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# Gathering different marine geology data (seismics, acoustics, sedimentological) to investigate active fluid seepage (AFS) in the southern region of the central Mediterranean Sea

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***Abstract* – Active Fluid Seepage (AFS) at the seafloor is a global phenomenon associated with seafloor morphologies in different geodynamic contexts. Advances geophysical techniques have allowed geoscientists to characterise pockmarks, mounds and flares associated with AFS. We present a range of marine geological data acquired in the central Mediterranean Sea (northern Sicily continental margin, northwestern Sicily Channel and offshore the Maltese Islands), which allow us to identify AFSs. The AFSs are spatially distributed as clusters, aligned or isolated at different depths, ranging from few decametres offshore the Maltese Islands, up to 400 m offshore north Sicily and in the northwestern Sicily channel. Mounds have heights ranging from 2 to 15 m and form hummocky surfaces. Pockmarks with sub-circular planform shapes and U/V-shaped cross-sections are found in sizes ranging from 5 to 530 m. Gas flares occur on both the continental shelf and upper slope.**

## I. INTRODUCTION

Fluid seepage is a phenomenon that characterises different geodynamic contexts, producing diverse types of seafloor morphologies [1]. Positive relief (e.g. mounds and mud volcanoes) or negative relief (e.g. pockmarks) morphologies [2], [3], [4], [5], [6], [7] result from gas seepages and fluid-rich, fine-grained sediment extrusion [8]. Occasionally, these morphologies are associated to active fluid vents (flares).

Over the last 20 years, advances in tools for the acquisition of marine geology data have enhanced the knowledge of submarine areas globally. Several research projects, based on new very high resolution geophysical and sedimentological data, water samples, and imagery and videos acquired by ROV, have identified and mapped different kinds of AFSs and associated morphological structures in both active and passive continental margins [9], [10].

AFVs have geological, biochemical and hazard implications. They also have a great economic importance as they are often linked to the large accumulations of sub-seafloor hydrocarbon deposits or to freshwater reservoirs. Finally, AFS have direct implications for the biosphere (e.g. growth and development of coral mounds, chemosynthetic communities and big shoals of fish), the hydrosphere (e.g. ocean acidification), and the atmosphere (e.g. contributing $CH_4$ and $CO_2$).

In a number of small areas of the northern Sicily continental margin, the occurrence of mounds and pockmarks has been linked to AFSs [11]. In the eastern Sicily Channel, AFS and relative fluid escape features (e.g. pockmarks, mounds) have been reported across a wide depth range [10], [12].

In the western Sicily Channel, AFS has only been investigated for Pantelleria Island and other small areas. Such manifestations are distributed along recent tectonic discontinuities, which are also known to have given rise to the emergence of Ferdinandea Island on the Graham Bank, where the degassing of fluids is rooted in depth, either aligned to the main trends of fault systems or linked to the neotectonic activity [12].

Despite a general interest in the occurrence and location of fluid escape structures and AFS in the Sicily, a systematic study aimed at understanding the spatial distribution and inferring the general physical and geochemical features of the fluid vents from the seafloor at the present time is still missing so far.

In this paper, we show the key geophysical techniques (both low and high resolution) and geochemical analysis by “scanning electron microscopy” (SEM) and (EDX) used for the investigation of sub-seafloor fluids in different parts of the central Mediterranean and the relation between AFS and structural and stratigraphic controls.

## II. MATERIALS & METHODS

Our study areas comprise different region of the middle-lower continental shelf and upper continental slope from offshore northwestern Sicily, northwestern/central region of the Sicily Channel and the region around the Maltese Islands, covering the bathymetric depth range of 5–1000 m (Figure 1).

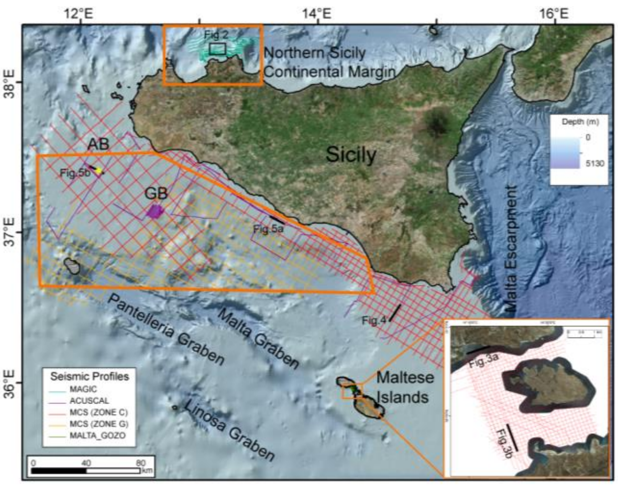


*Figure 1 Bathymetric map (source: EMODnet) of the central Mediterranean Sea, showing the principal morphological features (e.g. Adventure Bank (AB), Graham Bank (GB)) and the location of the study areas (orange boxes). The yellow star shows the position of the box corer collected during ACUSCAL 2015 Cruise.*

The study is based on different types of marine geology data acquired during the research cruises CARG (2001, 2004), MAGIC (2009), CNR ACUSCAL (2015), and MALTA-GOZO (2016) on board the research vessels R/V Minerva1, and M/V Midas Express (Figure 1):

- MBES data: an overall area of 2000 km$^2$ seafloor was surveyed using two different hull-mounted Reson SeaBat 8111, the Reson SeaBat 8160, Reson SeaBat 7160 and Reson SeaBat 7125. Differential Global Positioning Systems (dGPS) by FUGRO SEASTAR provided positional data. During the survey, many vertical measurements of sound velocity profiles were performed with the CTD YSI CastAway and Navitronic Systems AS-SVP-25. The Multibeam data were acquired, stored and post-processed by the Marine Geology &seafloor Surveying (University of Malta) and Marine geology Group of DiSTeM (University of Palermo) by accounting for sound velocity variations, and by implementing basic quality control. To obtain the final Digital Terrain Model (DTM), the images were produced with a footprint resolution appropriate to the depth. ArcGIS, Golden Software Surfer and Global Mapper were used to obtain 3D maps and DTM from the bathymetric data. The seafloor slope gradient maps (Figure 2a) were generated using ArcGIS to facilitate the identification of the AFSs (pockmark and mounds). For each pockmarks, we have measured (using ArcGIS and Global mapper) and tabulated a number of morphometric parameters (such as diameter, depth, perimeter, surface, volume, plan-view shape, cross-section shape, water depth) with the aim to carry out a statistical analysis.
- Multichannel seismic reflection records of “Zones C and G” by the Department of Industry of the Italian Government). The G Lines were acquired used an AirGun array with a capacity of 2000 m$^3$ and 1600 m long streamer equipped with 96 groups, 15 geophones per group, group interval of 25 m and an active section length of 50 m. The C Lines were acquired used an AquaPulse source and an array 2400 m long. Multichannel seismic reflection profiles were obtained from www.videpi.it and converted to SEG-Y format. This entailed merging all files, geo-referencing (using Datum WGS84, UTM33), and conversion using a Matlab script (image2segy).
- High resolution seismic data: during the CARG cruise, a grid of Sparker profiles were acquired using a multi-tip sparker array, with a base frequency of around 600 Hz, at 12.5 m shot intervals. Data were received with a single-channel streamer with an active section of 2.8 m, containing seven high resolution hydrophones recording for 3.0 s two way time (TWT) at a 10 kHz (0.1 ms) sampling rate. Data processing included the following mathematical operators: Traces Mixing, Time Variant Filter, Automatic Gain Control, Time Variant Gain and Spherical Divergence Correction. The resulting signal penetration exceeded 400 ms (TWT) and the vertical resolution reached 2.5 m at the seafloor.
- Very High Resolution seismic data: during MALTA-GOZO cruise, 225 km of seismic reflection profiles have been acquired using a Boomer source. Data have been acquired at a speed of about 4 knots, using an inter-trace of ~1 m. The reflection signals have been collected with a pre-amplified streamer (oil filled) composed of eight piezoelectric elements connected in series with a 2.8 m active array. In order to minimise the spatial filtering produced by the hydrophones array, the streamer was towed near the source with a 5 m longitudinal offset and a 3.5 m lateral offset. The streamer was kept as shallow as possible to avoid destructive interference between reflected signals and multiple events from the air/water (ghost). The plate produces a theoretical minimum phase wavelet with an amplitude spectrum between 400 and 4000 Hz obtaining data with decimetric resolution. As the water depth in the investigation area was < 120 m, a shot rate of 2 pulses per second was used. While, during MAGIC and CNR ACUSCAL cruise, a total length of 1054 km of CHIRP lines were acquired simultaneously with MBES data.
- The seismic lines were collected using a hull-

mounted 16 transducer Teledyne/Benthos CHIRP III profiler with operating frequencies ranging between 2 and 7 kHz and a trig rate between 250 and 750 ms, Tx power between 5 and 7, pulse length of 10 ms and a 30 or 42 db gain for a better visualization of data. The seismic reflection profiles were acquired and displayed using the "Communication Technology SWANPRO software". The seismic data processing was performed by running the following routines of the Kingdom and Geosuite softwares: edit, muting, swell filter, digital filters, AGC, gain; they were successively interpreted by using seismostratigraphic analysis, which allowed depositional units characterized by seismic facies with different attributes to be distinguished.

- Seafloor samples: in correspondence of the mounds or pockmarks, identified by very high resolution seismic lines, 14 box corer samples were collected during ACUSCAL cruise. Thirteen grab samples were collected during MALTA-GOZO cruise with a 5 l modified Van-Veen Grab. These samples were described, photographed and sub-sampled on board. Positional information was determined with buoys and dGPS.

Scanning electron microscopy for hard ground sample were performed using SEM (Scanning Electron Microscope) attached with EDX spectrometer unit, with accelerating voltage 10 K.V, at the Department of Earth and Marine Sciences, University of Palermo, Italy.

## III. MORPHOLOGICAL AND SEISMOSTRATIGRAPHIC FEATURES OF THE ACTIVE FLUID SEEPAGE

The Sicily Channel is a mainly shallow water region of the central Mediterranean Sea comprising several morphological highs such as Adventure, Graham (-7 m), Nerita (-16 m), and Terrible (-20 m) Banks, and Malta Plateau, as well as a number of elongated basin (e.g. Pantelleria, Linosa and Malta Graben and Gela Basin).

We focused on the area comprising Adventure and Graham Bank and the region around the Maltese Islands.

Northern Sicily continental shelf and continental slope are part of the continental margin that links the Sicily chain to the Tyrrhenian back-arc basin [11]. The size of the continental shelf from west to east increasing from 5 to 8 km and is constituted by an internal and an outer shelf separated by a convex break-in slope located at about 70 m. The inner shelf showing a number of breaks-in-slope in the 0-70 m depth interval has a gentle slope of 0.6°- 1.0°. While, the outer shelf with a slope of 0.7°-1.3° has only a prominent break-in-slope located at -110/120 m depth.

Acoustic and seismic data highlight, in these three regions, the presence of a large spectrum of seafloor and subseafloor features of the shelf to slope system:

### A. *NEGATIVE FEATURES*

In the three study areas, we have identified numerous negative-like features, at a depth ranging between 200 and 320 m (in the northwestern Sicily Channel), between 10 and 80 m (around the Maltese Islands) and between 200 and 700 m (in the northern Sicily continental Margin) (Figure 2a).

The identified negative-like features are circular or elliptical in plan-view and have a symmetric U/V-shaped cross-section (Figure 2b). In this paper, depressions are defined circular in plan view if Length/Width=1.0-1.2, and elliptical if Length/Width>1.2.

Their size (axis, depth, surface and volume) was measured using the reconstructed slope maps, which have allow us an easy identification of them (Figure 2a).

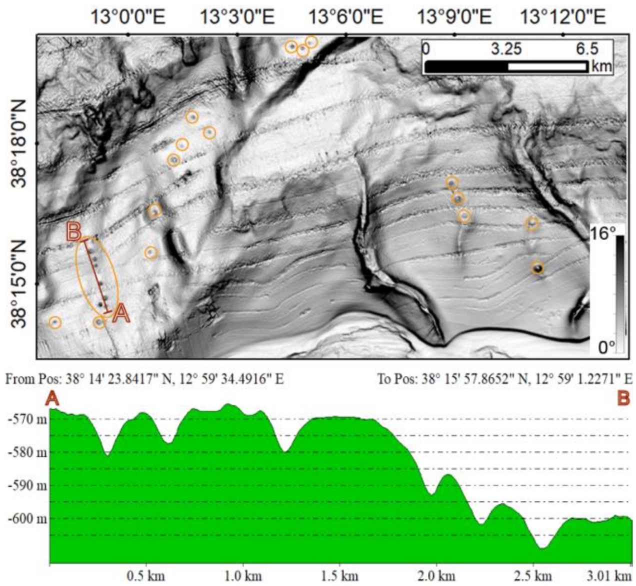


*Figure 2 Slope map (a) of the northern Sicily Continental margin showing the presence of several circular depressions. The bathymetric profile (b) shows the cross-section shape of six aligned circular negative-like features. The location is shown in Figure 1.*

Around the Graham Bank (northwestern Sicily Channel), eighteen circular and elliptical depressions (GBD_1-18 in supplementary material), organised as two main clusters and as two isolated morphologies, occur, with their mean axis varying between 50 and 500 m in diameter. Their mean depression depth is 8 m (over the range 3-15 m) and their wall slope gradient is 3-4°.

Around the Maltese Islands, we identified fifty-seven circular depressions (GCD_1-58 in supplementary material) distributed in three main clusters. Their mean axis is about 12 m in diameter and the wall slope gradient is 3-4°, while their mean depth is 4 m (over the range 3-10 m).

Finally, in the northern Sicily continental margin, we identified twenty-eight circular and elliptical depression organised in five main arrays (SCMD_1-28 in supplementary material). These depressions have a mean axis of 400 m, mean depth of 20 m and wall slope gradient of 2-4°. Some of them appear contiguous with others depressions, forming an elongated channel in a uniform direction (Figure 2a). Other depressions are organised in clusters or are isolated.

High and very high resolution seismic profiles (Boomer and CHIRP) crossing above these circular depressions show down-bending of the reflectors up to the seafloor (Figures 3a, b). Their sub-seafloor character consists of continuous reflectors with concave upward geometry accompanied by acoustic anomalies (Figures 3a, b).

All measured size parameters have been tabulated in table (see supplementary material).

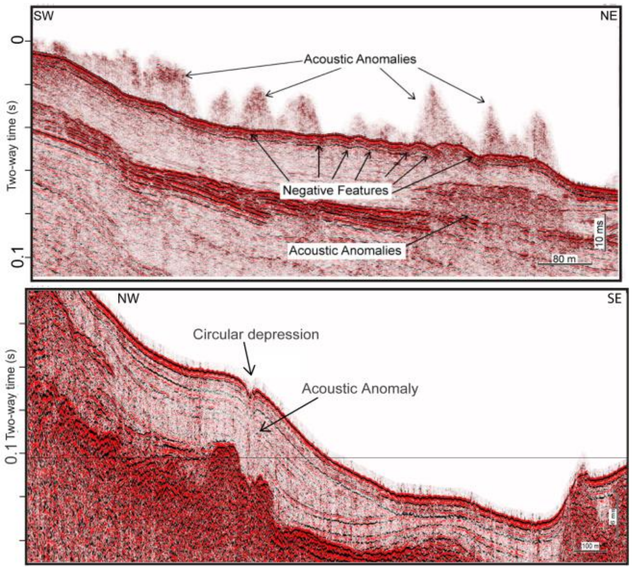


*Figure 3 a) Boomer profile acquired around the Maltese Islands showing a number of acoustic anomalies in the water column in correspondence of negative features. b) a boomer profile showing a circular negative-like feature. The location is shown in Figure 1.*

### *B. POSITIVE FEATURES*

The continental shelf and the upper continental slope in the Sicily Channel (both in the western region and around the Maltese Islands), as well as the northern Sicily continental margin, are characterised by several positive features (mounds), buried or outcropping, with different sizes and shapes, creating a very jagged seafloor and subseafloor (hummocky morphology)(Figure 4, 5b).

In the Adventure Bank, northwestern Sicily Channel, there are numerous isolated, clustered or aligned mounds, on the western and southwestern flanks of the Graham Bank oriented about NW-SE and NNW-SSE forming mound ridges, extending as far as 600 m in length and reaching heights of 1.5-10 m.

Around the Maltese Islands, 90 mounds (few meters high) form five main cluster oriented about NW-SE at a depth ranging between 12 and 90 m.

In the northern Sicily continental margin, several small mounds are arranged predominantly along the N-S trend, being about 10 m high, 700 m long and 250 m wide.

Both in the Sicily Channel and in the northern Sicily continental margin, we also identified a number of buried mounds often showing a transparent seismic facies (Figure 5a, b) and in some cases at the top of the mounds we identified also acoustic anomalies in the water column (Figure 5a, b).

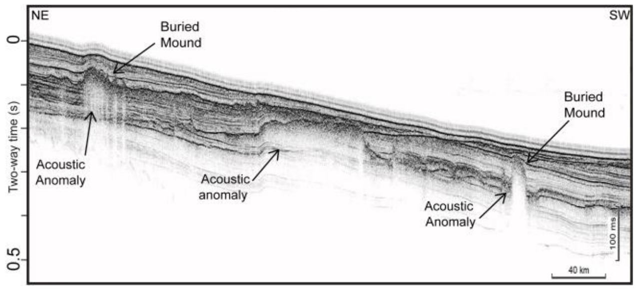


*Figure 4 Chirp profile acquired in the Malta Plateau displaying the occurrence of three buried mounds showing acoustic anomalies (transparent seismic facies). The location is shown in Figure 1.*

### *C. ACOUSTIC ANOMALIES*

In the Sicily Channel (from west to east), several acoustic anomalies in the water column and in the sub-seafloor have been recognised using high resolution seismic profiles.

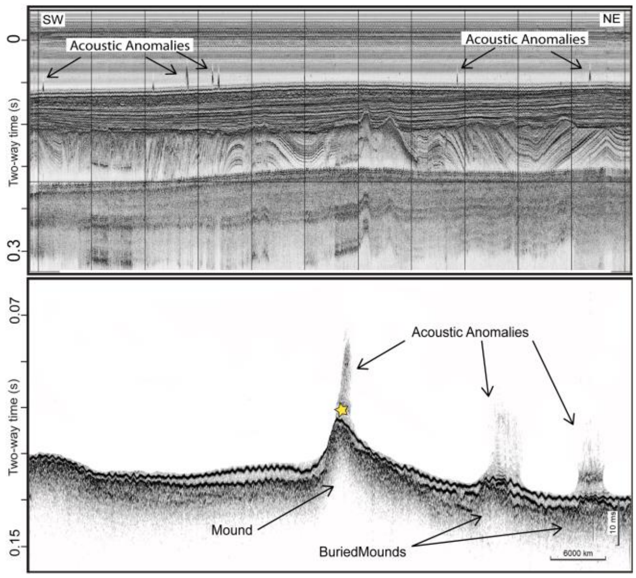


*Figure 5 a) Chirp profile acquired in the north-central Sicily Channel showing the occurrence of a number of acoustic anomalies in the water column; b) Chirp profile acquired in the Adventure Bank showing the occurrence* *of acoustic anomalies in the water column at the top of mound and buried mounds showing a transparent seismic facies, the yellow star indicate where a box corer has been collected during ACUSCAL 2015 Cruise. The location is shown in Figure 1.*

Large flares have been recognised at the top of the mounds in the Adventure Bank, in the northern flank of the Graham Bank and at the top of a number of seamounts and in northern region of the Sicily Channel (Figure 5a, b).

Minor acoustic anomalies occur in correspondence to negative depressions or acoustic signals in the sub-seafloor. They often consist of high-amplitude pyramidal acoustic anomalies extending from the seafloor to the sea level (Figure 3a).

The dense network of CHIRP and multichannel seismic profiles reveal some localised blanked areas in the sub-seafloor. In the Sicily Channel, we have identified a number of blanked areas showing a transparent seismic facies often associated with a conical shape in the water column (acoustic anomalies, Figures 5 and 6).

## IV. SCANNING ELECTRON MICROSCOPY (SEM)

The SEM and the EDX examination shows that O, S and Ba are the dominant elements in the studied sample, which suggests the presence of Barium Sulfate (Barite) (Fig. 2).

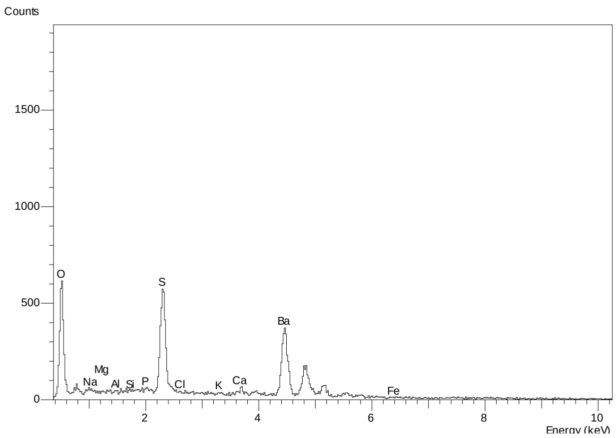


*Figure 6 EDX spectrum of the hard ground sample collected at the top of a mound (Adventure Bank) showed in Fig. 5b.*

## V. INTERPRETATION

The mapped and described submarine features are interpret to be signature of AFSs at the seafloor.

The 103 identified circular or elliptical depressions identified and mapped in the three study areas are interpreted as pockmarks formed by emission of fluids from the seafloor [9], [13], [14]. Pockmarks are described as circular erosive structures with variable diameters and depths [1]. They have physical features (size parameters, shape) comparable to similar features with the pockmarks described in recent works in the central Mediterranean Sea [10], [11].

The hydroacoustic anomalies observed in the CHIRP and in the Boomer profiles are interpreted as gas flares. Gas flares associated with vents of methane are well documented in different pockmarked region [11], [15]. The acoustic anomalies in the subseafloor are interpreted as possible gas chimneys. These gas chimneys are usually linked to pull-down and disturbance of adjacent reflectors. We thus suggest that the transparent seismic facies shown in Figures 4b, 5 are due to a strong contrast in acoustic impedance probably associated with the presence of fluid (or gas) in the sedimentary multilayer.

Roberts et al. 2006 suggest that “Slow-flux systems” are characterised by hardgrounds and mound-like buildups of authigenic carbonates.

Morphobathymetric and seismostratigraphic analyses highlighted the occurrence of mound-like structures revealing AFS because:

1) they have seismic features, shapes and sizes similar to the main mound-like structures described in different regions of the central Mediterranean Sea [10], [11];
2) they show a transparent seismic facies typical of presence of gas or fluid in the sub-seafloor (Figures 3a, 4, 5b);
3) they show at their top evidence of the gas chimney;
4) the Scanning Electron Microscopy analysis and EDX spectrum showing the presence of barite suggest the occurrence of fluid emission from the seafloor supporting our interpretation of these positive features as active fluid seepage.

## VI. CONCLUSIONS

In the present work, we show and discuss the morphological, seismic and geochemical features of a number pockmarks, mounds, flares and gas chimneys, using different types of marine geological data combining high resolution acoustic data and seismic profiles (low and high resolution) with sedimentological and geochemical data acquired in the Northern Sicily offshore and in the Sicily Channel. The presence of these features comprise evidence of the occurrence of AFSs in the northwestern Sicily continental margin, northwestern Sicily Channel and in the Maltese Islands Offshore (central Mediterranean Sea).

## VII. ACKNOWLEDGEMENT

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