Introduction. Cold seeps are seafloor expressions of focused and diffuse fluid flow in the marine environment (Judd and Hovland, 2007). Cold seeps can have different seabed morphologies and deeper structures to form their plumping system, they can be distinguished in: oil and gas seeps, gas hydrate pingoes, brine pools, pockmarks, mud volcanoes and diapirs. Several processes have been invoked to explain, for example, the main mechanisms involved in the formation and growth of pockmarks, which are the most distinct feature at gas seeps and escapes, but these have remained, so far, largely unclear (Marcon et al., 2013), thought physical models have been advanced (Cathles et al., 2010). Normal fault mechanisms are now often recognized to be associated with the presence of seeps, mud volcanoes and pockmarks (Ostanin et al., 2013; Sultan et al., 2014), with faults acting as the deep-rooted plumbing system, often along salt diapir flanks and related faults, along which the fluid flux is high (Serié et al., 2012).

Cold seeps slowly release hydrogen sulfide, methane and other hydrocarbon-rich fluids in the water column and, for this reason, they are considered possible players in the global greenhouse gas emission budget and the consumption of oxygen at the seafloor (Boetius and Wenzhöfer, 2013). Uncertainties remain regarding the quantity of free methane that is emitted from deep-water seeps into the water column, with several authors showing that, at least in gas hydrates scenarios, most of the methane emitted per year within the gas hydrate stability zone remain trapped in the deep ocean (Römer et al., 2012). The detection of the gas bubbles can be direct, using sophisticated sampling methodologies, or indirect by means of acoustic echo-sounders that detect gas bubbles in the water column, due to the acoustic impedance contrast between water and the free gas in the bubbles. More and more often swath bathymetry multibeam systems are now used not only to detect the gas flares (Schneider von Deimling et al., 2007), but also to precisely locate and map them and to assess a gross quantification of gas emission (Nikolovska et al., 2008).

The recognition of seep sites on the seafloor is often favoured by the detection of anomalously high acoustic seafloor backscatter on side-scan sonar or multibeam backscatter (Klaucke et al., 2008). High seafloor backscatter is caused by the enhanced acoustic impedance contrast between certain regions of the seafloor and their surroundings. At cold seeps, this contrast is caused by: sharp changes in the seafloor morphology (pockmarks, mud volcanoes); precipitation of authigenic carbonates at the seafloor; chemosynthetic organisms (clams, tube worms); bubbles or gas hydrates in the sediment (Naudts et al., 2008, for a complete review).

The cold seeps support biomes whose primary producers do not depend directly on photosynthesis. The alternative function is served by chemotrophic bacteria and archaea, which have symbiotic relationships to heterotrophic organisms which host them, often intracellularly. These bacteria are sulfide oxidizers, using the free energy yield from the oxidation of sulfide with oxygen to fix carbon dioxide. In exchange for providing nutrition for the host, the symbionts are sheltered from grazing and they receive a steady source of sulfide and oxygen (Boetius, 2005). The most common heterotrophic organisms found at these sites are: Vestimentiferan tube worms, mytilid mussels, vesicomyid clams and infaunal lucinids. Chemosynthetic bivalves are prominent constituents of the cold seep fauna and are represented by five families: Solemyidae, Lucinidae, Vesicomyidae, Thyasiridae and Mytilidae (Oliver et al., 2011). Bacterial mats are also frequently present at active sites.

Study area. Cold seeps were discovered at 500-1000 m water depth along the Paola Ridge, on the continental slope of the NW Calabrian margin (south-eastern Tyrrenian Sea, Fig. 1a),
first with the aid of only full-ocean depth multibeam and backscatter data (Gamberi and Rovere, 2010). The Paola Ridge is a NNW-SSE 60-km-elongated anticline that confines the Paola Basin westward. The Paola Basin lies at the rear of the Calabrian Arc, in the upper plate of the Ionian subducting slab (Faccenna et al., 2011), and formed due to the extensional tectonics that led to the opening of the Tyrrhenian Sea (Fig. 1b). On land, the Calabrian Arc is dissected by extensional fault zones (Van Dijk et al., 2000) and rift basins such as the Crati Graben (Fig. 1a), with ≈ 1 mm/yr E-W-oriented extension rate (D’Agostino et al., 2011).

Fig. 1 – a) Bathymetry of the Paola Ridge, seismicity is from Castello et al. (2006) and focal mechanisms are from Pondrelli et al. (2006). Information about symbols and features are provided in the legend. b) Geodynamic setting of the study area.
Higher resolution acquisitions and seafloor sampling were carried out in 2011 (Rovere et al., 2014a). The cold seeps in the area are represented by 2 mud volcanoes (RMV and R1MV structures) and 3 main mud diapir structures characterized by the presence of pockmarks (D1, D2, D3). There are other 4 pockmark-related dome structures in the area dissected by normal faults (Fig. 1a). The data lead to important findings and the discovery of active gas venting at the seafloor in the mud volcanoes and ceased seepage activity in the mud diapirs. In the study area, when the fluid flow is vigorous, it produces mud volcanoes, gas plumes in the water column and precipitates oxy-hydroxides, sulfides and siderites in the sub-seafloor. Conversely, when the flux is very low or even absent, authigenic calcite and aragonite, associated with chemosymbiotic fauna, are formed near the seabed on pockmarks-punctuated mud diapirs.

The mud volcanoes RMV and R1MV are characterized by high backscatter signature, related to the presence of gas venting at the seabed. Intermediate backscatter typifies areas where free venting is hampered by the presence of mudflows at the seafloor, downslope the mud volcano summits. The mud diapirs are, on the contrary, characterized by low seafloor backscatter, because the authigenic limestones are mostly buried below 1-2 m of sediment and locally exposed only along the normal faults. The carbonates have the typical isotopic signature indicating formation during sulfate-dependent microbially-mediated anaerobic oxidation of methane. They are associated with Lucinoma borealis, the youngest being dated 490 +/- 30 BP and with Acharax sp. the youngest dated 20,010 +/- 90 BP. This is the first documented occurrence of Acharax sp. in the Quaternary of the Mediterranean region and probably shows the replacement of the Acharax sp. with Lucina sp. in the cold seep habitat during the last sea level rise and general warmer conditions (Rovere et al., 2014b).

Siderites precipitated in burrows below the mud volcanoes and mud flows showed enrichment in $\delta^{13}$C and $\delta^{18}$O, which are compatible with their precipitation in the methanogenic zone (Rovere et al., in press). The heavy-oxygen isotopic compositions of the siderites are possibly related to the dissociation of gas hydrates, which have not been mapped in the seismic data (1 kJ sparker).

The same seismic data showed that NW-SE and NNW-SSE-oriented normal faults were the most probable mechanism for the emplacement of the mud mobile structures (Fig. 1). These faults can be regarded as the marine prolongation of the fault zones that dissect the Calabrian Arc from SE to NW (Fig. 1a). According to the seismic data, diapirism is no longer active. The normal faults are exploited as primary conduits for upward fluid migration and control the seepage distribution and activity. In particular, tectonic structures control the shape and the distribution of the pockmarks, and the location where authigenic carbonates, associated with chemosymbiotic fauna, formed hardgrounds at the seafloor (Rovere et al., 2014a).

**Data and methods.** In June 2014 a multichannel seismic survey was undertaken in the cold seep area during the campaign MarBeep 2014 on board the R/V CNR Urania. The seismic was designed to image the deeper faults which were already suggested to be related to the seeps and that were not perfectly visible in the previously available data. 322 km of multichannel profiles were acquired (Fig. 1a). The seismic source was a single 60 in$^3$ mini GI-gun set in Harmonic Mode (30 Generator + 30 Injector) with a shot interval of 9.375 m at 2000 psi. The data were collected by a 300 m long, 96 channels digital streamer with a trace distance of 3.125 m. Both the gun and the streamer were towed at 1.5 m below sea level to minimize the ghost effect on the emitted spectrum (centred well above 200 Hz), thus preserving the high frequencies needed to better resolve the shallower targets. During the acquisition four birds leveller were used as a whole to keep the streamer at a constant depth. The choice of such an equipment and parameters drove to an excellent compromise between penetration (700 – 800 m) and resolution (metric along the vertical axes if assuming a $\lambda/4$ criterion, with an actual 1.56 m lateral distance between the traces in the stack section). The acquisition parameters are summarized in Tab. 1.

With this configuration, resulting in an effective horizontal sampling of 1.56 m in the stacked section, the maximum attainable fold coverage was 16 traces / CDP.
The SEG-D raw data were processed on a dedicated workstation. The quality control was performed on board, both on the single shots and the whole profiles by screen display and plotting of the near trace sections.

The quality control and the preliminary processing were performed on board by means of the GEDCO Vista Seisimage package. A conventional processing sequence was applied that included trace editing, amplitude recovery, band pass filtering, interactive velocity analyses, normal move out corrections and stack.

The seismic data acquisition was coupled with the acoustic detection of the water column using the Kongsberg EM710 and EM302 multibeam systems that are both hull-mounted on board the R/V Urania. Water column data were processed with the Fledermaus Midwater

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<th>Acq. Parameter</th>
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Fig. 2 – Stacked gas plumes detected in the water column by the EM302 multibeam system along a transect over the R1MV mud volcano. Location in Fig. 1.
module (Quality Positioning Services B.V.). This tool shows water column data with their exact position in space and time, preserving relevant information, such as time-based navigation and attitude (roll, pitch and heave corrections). The time series were sub-sampled during format conversion, yet preserving the full resolution of the water column features.

**Preliminary results and conclusions.** Due to the optimal compromise solution of penetration/resolution, it was possible to achieve two main results:

1) to map the sedimentary sequence down to the M reflector, which is generally interpreted to be the top of the Messinian evaporites (about 1-1.5 TWT seconds deep, Fig. 3) in the Mediterranean area;

2) and to keep the highest resolution in the shallower part of the sub seafloor, where free gas accumulations and seep conduits were the primary target of the investigation.

It has been thus confirmed that gas emissions at the seafloor occurred exclusively in the areas of highest backscatter. Only one point of high backscatter was not associated with gas venting at the seafloor. The sampling of sediment over this high backscatter spot revealed that the high reflectivity was due to the presence of a steep slope and hardground at the seafloor.

Free gas is visible in the seismics close to the seafloor (Fig. 3) and almost everywhere coincides with the gas flares. This setting is very similar to the Hikurangi Margin, New Zealand, where seepage is associated with the gas hydrate system (Crutchley *et al.*, 2010). Very suspicious and anomalous signals, that are present in the seismic data, can be related to bright spots or to the presence of a deep BSR, but this must be analyzed in more detail with a specific processing sequence.

Mud diapirs (not depicted here) lie directly on top of convex bending of the Messinian reflectors; this occurs also, even if geometries are questionable there, in the mud volcanoes (Fig. 3). The mud diapirs develop along deep-rooted normal faults, which are now fully imaged by seismic data, and are covered by at least 200 TWT ms of sediment which appear to lie directly on top of the M reflector. The relationships between the supposed salt diapirs and the pockmark-related mud structures must be constrained in more detail.

A new fault segment was imaged in the sedimentary sequence of the southern Propeller basin, this fault does not reach the seafloor and has no bathymetry morphology, but it can be interpreted as the prolongation of the fault dissecting diapir D2 (Fig. 1a). This fault is also the theoretical prolongation of the fracture zone SDFZ (Fig. 1a) on land, and this finding seems to confirm the main fault axes that were already hypothesized to be responsible for the geometry of the Propeller Basin (Fig. 1a).

Further lines were shot on the very southern end of the Paola Ridge to cross the possible offshore part of the SLFZ fault zone (Fig. 1a), where also some earthquakes show a faint alignment, but preliminary interpretation of the stacked sections did not image any active fault, with faults ending their activity probably at the base of the Plio-Quaternary reflector.

Another interesting goal achieved with the new seismic data is in fact the possibility to clearly differentiate between active and buried faults. Most of the faults that appear not being
active, they still offset the sediments till very recent time (a precise seismic stratigraphy of the area is not available) and must be reconsidered in the seismo-tectonic assessment of the eastern Tyrrenian margin.

In brief, during the MarBeep 2014 multichannel seismic investigations and detection of the acoustic backscatter of the water column by multibeam systems were carried out together. The results of these surveys allowed to define the depths of the free gas zones and to map their extent ratio. Further analyses, including seismic amplitude, will be necessary to precisely locate the seeps and define their exact geometry and to tie them to their deepest source, which indeed look to be the Messinian evaporites, as previously suggested.

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