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Fluid escape structures in the north Sicily continental margin

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A B S T R A C T

High resolution and multichannel seismic profiles coupled with multibeam echosounder (seafloor relief) data, acquired along the northern Sicily continental margin (southern Tyrrhenian Sea), document the occurrence of mound and pockmark features, revealing fluid escape processes. Along this margin, morphology of the high-gradient continental slope is irregular due to the presence of structural highs, slope failures and canyons, and is interrupted by flat areas at a mean depth of 1500 m.

Seismostratigraphic analysis tools and methods were used to identify fluid escape structures and to work out a classification on the basis of their morpho-acoustic characteristics. The detailed 3D bathymetric chart was used to define the top view morphologic features and their areal distribution. With the aim to evaluate the geochemical content of fluids, we collected a 2.3 m long sediment core in correspondence of a pockmark at a depth of 414 m. Pore waters were sampled every 10 cm and analysed in relation to their conductivity (EC) and composition ($\delta^{18}O$, δD, Li, Na, K, Mg, F, Cl, Br, NO_3, SO_4).

The new data show the occurrence of different types of structures with highly contrasting seismic and morphologic signatures, both dome-type and concave-upward structures. The latter have a characteristic circular shape and are known as pockmarks. Morphobathymetric, stratigraphic and structural data suggest that these structures occur along fault planes, mainly associated with diagenetic carbonates and fluid venting activity. Pockmarks could be the result of both fault and landslide structures, as they appear aligned along a straight direction and occur in proximity of the slope, and are associated with slope instabilities. The structural features are possibly associated with the recent tectonics mapped on-land as well as the widespread seismicity of the margin.

Geochemical features reveal that pore water is slightly enriched in heavy isotopes with respect to Mediterranean seawater, while the distribution profiles of EC, ion concentration (Cl, SO_4, Na, K, Mg, Ca), ion/Chloride ratios (Na/Cl, K/Cl, Ca/Cl, Mg/Cl and Alk/Cl) seem to indicate the existence of an external source of fluids and the occurrence of sediment-fluids interaction processes. A possible mechanism causing pore water freshening could be the destabilisation of gas hydrates.

1. Introduction

The presence of morphological submarine structures linked with escaping fluids alongside continental margins has been largely documented, due to the growing development of techniques of shallow-deep-water exploration. At continental margins, seafloor manifestations of fluid seepage include positive relief structures such as mud volcanoes, mud diapirs, authigenic carbonates (chemoherm structures), as well as negative ones such as pockmarks, and also gas flares reaching several hundreds of metres into the water column (Hovland et al., 2005). These structures can be found in different tectonic settings, but they generally form in active margins (Milkov, 2000; Kopf, 2002). Released fluids have effects on the global carbon cycle (Judd, 2003) and improves the development of the seabed ecosystems (Berndt, 2005).

Fluid escape structures are most common in rapidly deposited, poorly sorted, fine- to medium-grained sands (Lowe, 1975). Fluids during consolidation, escape from sediments; and can interact with grains in four ways: seepage, liquefaction, fluidization, and elutriation (Lowe, 1975; Owen, 1987; Nichols et al., 1994), modifying their packing.

Masson et al. (2003) suggest that mounds and pockmarks are both related to escaping fluids (pore waters) from the seafloor; mounds are formed when subsurface sand is carried to the surface by the escaping fluids and is not dispersed by weak currents, whereas pockmarks occur in the absence of subsurface sand where

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muddy material is eroded and dispersed by bottom currents (Hovland and Judd, 1988).

Consequent to King and MacLean's (1970) initial discovery of pockmarks, many authors have proposed several theories explaining their formation (meteor impacts, iceberg dropstones, events related to the last ice age, scour hollows around boulders and biological activity); nevertheless all of them agree that ascending gas or water is the main cause (Hovland and Judd, 1988; Kelley et al., 1994; Plaza-Faverola et al., 2011). In areas where pockmarks are not active, they could have been formed during sea level falls, which cause a reduction in hydrostatic pressure and, consequently, an excess in pore pressure (Lafuerza et al., 2009). They can be identified by acoustic turbidity and bright spots, occurrence of bacterial mats, high methane concentrations in seabed cores, gas bubbling and sediment plumes in the water column.

Pockmarks are usually described as circular or nearly circular erosive structures, 10–700 m in diameter, and from a few metres to 45 m in depth (Judd and Hovland, 2007; Hovland et al., 2010). They occur singly or randomly, in cluster, and aligned along the strike of faults (Pilcher and Argent, 2007). They can be formed at all water depths in any marine or lake environment when sources of fluid and fine grained clays are present. The pockmarks are common in oil-rich regions (Hovland et al., 1984; Rise et al., 1999), areas with crystalline basement sub-outcropping, estuaries and coastal zones (Hill et al., 1992; Garcia et al., 1999), and in areas of high groundwater flow (Bussmann and Suess, 1994), lakes, with or without hydrothermal activity (Pickrill, 1993).

Pockmarks are recognised in areas subject to submarine landslides, adjacent to the main scarp of the landslide in unconsolidated sediments (Hovland et al., 2002), such as Storegga in the Norwegian margin, and the Humboldt Slide on the Californian offshore (Baraza et al., 1999; Yun et al., 1999). They provide information on the change in pressure, which can be useful for the control of the stability in areas prone to sliding (Berndt et al., 2012).

The fluid escape structures are often associated with tectonic elements and are aligned along the same direction. Sometimes, the migration of fluid along fault planes to the seafloor as gas venting is observed (Forrest et al., 2005). Fault planes and permeable layers are preferential ways both horizontal and vertical of fluid migration.

Moreover, several observations suggest that pockmarks are earthquake precursors, as it has been noted that before the seismic events the seawater temperature increases and afterwards pockmarks still vent gas bubbles (Dando et al., 1995; Hasiotis et al., 1997; Soter, 1998). So, it is evident that there is a correlation between fluids and seismic activity due to the fact that fluids tend to act as a lubricant in faults (Kanamori and Brodsky, 2001).

Morphobathymetric and seismic reflection data, collected during several cruises in the northern Sicily continental margin, allowed a detailed mapping of the platform-upper slope system, revealing the presence of submarine structures, both on the seafloor and in the subsurface, associated with rising fluids.

In this study, we illustrate the morphology, seismostratigraphic characters and geochemical features of pockmarks occurring in the Palermo Gulf continental slope (northern Sicily offshore), by using morphobathimetric, high resolution and multichannel seismic reflection profiles, calibrated by lithological and sedimentological data coming from a core drilled inside a pockmark and geochemistry of pore water trapped in the core sediments. The main focus of this study is to reconstruct the origin of the morphological submarine structures linked with escaping fluids and their buried pathways, in order to characterise the subsurface source of gases and waters, as well as the geological–geochemical processes developing during the evolution of the northern Sicily continental margin.

2. Geological setting

The Palermo Basin forms part of the northern Sicilian continental margin (Fig. 1), in the transitional area between the thick continental crust of the Sicilian-Maghrebian Chain to the south, and the thin transitional-oceanic crust of the Tyrrhenian back-arc basin to the north (Kastens et al., 1988; Scarascia et al., 1994).

This region originated as a consequence of a complex interaction of compressional events, crustal thinning and strike-slip faulting (Pepe et al., 2005). Tectonic activity started in the early–middle Miocene with the thrusting of the Kabilian-Calabrian units and deformation of the most internal units of the Sicilian–Maghrebian chain (Catalano et al., 1985; Pepe et al., 2005), while the opening of the Tyrrhenian Sea led to the subsidence of the margin since the Late Tortonian (Bacini Sedimentari, 1980; Fabbri et al., 1981). Late Miocene–early Pliocene high-angle reverse faults, involving mainly deep seated carbonate units, produced structural highs (Avellone et al., 2010), representing the northern shoulders of intraslope basins (e.g. the Palermo Basin), termed "peri-Tyrrhenian basins" (Selli, 1970), which originated as a consequence of crustal thinning. These basins were eventually filled with Upper Neogene to Quaternary evaporitic, hemipelagic, siliciclastic and volcaniclastic deposits, up to 1200 m thick (Bacini Sedimentari, 1980). Normal faults affected the inner side of the margin during the middle(?)–late Pliocene, partly dissecting the back- and fore-limbs of the structural high, and generating major extensional basins with a prevailing syn-tectonic deposition (Pepe et al., 2003). E–W, NW–SE and NE–SW-trending normal faults with a local strike-slip component, exerted control on the morphology of the present day shelf and coastal areas during the Pleistocene. Folding of Upper Pliocene–Pleistocene basin infill (Agate et al., 1993) and positive flower structures (Del Ben and Guarnieri, 2000) reveal the alternation of extensional/transtensional and compressional/transpressional activity until the recent time. The present-day resulting morphology is an alternation of morphostructural highs and depressions from west to east, and the occurrence of structural thresholds from the continental shelf to the bathyal plain.

Tectonic activity persists today with the occurrence of shallow (<25 km) seismic events of low to moderate magnitude (max Md 5.6 in September 2002; www.ingv.it). The upper plate seismicity of the northern Sicilian margin is defined by compressional focal mechanisms to the west and extensional to strike-slip mechanisms to the east. In the study area, seismicity is mainly located northward along an ENE–WSW trending belt in agreement with a dominant NE–SW fault trend coupled with a NW–SE compressive stress field (Agate et al., 2000; Giunta et al., 2009).

The highest uplift rates during the last 125 ky, in northern Sicily, were found on inner margin-terraces located along the eastern coast (0.8–1.63 mm/y). The vertical tectonic rates show a decrease from E to W, with the relative movements of adjacent sectors highlighting the role of coseismic activity of main structural features during the Pleistocene (Sulli et al., 2012). Inshore and offshore geologic data on the north-eastern margin demonstrate that while the mainland sector is uplifting, the offshore area is presently subsiding, suggesting the activity of fault systems parallel to the coastline, causing differential vertical movements (subsidence vs. uplift) (Sulli et al., 2012). On the other hand, observations from the northwestern margin suggest a present-day stability, except for local vertical movements in the Castellammare area, where uplift rates reach 0.1–0.2 mm/y (Mauz et al., 1997; Antonioli et al., 2006).

The present-day northern Sicily continental margin is composed of: (1) a narrow (up to 10 km) and steep (up to 2.5°) continental shelf, with the edge between −95 m and −140 m; (2) a steep (up to 14°) upper continental slope ranging in water depth from 150 to 1000 m; (3) a flat intra-slope basin at a depth of 1500 m; (4) a lower