometers: 5 Broad-band OBS, 10 LOT-OBS and 15 German (Geomar, Kiel) OBS stations. Together they will acquire data for 9 months. Nine months after the FocusX2 expedition, another cruise (about 15 days) FocusX3 will be necessary with a medium sized vessel (e.g. Thalassa or Europe) in order to recover the 5 OBS broad-band stations, 10 LOT-OBS and 15 Geomar OBS instruments (passive seismological network). Data will be uploaded from the seafloor geodetic stations by acoustic communication (and stations can be reprogrammed if an anomaly is detected). Next, the 5 OBS-BB and 10 LOT-OBS will receive new battery packs and be redeployed for one additional year. The final expedition (FocusX4) will take place 3-4 years after FocusX1 in order to recover all the instruments on the seafloor. This includes 14 seafloor geodetic instruments (8 French, 6 German), the 5 OBS-BB and the 10 LOT-OBS. This will require about 15 days of ship time aboard a large vessel (with ROV). Between these major expeditions, shorter surveys (6-8 days of ship time) on board a small vessel (e.g. Tethys2) would permit downloading of geodetic data (relative positioning) and would also allow absolute positioning geodetic experiments to be performed, most likely through use of an Automated Surface Vehicle (ASV) like the PAMELI ASV from the LIENS laboratory, Univ. LaRochelle.



Timetable indicating the sequence of marine expeditions planned for the duration of the FOCUS ERC project, beginning with the 10-day FocusX1 expedition in October 2020 and FocusX2 (18 days requested for 2021-22).

Partnerships, national and international research framework:
The FocusX1 and FocusX2 expeditions are the operational and experimental portion of the **ERC Advanced Grant project FOCUS (funded for 3.5 million € which began on 1 Oct. 2018)**, with numerous national and international partners. National (French) partners include: Ifremer GM (Géosciences Marines) LAD - Laboratoire Aléas Géologiques et Dynamique sédimentaire and RDT - Laboratoire Recherche et Développement Technologique); IDIL (small to medium sized private company in fiber optics in Lannion); Géosciences Montpellier; GeoAzur, Nice. **International partners include: Geomar, Helmholtz Centre for Ocean Research, Kiel, Germany; Univ. Kiel, Germany; INGV Rome, Italy; Univ. Catania, Italy, INFN-LNS (Physics Institute), Catania, Italy.**

The **INGV Rome, Italy** is responsible for seismological and volcanological monitoring and early warning in Italy. They are also one of the leading Italian institutes in earth science research. They operate, together with the partners **INGV Catania** (seismology partner Luciano Scarfi) the network of permanent seismic stations in Italy and in the Sicily – Calabria area. **INGV Rome** (Lucia Margheriti and Milena

Moretti) will be responsible for deployment of temporary seismic stations on land during the passive seismological experiment. They already collaborated with Brest (Univ. Brest - CNRS lab and Ifremer) and Geomar during the Dionysus wide-angle seismology experiment (Dellong et al., 2018; Dannowski et al., 2019) PI - Heidrun Kopp Geomar, Meteor Expedition M111 in Nov. 2014. (see also support letter drafted by Lucia Margheriti). Cooperations between the German and French seafloor geodetic networks are planned with **INGV Catania** (Mimmo Palano) ans well as **Univ. Catania** (Giorgio DeGuidi), who have already conducted on land GPS studies of the SE flank faults of Mt. Etna (De Guidi et al., 2018).

Geomar Helmholtz Research Centre, Kiel, Germany has a long history of close collaboration with PI Gutscher (see Dionysus survey mentioned above) and has agreed to provide 15 OBS for the passive seismological experiment as well as coordinate data acquisition and interpretation from their 6-station seafloor geodetic network as described in the project above. (see also support letter drafted by Heidrun Kopp)

Most of the other French (**Geosciences Montpellier, GeoAzur Nice**) or international partners (**Geomar, Kiel; Univ. Catania**) have previously conducted research with PI Gutscher on the seismicity, tectonics, crustal structure and deformation in the Ionian Sea - East Sicily / Calabria region (see list of recent marine expeditions and reference list). The ERC project (FOCUS), the marine expedition FocusX1 and this ship time proposal (FocusX2) are the product of many years of scientific cooperation.

The **Italian Physics Institute (INFN-LNS)**, operator of the cable infrastructure in Sicily (Catania and Capo Passero) collaborated with PI Gutscher and IDIL in order to perform preliminary experiments. They will be closely involved in the FocusX1 expedition (April 2020) and provide logistical and operational support during the expedition and in particular the operations of cable deployment and cable connection.

A private company, **IDIL fiber optics, Lannion is a partner of the ERC project FOCUS** and responsable conducted preliminary experiments on the INFN-LNS cable infrastructure together with PI Gutscher (in the framework of a Brittany Region funded BoostERC project - pre-FOCUS in 2017). **L Quetel** will be in charge of the laser reflectometry measurements to be performed over several years on the EMSO Catania cable and the 6-km long extension (dedicated fiber optic strain cable).

GFZ Potsdam is a pioneer in the field of DAS (distributed acoustic sensing) for seismic studies. Philippe Jousset is the leader of this effort and has obtained funding and purchased two DAS laser reflectometry interrogators (from the company Silixa). He has worked on Iceland demonstrating the application of DAS for land-based seismology (Jousset et al., 2018) and for 2 years has begun DAS work in Catania Sicily, both on land (on Mount Etna) and offshore on the submarine fiber-optic cable run by INFN-LNS. The FOCUS team is in close contact with Jousset and project members (Gutscher, Quetel and Murphy) have assisted several of his experiments on Etna and the submarine cable. He is interested and eager to perform a DAS experiment during the seismic acquisition (HR seismics) planned during the FocusX2 expedition.

Conclusion

The ultimate goal of the ERC project FOCUS is the demonstration of BOTDR laser reflectometry, combined with seafloor geodetic measurements, to observe and quantify slip on the seafloor along the active North Alfeo fault. However, given the slow and probably sporadic movements along the studied fault, acquisition of a long time series (~3 years) will be necessary before significant results can be obtained. The fiber-optic and acoustic geodetic observations (begun in October 2020) must be supplemented by other geophysical (seismic recordings and imaging) and sedimentological (rheology, fluid geochemistry) observations. Only by combining these complementary types of data can we learn about the long-term behavior of faults and the different expressions of strain, e.g. seismic or aseismic (slow slip / creeping). If successful, the work started during the FocusX1 expedition will contribute to improving the natural hazard assessment related to a newly mapped active fault, 20 km east of a major urban center of 1 million people (Catania).

References

Aloisi, M., Bruno, V., Cannavo, F., Ferranti, L., Mattia, M., Monaco, C., and Palano, M., 2013. Are the source models of the M7.1 1908 Messina earthquake reliable? Insights from a novel inversion and sensitivity analysis of leveling data: Geophys. J. Int., v. 192, 1025-1041, doi:10.1093/gji/ggs062.

Argnani, A., Armigliato, A., Pagnoni, G., Zaniboni, F., Tinti, S. and Bonazzi, C., 2012. Active tectonics along the submarine slope of south-eastern Sicily and the source of the 11 January 1693 earthquake and tsunami. Nat. Hazards Earth Syst. Sci., 12, 1311-1319. doi:10.5194/nhess-12-1311-2012.

Armijo, R., Pondard, N., Meyer, B., Ucarkus, G., Mercier de Lepinay, B., Malavieille, J., Dominguez, S., **Gutscher, M.-A.**, Schmidt, S., Beck, C., Cagatay, N., Cakir, Z., Imren, C., Eris, K., Natalin, B., Özalaybey, S., Tolum, L., Lefevre, I., Seeber, L., Gasperini, L., Rangin, C., Emre, O., and Sarikavac, A., 2005. Submarine fault scarps in the Marmara Sea pull-apart (North Anatolian Fault): Implications for seismic hazard in Istanbul. Geochemistry Geophysics Geosystems, v. 6, Q06009, doi:10.1029/2004GC000896.

Barreca, G., Bonforte, A., and Neri, G., 2013. A pilot GIS database of active faults on the flank of Mt. Etna (Sicily): A tool for integrated hazard evaluation: J. Volcanol. Geotherm. Res., v. 251, p. 170-186.

Blum, J.A., Nooner, S.L., and Zumberge, M.A., 2008. Recording earth strain with optical fibers, IEEE Sensors Journal, v.8, n.7, 1152-1160, doi:10.1109/JSEN.2008.926882.

Bonforte, A., Guglielmino, F., Colteli, M., Ferretti, A., and Puglisi, G., 2011. Structural assessment of Mount Etna volcano from Permanent Scatterers analysis: Geochemistry, Geophysics, Geosystems, v. 12, Q02002, doi:10.1029/2010GC003213.

Chiocci, F.L., Coltelli, M., Bosman, A., and Cavallaro, D., 2011. Continental margin large-scale instability controlling the flank sliding of Etna volcano: Earth and Planetary Science Letters, v. 305, p. 57-64.

D'Agostino, N., D'Anastasio, E., Gersavi, A., Guerra, I., Nedimović, M.R., Seeber, L., and Steckler, M.S., 2011. Forearc extension and slow rollback of the Calabrian Arc from GPS measurements. Geophysical Research Letters, v. 38, L17304, doi:10.1029/2011GL048270.

Dellong, D., Klingelhoefer, F., Kopp, H., Graindorge, D., Margheriti, L., Moretti, M., Murphy, S., and **Gutscher, M.-A.**, 2018. Crustal structure of the Ionian basin and eastern Sicily margin: results from a wide angle seismic survey. J. Geophys. Res., v. 123, 2090-2114, doi: 10.1002/2017JB015312.

De Guidi, G., Brighenti, F., Carnemolla, F., Imposa, S., Antonio Marchese, S., Palano, M., Scudero, S., Vecchio, A., 2018. The unstable eastern flank of Mt. Etna volcano (Italy): First results of a GNNS-based network at its southeastern edge. J. Volcanol. And Geotherm. Res., 357 418-424, doi: 10.1016/j.volgeores.2018.04.027.

De Novellis, V., Atzori, S., De Luca, C., Manzo, M., Valerio, E., Bonano, M., et al., 2019. DInSAR analysis and analytical modeling of Mount Etna displacements: The December 2018 volcano‐tectonic crisis. Geophysical Research Letters, 46, 5817–5827. doi.org/10.1029/2019GL082467.

Gallais, F., **Gutscher, M.-A.**, Graindorge, D., Chamot-Rooke, N., and Klaeschen, D., 2011. A Miocene tectonic inversion in the Ionian Sea (Central Mediterranean): evidence from multi-channel seismic data. JGR, v. 116, B12108, doi:10.1029/2011JB008505.

Gallais, F., **Gutscher, M.A.**, Graindorge, D., and Klaeschen, D., 2012. Two-stage growth of the Calabrian accretionary wedge in the Ionian Sea (Central Mediterranean): Constraints from depth migrated multi-channel seismic data. Marine Geology, v. 326–328, p. 28-45.

Gallais, F., Graindorge, D., **Gutscher, M.-A.**, and Klaeschen, D., 2013. Propagation of a lithospheric tear fault (STEP) through the western boundary of the Calabrian accretionary wedge offshore eastern Sicily (southern Italy): Tectonophysics, v. 602, p. 141-152 doi:10.1016/j.tecto.2012.12.026.

Govoni, A., Margheriti, L., D'Anna, G., Selvaggi, G., Patane, D., Moretti, M., Zuccarello, L. (2008) Messina 1908-2008: understanding crust dynamics and subduction in Southern Italy , Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract S43C-1899.

Gross, F., Krastel, S., Geersen, J., Behrmann, J.H., Ridente, D., Chiocci, F.L., Bialas, J., Papenberg, C., Cukur, D., Urlaub, M., and Micallef, A., 2016. The limits of seaward spreading and slope instability at the continental margin offshore Mt Etna, imaged by high-resolution 2D seismic data. Tectonophysics, v. 667, 63-76, doi:10.1016/j.tecto.2015.11.011.

Gutscher, M.-A., Roger, J., Baptista, M.A., Miranda, J.M., and Tinti, S., 2006. The source of the 1693 Catania earthquake and tsunami (Southern Italy): New evidence from tsunami modeling of a locked subduction fault plane. Geophysical Research Letters, v. 33, n.8, L08309 10.1029/2005GL025442.

Gutscher, M.-A., Kopp, H., Krastel, S., Bohrmann, G., Garlan, T., Zaragosi, S., Klaucke, I., Wintersteller, P., Loubrieu, B., LeFaou, Y., San Pedro, L., Dominguez, S., Rovere, M., Mercier de Lepinay, B., Ranero, C., and Sallares, V., 2017. Active tectonics of the Calabrian subduction revealed by new multi-beam bathymetric data and high-resolution seismic profiles in the Ionian Sea (Central Mediterranean). Earth and Planet. Sci. Lett., v. 461, 61-72, doi:10.1016/j.epsl.2016.12.020.

Gutscher, M.-A., Dominguez, S., Mercier de Lepinay, B., Pinheiro, L., Gallais, F., Babonneau, N., Cattaneo, A., LeFaou, Y., Barreca, G., Micallef, A., and Rovere, M., 2016. Tectonic expression of an active slab tear from high-resolution seismic and bathymetric data offshore Sicily (Ionian Sea). Tectonics, v. 35, n.1, doi:10.1002/2015TC003898.

Hensen, C; Nuzzo, M; Hornibrook, ERC; Pinheiro, LM; Bock, B; Magalhães, VH; Brückmann, W. 2007. Sources of mud volcano fluids in the Gulf of Cadiz - indications for hydrothermal imprint. Geochimica et Cosmochimica Acta, Vol. 71 (5), 03.2007, p. 1232-1248, doi: 10.1016/j.gca.2006.11.022.

Hensen, C., Scholz, F., Nuzzo, M., Valadares, V., Gràcia, E., Terrinha, P., Liebetrau, V., Kaul, N., Silva, S., Martínez-Loriente, S., Bartolome, R., Piñero, E., Magalhães, V.H., Schmidt, M., Weise, S.M., Cunha, M., Hilario, A., Perea, H., Rovelli, L., Lackschewitz, K., 2015. Strike-slip faults mediate the rise of crustal-derived fluids and mud volcanism in the deep sea. *Geology* ; 43 (4): 339–342. doi: 10.1130/G36359.1.

Hirn, A., Nicolich, R., Gallart, J., Laigle, M., Cernobori, L., and the ETNASEIS Scientific Group. 1997. Roots of Etna volcano in faults of great earthquakes. Earth Planet. Sci. Lett. 148, 171-191.

Husen, S., E. Kissling, N. Deichmann, S. Wiemer, D. Giardini, and M. Baer, 2003. Probabilistic earthquake location complex three-dimensional velocity models: Application to Switzerland, J Geophys Res, 108(B2), 1437–26, doi:10.1029/2002JB001778.

Jenny, S., Goes, S., Giardini, D., and Kahle, H.-G., 2006. Seismic potential of Southern Italy: Tectonophys., v. 415, p. 81-101 doi:10.1016/j.tecto.2005.12.003.

Jiang, X., Gao, Y., Wu, Y., Lei, M., 2016. Use of Brillouin optical time domain reflectometry to monitor soil-cave and sink hole formation, Environ Earth Sci, 75, 225, doi:10.1007/s12665-015-5084-1.

Jousset, P., Reinsch, T., Ryberg, T., Blanck, H., Clarke, A., Aghayef, R., Hersir, G.P., Henninges, J., Weber, M., and Krawcyk, C.M. 2018. Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features. Nature Communications, 9, 2509, doi: 10.1038/s41467-018-04860-y

Krastel, S., Krabbenhoeft, A., Hannemann, K., Petersen, F., Schröder, P., Steffen, K.-P., Gross, F., Schulze, I., and Micallef, A.., 2016. RV Poseidon Cruise Report 496, Malaga - Catania, 24.03.2016 - 04.04.2016, MAGOMET Offshore flank movement of Mount Etna and associated landslide hazard in the Ionian Sea (Mediterranean Sea) Short Cruise Report 8pp., (unpubl.).

Lindsey N. J., Martin, E. R., Dreger, D. S., Freifeld, B., Cole, S., James, S. R., Biondi, B.L., and Ajo-Franklin, J.B., 2017. Fiber-optic network observations of earthquake wavefields. Geophysical Research Letters, 44. https://doi.org/10.1002/2017GL075722

Loveless, J. P., and B. J. Meade (2011), Spatial correlation of interseismic coupling and coseismic rupture extent of the 2011 M W= 9.0 Tohoku-oki earthquake, *Geophys. Res. Lett*, *38*(17), doi:10.1029/2011GL048561.

Maesano, F.E., Tiberti, M.M., and Basili, R., 2018. The Calabrian Arc: three-dimensional modelling of the subduction interface. Sci. Reports 7, 8887, doi:10.1038/s41598-017-09074-8.

Maraval, D., Gabet, R., Jaouen, Y., Lamour, V., 2017. Dynamic optical fiber sensing with Brillouin Optical Time Domain Reflectometry: Application to pipeline vibration monitoring. J. Lightwave Technology, doi: 10.1109/JLT.2016.2614835

Marchetti, A., Narid, A., Margheriti, L., Lattorre, Ciaccio, M.G., Lombardi A.M., Improta, L., Bono, A., Mele, F.M., Rossi, A., Battelli, P., Melorio, C., Castello, B., Lauciani, V., Berardi., M., Castellano, C., Baccheschi, L., Miconi, L., Spadoni, S., Sciarra, A., Colini, L., Villani, F., Sgroi, T., D'Addezio, G., Pinzi, S., Smedile, A., Montouri, C., Tardini, R., Di Maro, R., Monna, S., Mariucci, T., Pintore, S., Quintiliani, M. , Mandiello, A., Fares, M., Cheloni, D., Frepoli, A., Moretti, M., Scognamiglio, L., Basili, A., 2019. Rapporto Bollettino Sismico Italiano sulla revisione della sequenza sismica del centro Italia 24 agosto 2016- 31 agosto 2018. Bollettino Sismico Italiano,

Marra, G., Clivatti, C., Luckett, R., Tampellini, A., Kronjäger, J., Wright, L., Mura, A., Levi, F., Robinson, S., Xuereb, A., Baptie, B., and Calonico, D., 2018. Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables. Science 10.1126/science.aat4458.

Meli, F., Bono, A., Laucinai V., Mandiello, A., Marcocci, C., Pintore, S., Quintiliani, M., Scognamiglio, L,, Mazza, S., 2010. Tuning an earthworm phase picker: some considerations on the PICK_EW parameters, Rapporto Tecnico INGV No. 164

Minelli, L. and Faccenna, C., 2010. Evolution of the Calabrian Accretionary wedge (Central Mediterranean). Tectonics, 29: doi:10.1029/2009TC002562.

Murray, J.B., van Wyk de Vries, B., Pitty, A., Sargent, P., and Wooller, L., 2018. Gravitational sliding of the Mt. Etna massif along a sloping basement. Bull. Volcanology, 80:40, doi:10.1007/s00445-018-1209-1.

Nicolich, R., Laigle, M., Hirn, A., Cernobori, L., and Gallart, J., 2000. Crustal structure of the Ionian margin of Sicily: Etna volcano in the frame of regional evolution. Tectonophysics, v. 329, p. 121-139.

Palano, M., Ferranti, L., Monaco, C., Mattia, M., Aloisi, G., Bruno, V., Cannavò, F., and Siligato, G., 2012. GPS velocity and strain fields in Sicily and southern Calabria, Italy: Updated geodetic constraints on tectonic block interaction in the central Mediterranean: Journal of Geophysical Research, v. 117, B07401, doi:10.1029/2012JB009254.

Palano, M., 2016. Episodic slow slip events and seaward flank motion of Mt. Etna volcano (Italy). Journal of Volcanology and Geothermal Research, v. 324, 8-14, doi:10.1016/j.volgeores.2016.05.010.

Peng, Z., and J. Gomberg, 2010. An integrated perspective of the continuum between earthquakes and slow-slip phenomena, Nature Geoscience, 3(9), 599–607, doi:10.1038/ngeo940.

Piatanesi, A., and Tinti, S., 1998. A revision of the 1693 eastern Sicily earthquake and tsunami, J. Geophys. Res., 103, 2749–2758.

Polonia, A., Torelli, L., Mussoni, P., Gasperini, L., Artoni, A., and Klaeschen, D., 2011, The Calabrian arc subduction complex in the Ionian Sea: regional architecture, active deformation and seismic hazard: Tectonics, v. 30, TC5018, doi:10.1029/2010TC002821.

Polonia, A., Bonatti, E., Camerlenghi, A., Lucchi, R.G., Panieri, G., Gasperini, L., 2013. Mediterranean megaturbidite triggered by the AD 365 Crete earthquake and tsunami. Sci Rep 3, 1285; doi:10.1038/srep01285.

Reilinger, R., McClusky, S. Paradissis, D., Ergintav, S., and Vernant, Ph., 2010. Geodetic constraints on the tectonic evolution of the Aegean region and strain accumulation along the Hellenic subduction zone. Tectonophysics, 488, 22-30, doi:10.1016/j.tecto.2009.05.027.

Ryan, W.B.F. and Heezen, B.C., 1965. Ionian Sea submarine canyons and the 1908 Messina turbidity current. Geological Society of America Bulletin., v. 76, p. 915-932.

San Pedro, L., Babonneau, N., **Gutscher, M.-A.**, Cattaneo, A., 2017. Origin and chronology of the Augias deposit in the Ionian Sea (Central Mediterranean Sea), based on new regional sedimentological data. Marine Geology, sp. Vol. on Subaqueous Paleoseismology, v. 384, 199-213, doi:10.1016/jmargeo.2016.05.005.

Satriano, C., A. Lomax, and A. Zollo (2008), Real-Time Evolutionary Earthquake Location for Seismic Early Warning, Bulletin of the Seismological Society of America, 98(3), 1482–1494, doi:10.1785/0120060159.

Sun, Y., Shi, B., Zhang, B., Tong, H., Wei, G., and Xu, H., 2016, Internal Deformation Monitoring of Slope Based on BOTDR, J. Sensors, 2016, Article ID 9496285, doi :10.1155/2016/9496285.

Urlaub, M., Petersen, F., Gross, F., Bonforte, A., Puglisi, G., Guglielmino, F., Krastel, S., Lange, D., Kopp, H., (2018). Gravitational collapse of Mount Etna's south-eastern flank. Science Advances. 4, eaat9700, doi: 10.1594/PANGAEA.893036.

Yamate, T., Fujisawa, G., and Ikegami, T., 2017. Optical sensors for the exploration of oil and gas. Journal of Light Technology, in press, 9pp, doi : 10.1109/JLT.2016.2614544.

Zeng, X., Lancelle, C., Thurber, C., Fratta, D., Wang, H., Lord, N., Chalari, A., and Clarke, A., 2017. Properties of noise cross-correlated functions obtained from a distributed acoustic sensing array at Garner Valley, California. Bulletin of the Seismological Society of America, v. 107, p. 603-610, doi: 10.1785/0120160168.

Zhao, L., Li, Y., Xu, Z., Yang, Z., Lü, A., 2014. On-line monitoring system of 110 kV submarine cable based on BOTDR. Sensors and Actuators A : Physical, 216, 28-35. doi:10.1016/j.sna.2014.04.045.

Annex 1 follows - the detailed, French version of the processing of the bathymetric and micro-bathymetric data