Biogeosciences Discuss., 10, 967–1009, 2013
www.biogeosciences-discuss.net/10/967/2013/
doi:10.5194/bgd-10-967-2013

Biogeosciences
Discussions

The Gela Basin pockmark field in the strait of Sicily (Mediterranean Sea): chemosymbiotic faunal and carbonate signatures of postglacial to modern cold seepage

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Received: 10 December 2012 – Accepted: 12 December 2012b – Published: 22 January 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The geo-biological exploration of a pockmark field located at ca. −800 m in the Gela basin (Strait of Sicily, Central Mediterranean) provided a relatively diverse chemosymbiotic community and methane-imprinted carbonates. To date, this is the first occurrence of such type of specialized deep-water cold-seep communities recorded from this key region, before documented in the Mediterranean as rather disjunct findings in its eastern and westernmost basins. The thiotrophic chemosymbiotic organisms recovered from this area include empty tubes of the vestimentiferan *Lamellibrachia* sp., loose and articulated shells of lucinids (*Lucinoma kazani, Myrtea amorpha*), vesicomyids (*Isorropodon perplexum*), and gastropods (*Taranis moerchi*). A callianassid decapod (*Calliax* sp.) was consistently found alive in large numbers in the pockmark mud. Their *post-mortem* calcified parts mixed with molluscs and subordinately miliolid foraminifers form a distinct type of skeletal assemblage (named DECAMOL). Carbonate concretions display δ^{13}C values as low as −40 ‰ PDB suggesting the occurrence of light hydrocarbons in the seeping fluids. Since none of the truly chemosymbiotic organisms was found alive, although their skeletal parts appear at times very fresh, some specimens have been AMS-^{14}C dated to shed light on the historical evolution of this site. *Lamellibrachia* and *Lucinoma* are two of the most significant chemosymbiotic taxa reported from various Mediterranean cold seep sites (Alboran Sea and Eastern basin). Specimens from station MEDCOR78 (pockmark#1, Lat 36°46′10.18″ N, Long 14°01′31.59″ E, −815 m) provided ages of 11 736 ± 636 yr cal BP (*Lamellibrachia* sp.), and 9609.5 ± 153.5 yr cal BP (*L. kazani*). One shell of *M. amorpha* in core MEDCOR81 (pockmark#6, Lat 36°45′38.89″ N, Long 14°00′07.58″ E, −822 m) provided a sub-modern age of 484 ± 54 yr cal BP. These ages document that fluid seepage at this pockmark site has been episodically sustaining thiotrophic macrobenthic communities since the end of the Younger Dryas stadial up to sub-recent times.

1 Introduction

Pockmarks are circular to sub-elliptical crater-like depressions of variable size (few to many hundreds of meters in diameter) and depth (up to few tens m) typically due to degassing of fluids through fine-grained unconsolidated marine sediment under a variety of geologic scenarios (King and McLean, 1970; Hovland, 1989, 1992; Scanlon and Knebel, 1989; Kelley et al., 1994; Gay et al., 2003; Trincardi et al., 2004; Paull et al., 2007). Pockmarks often occur in clusters and cover wide areas, representing a common and widespread feature on the continental margins worldwide (Hovland and Judd, 1988). They receive much attention especially because escaping fluids are often hydrocarbon-enriched venues in the form of slow seepage, vigorous venting or even eruptions, at times representing a distinct geo-hazard for offshore constructions and navigation (Newton et al., 1980; Hovland, 1987; Curzi et al., 1988; Curzi, 2012). Such fluid releases are also considered as a potential co-actor in triggering mass-sediment failure along continental margins, in conjunction with sea level changes or earthquakes (Minisini and Trincardi, 2009). Pockmarks are known to host at times peculiar biota in response to nature of escaping fluids, rate of emissions, seepage resilience and water depth (Hovland and Thomsen, 1989; Hovland and Judd, 1988; Taviani, 2011, 2013). Gas charged sediments may in fact sustain microbiological communities operating on common compounds in fluids, i.e. hydrogen sulphide and hydrocarbons like methane (Cavanaugh et al., 2006; Dando, 2001; Duperron, 2010). In turn, such communities could be exploited by specialized metazoans through complex symbiotic relationships (see MacDonald et al., 1990; Olu-Le Roy et al., 2007; Taviani, 2001; Duperron, 2010, with references). Pockmarks are also sites were methane-related authigenic carbonates could be generated (Hovland et al., 1987; Hovland and Judd, 1988; Gontharet et al., 2007).

In the frame of the EU Hermes and Hermione projects, the Strait of Sicily in the central Mediterranean was targeted as a key area where to study sediment instability processes that affect continental margins. During such exploration a field of pockmarks

was charted and sampled in detail off the southern margin of Sicily (Fig. 1). Here we present first data on deep sea pockmarks in the Gela basin resulting in novel information about resident chemosymbiotic communities, bio-sedimentological processes, authigenic carbonates and seepage temporal variability in this sector of the Mediterranean Sea connecting its western and eastern basins.

2 Material and methods

The study area was surveyed during cruises HERMES05 (July 2005), MEDCOR and DECORS December 2009 and August 2011 respectively of R/V *Urania*. Swath-bathymetry data were acquired using a Kongsberg Simrad EM710 multibeam echo-sounder with a nominal sonar frequency of 70–100 kHz an angular coverage sector of 140°, a beam width of 1° × 1° and 800 soundings per ping in dual mode. Chirp-sonar profiles were obtained using a hull-mounted sixteen-transducer source with a sweep modulated 2–7 kHz outgoing signal equivalent to a 3.5 kHz profile

Bottom sampling were performed using a 1.2 ton gravity corer, large volume grab and epibenthic hauls (Table 1).

Water-column attributes were measured with a Conductivity/Temperature/Depth profiler (CTD) using a Seabird SBE 11 PLUS employing the SEASAVE V5.33 software.

Stable isotope analyses were performed at the Mass Spectrometry Laboratory of the CNR-IGG (Institute for Geosciences and Earth Resources) Pisa, using a Finnigan MAT252 mass-spectrometer. The carbonate samples were cleansed, powered and then analysed following standard procedures by reacting carbonate aliquots with 100 % orthophosphoric acid under vacuum. Results are expressed as ‰ relative to VPDB (Vienna-Pee Dee Belemnite) standard by assigning a value of +1.95 ‰ (^{13}C) and a value of −2.2 ‰ (^{18}O) exactly to NBS 19 calcite; the analytical error is $\pm 0.1\delta$ (Table 2).

^{14}C-AMS dating was carried out at the Poznán Radiometric Laboratory, Poland (Table 3).

3 The pockmark field of Gela

Pockmarks are common features at many continental margins in the Mediterranean basin (Stefanon, 1981; Stefanon et al., 1983; Curzi and Veggiani, 1985; Mazzotti et al., 1987; Hovland and Curzi, 1989; Trincardi et al., 2004; Geletti et al., 2008; Coleman et al., 2012; Curzi, 2012; Somoza et al., 2012). They have been recently documented also in various locations of the Strait of Sicily, although most published studies regard relatively shallow-water (ca. 70–200 m) occurrences (Savini et al., 2009; Cangemi et al., 2010; Micallef et al., 2011). Pockmarks do occur in the Gela basin at bathyal depths (Minisini and Trincardi, 2009, this paper).

Gela basin is the Plio-Quaternary foredeep of the Maghrebian fold-and-thrust belt and is a site of widespread and repeated mass transport. Gela Slide, the largest mass-transport complex in the area, has affected the northern margin of the basin mobilizing a volume of sediment in the order of 1000 km^3 in mid-Pleistocene times (Trincardi and Argnani, 1990). Following this major basin-wide event, several smaller-scales mass-failure events impacted the area up to the Holocene (Minisini et al., 2007) and with recurrence intervals in the order of few thousands of years between successive events (Minisini and Trincardi, 2009). The most recent mass-transport events involved, in various mixes, two basic distinctive kinds of slope sediments: the Pleistocene clinoforms that prograde with increasing slope angle and outbuilding the shelf seaward; and upper-Pleistocene to Holocene muddy contourite deposits characterized by water-saturated and poorly consolidated sediment (Verdicchio and Trincardi, 2008). In all cases where stacked MTD deposits appear sandwiched within basin-wide draped units, the latter units appear disrupted by vertical features that have been ascribed to fluid-escape features from MTDs that became rapidly buried and perhaps pressurized (Minisini and Trincardi, 2009).

The Gela basin pockmark field (GBPF) is located in the Strait of Sicily, ca. 20 nm offshore the southern coast of Sicily in a depth range of 800–900 m (Fig. 1). Firstly detected upon TOBI side scan sonar in 2003 and by low-resolution multibeam bathymetric

data in 2005, the GBPF was then surveyed more in detail in winter 2009 and again in summer 2011 during Hermione cruise DECORS when high resolution multibeam data were acquired, and additional pockmark fields further west, identified.

The resulting detailed morpho-bathymetric map documents the existence of discrete clusters of pockmarks in a restricted sector of the Gela basin (Figs. 1–4). Our data do not show any clear preferential orientation of these features. All pockmarks in the studied field are clustered in seven seafloor patches for a total area of about 18 km^2. The pockmarks presents generally a sub-circular shape, with the exception of the pockmark 1 (Fig. 2) which is elliptical-shape, and range in diameter from 40 to 310 m, although most of them are between 40 and 100 m and only 11 (Fig. 2) are between 200 m and 310 m. The bottom of some of these is as much as 20 m below the surrounding seafloor; most however are less then 6 m deep. In cross section, extracted from the bathymetric profile, the pockmarks in most case appear to be U-shaped; but four of them are V-shaped and (Fig. 2) show a positive relief ranging from 4 m to 7 m along their rim. The side slope ranges from 7° to 13° reaching the maximum of 16°. The regional surrounding slope is about 2–3°. Width to depth ratio were calculated for 11 pockmarks form bathymetric profiles crossed near the feature centres. The ratio fell between 11 : 1 and 40 : 1 with most near 18 : 1. There is not consistent relation between this ratio and relative size of the pockmark.

Noticeably, acoustic signals relatable to the presence of gas entrapped in the sediment (such as BSR) or to active degassing (plumes) were not detected during both surveys (Fig. 5). Furthermore, CTD profiles show no T-S anomalies.

The largest depression with an internal bulge, resulting from the coalescence of two pockmarks, was selected as the prime target for bottom sampling. The entire area is a fishing ground subjected for many years to a peculiar local fishing (mal)practice known as *cannizzi* that litters the bottom by leaving behind scores of dead weights with long plastic threads attached (Taviani, 2010). Before proceeding with grab and core sampling, and CTD casting, it was therefore necessary to clear first the bottom by removing this litter. This goal was achieved by using a small modified haul that in fact successfully entangled some such *cannizzi* remains (threads and some weights), the former intensely overgrown by live cold water corals. A second trawl on the same trajectory intercepted the bottom collecting many dead shells of *Lucinoma* clams and tubeworms, living ghost shrimps and a few carbonate concretions amidst other benthic organisms and litter (Fig. 7a). Only at this stage, this large pockmark and some other pockmarks in the area were tested with grab sampling and coring, integrating the exploration with CTD casts. Additional bottom samples were acquired in 2011 and on this occasion other pockmarks were also sampled.

4 Fauna

The living component in the benthic macro- and megafauna inside the pockmarks at the time of sampling was rather scarce and mostly represented by sparse bivalves (*Ennucula corbuloides, Cardiomya costellata, Kelliella miliaris*), caprellid amphipods and ghost shrimps. Numerous specimens of a callianassid ghost shrimp (*Calliax* sp.: Fig. 7f, Table 4) were found in pockmark # 6. This is likely a still undescribed species morphologically close to an elusive callianassid taxon reported from shallower settings in the Western Mediterranean (de Gaillande and Lagardère, 1966). This species is consistently associated with such type of environments since a few specimens of this same shrimp have been also found in active pockmarks in the central Adriatic (Taviani et al., 2010). Members of family Callianassidae are known to inhabit deep sea reducing habitats worldwide (summarized by Komai and Fujiwara, 2012). In the eastern Atlantic sector close to the Mediterranean, a new subfamily (Vulcanocalliacinae) and a new species (*Vulcanocalliax arutyunovi*) have been recently described by Dworschak and Cunha (2007) from a mud volcano in the deep Gulf of Cádiz.

The macrofaunal death assemblages recovered from the GBPF show a predominance of benthic molluscs over other components, predominantly decapods, pelagic molluscs, echinoids, serpulids and octocorals, Non-seep organisms are more diverse in terms of number of species (Appendix A) but chemosymbiotic bivalves in the families

Lucinidae, and Vesicomyidae are at places noticeably abundant (Table 4). Lucinids are represented by the large Mediterranean endemic taxon *Lucinoma kazani* Salas and Woodside (2002) (Fig. 7c), and subordinately by *Myrtea amorpha* Sturany, 1896 (Fig. 7e). Vesicomyidae are represented by the Mediterranean endemic *Isorropodon perplexum* Sturany, 1896 (Fig. 7b), the sole species recorded that far from the recent Mediterranean basin. Such bivalves have been recorded from deep sea reducing habitats in the Mediterranean basin (Corselli and Basso, 1996; Cosel and Salas, 2001; Olu-Le Roy et al., 2004; Werne et al., 2004; Duperron et al., 2007; Duperron, 2010; Ivanov et al., 2010a, b; Ritt et al., 2010; Brissac et al., 2011; Shank et al., 2011; Taviani, 2011; Rodrigues et al., 2012).

Another remarkable megabenthic organism found in the GBPF is a siboglinid tubeworm of which only empty tubes have been collected by us (Fig. 7a). The morphology of the tube resembles *Lamellibrachia*, a genus recorded from deep water cold seep sites (Olu-Le Roy et al., 2004; Werne et al., 2004; Duperron et al., 2009; Ritt et al., 2010; Hilário et al., 2011; Taviani, 2011), sunken wrecks (Hughes and Crawford, 2006; Gambi et al., 2011), and hydrothermal vents (Lott and Zimmerman, 2012) in the basin. Tubes might belong to *Lamellibrachia anaximandri* Southward, Andersen and Hourdez (2011), described from the Anaximander mud volcano in the eastern Mediterranean (Southward et al., 2011), and possibly much widespread in the entire Mediterranean basin (references in Taviani, 2013).

In addition to these well known deep-water chemosymbiotic metazoans, we can further list few other taxa preferentially coping with reducing environments i.e. thyasirid (*Thyasira*, *Mendicula, Axinulus, Axinus*) and lucinid (*Myrtea spinifera*) bivalves (Dufour, 2005; Löffler et al., 2005; Taylor et al., 2007; Taylor and Glover, 2010; Brissac et al., 2011; Rodrigues and Duperron, 2011), and the turrid gastropod *Taranis moerchi* (Fig. 7d) that has been observed to be particularly common at such seep sites (Olu-Le Roy et al., 2004, M. Taviani, unpublished data). Only some pockmarks were found to contain spoils of truly seep communities that are instead totally absent from the seabottom outside the pockmarks (Appendix A). Furthermore, the more emblematic cold seep species (e.g., *L. kazani, I. perplexum, Lamellibrachia* sp.) are not co-occurring in all investigated pockmarks in the Gela basin, showing instead a spatial variability. On the other hand, spatio-temporal variability in analogue habitats responding to variability through time and space of fluids' composition and flow intensity is a well documented trait at modern and past seepage sites (Olu et al., 1997; Jenkins et al., 2007; Olu-Le Roy et al., 2007; Lessard-Pilon et al., 2010). As it is often the case, the sustainability of such chemosymbiotic bivalves and siboglinids relies upon high sulphide concentrations since their metabolic pathway is thiotrophic. Thus, they cannot be considered as direct fingerprints of hydrocarbon availability in the seeping fluids at the GBPF.

5 Seep carbonates

- *Sediments.* The pockmark field affects a predominantly silicoclastic-muddy sector of the southern Sicilian margin. Sampling however reveals the occurrence of biogenic carbonate production in the form of skeletal components shed primarily by calcified benthic organisms and subordinately by pelagics. A distinct type of carbonate biogenic sediment is produced here through cold seep factories in the form of medium to coarse skeletal assemblages enriched in shells of chemosymbiotic bivalves (mainly vesicomyids), and calcified parts of callianassid decapods. This remarkable sediment represents a novelty not contemplated in the current schemes of skeletal sediment classification (e.g., Hayton et al., 1995). While the geographic location of the study area would require placing related skeletal sediment here among heterozoan carbonates, their genesis is in fact substantially unrelated to climate but to chemical carbonate factories. Therefore, we introduce the name DECAMOL (Fig. 7) to highlight the two major forming skeletal components in the sand to hash fraction, i.e. DECApods (callianassid: 30–50 %) and MOLluscs (20–40 %). Secondary components in order of abundance are miliolid foraminifers (5–10 %), followed by echinoids, serpulids, ostracods and octocorals and pelagic shells. DECAMOL sediment was documented at various pockmarks in the Gela basin. Since deep-water cold seep habitats owing modern-type chemosymbiotic molluscs and seep-related decapods are geographically diffuse in the Ocean, Cainozoic to present, it is predictable that DECAMOL sediment would be identified at other sites beside the Strait of Sicily.

- *Authigenic carbonates*. Besides shells of chemosymbiotic bivalves and tubeworms, sampling from the GBPF produced also carbonate concretions, indurated burrows (Figs. 8 and 9), and cemented mudstones (Fig. 10). Microcrystalline pyrite druses were noticed on small darker carbonate concretions. Some carbonates were tested for the their stable carbon and oxygen isotopic composition (Table 2, Fig. 12). The δ^{13}C composition of chemosymbiotic bivalve shells display isotopic values around between −1.23 and +2.66 ‰ PDB reflecting the seawater carbonate reservoir as expected (Cobabe, 1998; Lietard and Pierre, 2009). The stable carbon composition of a poorly cemented layer in core MEDCOR 70, provided instead a δ^{13}C value of −40.77 ‰ PDB. A significantly carbon-depleted composition was also measured for concretioned mudstone encrusting a dead shell of the chemosymbiotic *Lucinoma kazani* which provided a δ^{13}C value of −37,57 ‰ PDB. Both very negative carbon signatures document unquestionably that at some time hydrocarbons were present in the seeping fluids of this pockmark field in the Gela basin). On the other hand this region is known to be highly productive for hydrocarbons (Etiope et al., 2002; Holland et al., 2003).

The stable carbon range is consistent with authigenic carbonates formed through the incorporation of carbon derived from anaerobic methane oxidation (Hovland et al., 1987; Roberts et al., 1987; Kulm and Suess, 1990; Aharon, 1994; Kelly et al., 1995; von Rad et al., 1996; Aloisi et al., 2000, 2002a, b; Elvert et al., 2000; Naehr et al., 2000; Greinert et al., 2001; Peckmann et al., 2001; Taviani, 2001; Gontharet et al., 2007; Campbell et al., 2008; Cangemi et al., 2010; Feng and Roberts, 2010; Ivanov et al., 2010a, b; Himmler et al., 2011; Capozzi et al., 2012). The presence of pyrite might represent a legacy of sulphate reduction in the formative environment of such carbonates (e.g., Gontharet et al., 2007). Interestingly, the GBPF concretions represent a case of incipient embedding of chemosymbiotic infaunal and epifaunal organisms in authigenic carbonates (Lalou et al., 1992), eventually turning into macrofossiliferous cold-seep rocks as those diffused in the Neogene Apennine chain (Taviani, 1994, 2001 and 2011). Finally, the stable oxygen composition of bivalves (δ^{18}O values comprised between +2.21–2.71 ‰ PDB) are interpretable as indicative of bottom cold temperatures (cf. Sakai et al., 1992), thus supporting the late glacial ages obtained by radiocarbon dating (see below).

6 Age constraints

The absence of distinct signals documenting either active degassing or gas charged-sediment close to surface and the lack of live chemosymbiotic macro- and megafauna was taken as an indication that seepage backing the genesis of the GBPF is at present either dormant/episodic or ended. In order to unravel this fundamental aspect we examined the core record, and carbon-dated faunas and carbonate concretions. Superficial bottom samples and two sedimentary cores were taken from pockmark 1 and 6 (respectively MEDCOR81 and MEDCOR70) to reconstruct the recent history of fluid seepage at this place (see Fig. 11). A tube of *Lamellibrachia* produced an AMS-^{14}C age of 11 732 ± 611 yr cal BP, while a valve of *Lucinoma kazani* provided an AMS-^{14}C age of 9610 ± 154 yr cal BP. A valve of *Myrtea amorpha* from sediment core MEDCOR 70 provided an AMS-^{14}C age of 484 ± 54 yr cal BP. Although potentially somewhat influenced by carbon sourced from seeping fluids, our radiocarbon ages clearly indicate that seepage activity in the pockmarks is lasting, albeit not necessarily continuatively, since the end of the last glacial epoch (Younger Dryas stadial) up to sub-recent times.

7 Discussion

The pockmark area investigated in this study is located at the base of the northern slope of Gela basin where Chirp-sonar profile detect the top of the last basin-wide MTD at a depth of few tens of meters under a succession of basin-floor muddy turbidites. The pockmarks area are not randomly distributed but corresponds to a bulge at the base of slope with a positive relief of few km^2 (Figs. 1 and 3) and the overlying succession, characterized by draped and onlapping plain-parallel reflectors (muddy turbidites?) thins toward the slope and are breached by the pockmarks (Fig. 6). The perfect matching of the pock mark field with the slide-related base-of-slope bulge is suggestive of a possible causal relationship. In this view the fluids emanating through the pockmarks would be fed from the MTD, acoustically-transparent and possibly gas-charged deposit. However, in the lack of deeper-penetration MCS profiles we cannot rule out the possibility that fluids come, at least in part, from beneath the MTD rather than from it.

The genesis of the GBPF under study is thus not fully understood yet but a potential link between defluidization (pockmarks) and one of the main motif of this part of the continental margin (mass sediment failure) merits to be considered. In fact, this cluster of pockmarks in the Gela basin are just located distally in front of a complex made up by stacked multiple submarine mass-transport deposits of late Pleistocene age (Minisini et al., 2007). These composite units are by large buried and only a few are exposed at present on the seabottom, the best examples of which are the “twin slides” whose multi-phase emplacement occurred since the last Post-Glacial (Minisini et al., 2007; Minisini and Trincardi, 2009). Pore fluid gradients, resulting in fluid migration and eventual expulsion onto the seabottom, are suggested to be a potential co-driving factor, although not necessarily the dominant, in triggering episodic mass-transport events that shape this region (Minisini et al., 2007; Minisini and Trincardi, 2009). The GBPF under scrutiny here lies ca. 5 nm away to the west of the “twin slides” and do not appear to have contiguity with such features, suggesting that no causative link between the two phenomena (twin-slide-slumping and pockmark-fluid expulsion) does exist. A series of still-unexplored pockmarks has been, however, identified at the toe of the "twin slides" (Minisini and Trincardi, 2009). It is predictable that they may in principle contain similar faunas and carbonates as their counterparts. The multiswath topographic map suggests the subsurface existence of now-draped lobate bodies northwards of the pockmarks, that in all likeness represent buried mass-transport deposits comparable to those described by Minisini et al. (2007) from this general area. The *mise-en-place* process of the slumping units may in theory cause squeezing out of entrapped fluids or, otherwise, the underpressuring of fluids related to sliding off sediment that may be conducive to gas release pockmarking the bottom. Release of hydrocarbons has been invoked as a likely mechanism to trigger submarine slumps (Carpenter, 1981 and many others). On-land, similar causative scenarios have been suggested to account for localized Miocene chemosymbiotic faunal assemblages and/or authigenic carbonates associated with slumped bodies in the Apennine chain (Berti el al., 1994; Conti and Fontana, 2002; Lucente and Taviani, 2005).

The GBPF shows a certain degree of homogeneity regarding the chemosymbiotic assemblages inhabiting individual pockmarks. This is especially true for small vesicomyids (*Isorropodon*), gastropods (*Taranis*) and callianassid decapods (*Calliax*) that are almost ubiquitous in our samples. Such homogeneity is not at all surprising once we consider the overall reduced variability of cold seepage at the GBPF when compared to larger and heterogenous seep sites as those observable elsewhere in the ocean (Olu et al., 1997; Sibuet and Olu-Le Roy, 2002; Olu-Le Roy et al., 2007; Cordes et al., 2010), or even in the Mediterranean itself (Olu-Le Roy et al., 2004). Such variability often reflects primarily variations in the fluid regimes (Teichert et al., 2003). Nevertheless, minor faunal differences are equally observable at the GBPF such as for example the comparable rarity of the large chemosymbiotic clam *L. kazani* or of the large vestimentiferan *Lamellibrachia* which are not recorded thus far from more than two pockmarks.

The GBPF is midway between the Eastern Mediterranean and Alboran basins where a variety of cold seep habitats is exploited by macro- and megabenthic organisms as

those found in the study area (e.g., *Lucinoma, Isorropodon* and *Lamellibrachia*). It thus represents a relevant site to be considered in the crucial and poorly-known issue of connectivity patterns among geographically disjunct but compositionally similar deep-sea chemosynthetic sites (e.g., Young, 2003; Tyler and Young, 2003; Olu-Le Roy et al., 2007; Marcus et al., 2009; Mullineaux et al., 2010).

8 Conclusions

1. The Gela basin deep-water pockmark field hosting Mediterranean-emblematic thiotrophic chemosymbiotic macro- and megafauna (*Lucinoma, Isorropodon, Lamellibrachia*) is relevant as it is the first such site in this key-region of the Mediterranean Sea transitional to its eastern and western basins;
2. the episodic occurrence of hydrocarbons in the seeping fluids is demonstrated by the occurrence of carbonate concretions and mudstones with very depleted stable carbon isotopic composition;
3. the quite different ages provided by organisms from individual pockmarks suggest that seepage activity in the area is not a uniformly-distributed and steady event but differs in space and time;
4. dating of chemosymbiotic *Lamellibrachia* tubeworms documents that these biota were thriving since the end of the last glacial epoch (Younger Dryas stadial) and up to very recent times;
5. a new type of skeletal sediment (DECAMOL: DECApods + MOLluscs) is here proposed whose formation is not controlled by temperature regimes as it is the general case evoked for most biogenic sediments, but by cold seepage on the seafloor sustaining specialized biota;
6. a possible causative link between seepage with related pockmark genesis, and mass-transport processes is tentatively suggested but still undemonstrated.

Acknowledgements. We are indebted to officers, crew, and colleagues for their skilful cooperation during the HERMES05, MEDCOR and DECORS Cruises supported by the FP-VI Integrated Projects HERMES (GOCE-CT-2005-511234-1) HERMIONE (grant agreement no: 226354). The article is also a contribution to the FP-VII-7 COCONET (Grant agreement no: 287844) of the European Community, and to the national projects PRIN "Carbonate conduits linked to hydrocarbons enriched seepages" and RITMARE (*Ricerca italiana per mare*) both funded by the Italian Ministry of Research and Technology (MIUR). This is ISMAR-CNR scientific contribution no. 1778.

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Table 1. Sampling station list of Cruises MEDCOR and DECORS in the Gela Basin.

Station	Date	Start Lat. GGMMSS.XX	Start Long. GGMMSS.XX	End Lat.	End Long.	Start Depth	End Depth	Gear
MEDCOR-68	19 Dec 2009	36°45′38.24	14°00′09.02			820.0		CTD
MEDCOR-69	19 Dec 2009	36°45′37.83	14°00′08.20			824.0		Grab
MEDCOR-70	19 Dec 2009	36°45′16.42	14°01′01.07			840,8		Gravity Core
MEDCOR-71	19 Dec 2009	36°45′16.07	14°00′58.79	36°45′35.00	14°00′10.82	840.0	820.0	Epibenthic modified haul
MEDCOR-72	19 Dec 2009	36°45′15.11	14°01′01.18	36°45′15.69	14°01′00.61	842.0	840.6	CTD (POM)
MEDCOR-74	19 Dec 2009	36°45′38.82	14°00′10.35	36°44′30.7	13°58′48.06	824.0	850.0	Epibenthic modified haul
MEDCOR-75	21 Dec 2009	36°45′48.41	14°01′15.29			833.0		Grab
MEDCOR-76	21 Dec 2009	36°45′34.56	14°00′24.85			820.2		Grab
MEDCOR-77	21 Dec 2009	36°45′44.57	13°58′52.79			831.7		Grab
MEDCOR-78	21 Dec 2009	36°45′40.13	14°00′08.90	36°46′10.18	14°01′31.59	815.0	811.0	Epibenthic modified haul
MEDCOR-80	19 Dec 2009	36°45′38.25	14°00′09.03			828.0		CTD
MEDCOR-81	19 Dec 2009	36°45′37.84	14°00′08.21			832.0		Grab
MEDCOR-82	19 Dec 2009	36°45′16.28	14°01′01.08			840.9		Gravity Core
DECORS-48	08 Aug 2011	36°46′16.86	14°00′06.80			816.0		CTD
DECORS-49	08 Aug 2011	36°45′39.24	14°00′06.64			818.0		Grab
DECORS-50	09 Aug 2011	36°46′16.86	13°55′28.42			827.0		Grab

Table 2. Stable Isotopes Analysis expressed in the conventional δ notation relative to the Vienna-Pee Dee Belemnite (VPDB) reference standard.

Sample	Material	Species	^{13}C δ ‰ vs. PDB	σ^{13}C	^{18}O δ ‰ vs. PDB	σ^{18}O
MEDCOR70	Shell	*Lucinoma kazani*	0.82	±0.1	2.71	±0.1
MEDCOR78	Shell	*Isorropodon perplexum*	2.66	±0.1	2.48	±0.1
MEDCOR81	Shell	*Myrtea amorpha*	−1.23	±0.1	2.33	±0.1
MEDCOR81	Shell	*Isorropodon perplexum*	0.16	±0.1	2.21	±0.1
MEDCOR81	Claw	*Calliax* sp.	−1.84	±0.1	3.23	±0.1
MEDCOR70	Mudstone		−40.77	±0.1	4.98	±0.1
MEDCOR78	Lithified burrow		−4.05	±0.1	3.18	±0.1
MEDCOR78	Carbonate concretion on shell	*Lucinoma kazani*	−37.57	±0.1	2.86	±0.1

Table 3. Radiocarbon data from the Poznán Radiocarbon Laboratory in Poznán, Poland. Radiocarbon years (^{14}C-yr) correspond to the true half-life. Calibrated age ranges reflect the 95.4 % probability window (2σ-error) and were calculated with Calib6.0.1, using the surface marine calibration curve MARINE 09 by Reimer et al. (2009).

Code #	Sample	Species	Radiocarbon Age (^{14}C-yr BP)	Delta R (yr)	Two-σ Ranges (yr cal BP)	Age cal BP (yr cal BP)	Calibration Data
Poz-38025	MEDCOR78	*Lamellibrachia* sp	10 500 ± 200	41 ± 7	11 121–12 343	11 732 ± 611	Marine09
Poz-37995	MEDCOR78	*Lucinoma kazani*	8960 ± 60	41 ± 7	9456–9763	9610 ± 154	Marine09
Poz-37994	MEDCOR81	*Myrtea amorpha*	1090 ± 30	41 ± 7	547–669	486 ± 54	Marine09

Table 4. List of major established (chemosymbiotic bivalves, and tubeworm) and putative (gastropods, callianassid) metazoans associated with pockmark cold seepage at the GBPF.

	MEDCOR 69	MEDCOR 71	MEDCOR 76	MEDCOR 78	MEDCOR 80	MEDCOR 82	DECORS 49	DECORS 50
Lucinoma kazani Salas and Woodside (2002)	x			x		x		
Myrtea amorpha (Sturany, 1896)				x				
Isorropodon perplexum Sturany (1896)	x	x		x	x	x	x	x
Taranis moerchii (Malm, 1861)	x				x	x	x	x
Lamellibrachia sp.				x	x	x		
Calliax sp.	x	x		x		x	x	x

Table A1. Benthic and pelagic molluscs recovered from the GBPF during cruises MEDCOR and DECORS: taxa of proven or putative chemosymbiotic type are bold.

	MEDCOR 69	MEDCOR 71	MEDCOR 76	MEDCOR 78	MEDCOR 80	MEDCOR 82	DECORS 49	DECORS 50
Benthic Molluscs								
MOLLUSCA								
Bivalvia								
Cardiomya costellata (Deshayes, 1833)	x	x	x	x	x		x	x
Cuspidaria rostrata (Spengler, 1793)	x	x		x				
Thracia sp.				x				
***Lucinoma kazani* Salas and Woodside, 2002**	**x**			**x**		**x**		
***Myrtea* sp.**							**x**	
***Myrtea amorpha* (Sturany, 1896)**				**x**				
***Myrtea spinifera* (Montagu, 1803)**	**x**			**x**		**x**		
***Axinulus croulinensis* (Jeffreys, 1847)**		**x**	**x**					
***Axinulus eumyarius* (Sars, 1870)**	**x**	**x**						
***Axinus grandis* (Verrill and Smith (in Verrill), 1885)**	**x**	**x**	**x**		**x**	**x**		
***Mendicula ferruginosa* (Forbes, 1844)**	**x**						**x**	**x**
***Thyasira* sp.**	**x**					**x**		**x**
***Thyasira succisa* (Jeffreys, 1876)**			**x**		**x**		**x**	
Corbula gibba (Olivi, 1792)				x		x		
Xylophaga sp.	x	x						x
Acanthocardia sp.						x		
Parvicardium sp.			x			x		
Kurtiella cf. *bidentata* (Montagu, 1803)						x		
Kelliella miliaris (Philippi, 1844)	x	x	x	x	x			x
***Isorropodon perplexum* Sturany, 1896**	**x**	**x**		**x**	**x**	**x**	**x**	**x**
***Waisiuconchia* sp.**	**x**							
Tellimya tenella (Lovén, 1846)			x					
Abra longicallus (Scacchi, 1835)	x	x	x	x	x	x	x	x
Timoclea ovata (Pennant, 1777)						x		
Venus sp.	x							
Bathyspinula excisa (Philippi, 1844)						x		
Katadesmia cuneata (Jeffreys, 1876)	x							
Malletia obtusa (G.O. Sars, 1872)	x							
Saccella commutata (Philippi, 1844)						x		
Microgloma sp.				x				
Yoldiella curta (Verrill and Bush, 1898)	x							
Yoldiella lucida (Lovén, 1846)	x		x	x	x	x		
Yoldiella nana (M. Sars, 1865)	x						x	
Yoldiella seguenzae Bonfitto & Sabelli, 1995	x	x	x	x	x		x	x
Yoldia minima (Seguenza, 1877)						x		
Ennucula sp.					x			
Ennucula aegeensis (Forbes, 1844)	x	x		x				
Ennucula corbuloides (Seguenza, 1877)	x	x	x		x	x	x	x
Nucula sulcata (Bronn, 1831)	x	x						
Nucula tumidula (Malm, 1861)	x			x			x	
Asperarca nodulosa (Müller, 1776)				x			x	
Bathyarca pectunculoides (Scacchi, 1835)	x	x	x		x		x	x
Limatula gwyni (Sykes, 1903)			x					
Limatula subauriculata (Montagu, 1808)		x	x		x	x		
Notolimea crassa (Forbes, 1844)		x						
Parvamussium sp.		x						
Pectinidae sp.					x			

Table A1. Continued.

	MEDCOR 69	MEDCOR 71	MEDCOR 76	MEDCOR 78	MEDCOR 80	MEDCOR 82	DECORS 49	DECORS 50
Gastropoda								
Bittium sp.	x							
Turritella communis (Risso, 1826)	x			x		x		
Epitonium sp.	x							
Haliella stenostoma (A. Adams, 1861)					x			
Triphoridae sp.	x							
Aclis attenuans (Jeffreys, 1883)						x		
Melanella sp.		x						
Naticidae sp.	x				x			
Lunatia fusca (Blainville, 1825)				x				
Alvania sp.1			x					
Alvania sp.2						x		
Alvania cimicoides (Forbes, 1844)	x	x	x	x	x	x	x	
Alvania elegantissima (Monterosato, 1875)	x	x		x		x		
Alvania subsoluta (Aradas, 1847)	x	x	x		x	x	x	x
Alvania testae (Aradas and Maggiore, 1844)			x					
Benthonella tenella (Jeffreys, 1869)	x	x	x	x	x	x	x	x
Aporrhais serresianus (Michaud, 1828)		x						x
Galeodea echinophora (Linnaeus, 1758)					x			
Amphissa acutecostata (Philippi, 1844)	x			x		x		
Fusinus rostratus (Olivi, 1792)								
Drilliola emendata (Monterosato, 1872)				x				
Drilliola loprestiana (Calcara, 1841)	x	x						
Spirotropis modiolus (de Cristofori & Jan, 1832)		x						
Mangelia serga (Dall, 1881)		x			x			
Pleurotomella gibbera Bouchet & Warén,1980		x	x		x		x	x
***Taranis moerchii* (Malm, 1861)**	**x**				**x**	**x**	**x**	**x**
Teretia teres (Reeve, 1844)		x						
Granulina gofasi Smriglio & Mariottini, 1996				x	x			
Pagodula echinata (Kiener, 1840)	x	x	x	x	x	x	x	
Trophonopsis barvicensis (Johnston, 1825)	x	x			x			
Bathysciadium xylophagum Warén & Carrozza in Warén, 1997	x	x						
Acteon pusillus (Forbes, 1844)			x					
Crenilabium exile (Jeffreys, 1870)	x		x		x	x		
Eulimella sp.					x			
Syrnola sp.					x			
Colpodaspis sp.			x					
Diaphana lactea (Jeffreys, 1877)		x			x		x	
Philine sp.					x			
Philine scabra (Müller, 1784)					x			
Philine monterosatoi (Sykes, 1905)	x						x	
Roxania monterosatoi Dautzenberg & H. Fischer, 1896	x	x					x	x
Fissurisepta granulosa Jeffreys, 1883						x		
Putzeysia wiseri (Calcara, 1842)				x		x		
Dikoleps sp.					x			

Table A1. Continued.

	MEDCOR 69	MEDCOR 71	MEDCOR 76	MEDCOR 78	MEDCOR 80	MEDCOR 82	DECORS 49	DECORS 50
Polyplacophora								
Hanleya sp.						x		
Scaphopoda								
Antalis agilis (M. Sars in G.O. Sars, 1872)		x	x	x	x			x
Dentalium sp.						x		
Entalina tetragona (Brocchi, 1814)	x					x		
Pelagic Molluscs								
Caenogastropoda								
Janthina sp.					x			
Carinaria lamarckii Blainville, 1817		x						
Atlanta brunnea J. E. Gray, 1850	x	x			x			
Atlanta peronii Lesueur, 1817	x	x	x	x	x	x	x	x
Heterobranchia								
Cavolinia inflexa (Lesueur, 1813)		x		x		x	x	x
Cavolinia tridentata (Forskål, 1775)	x	x	x	x			x	x
Cavolinia uncinata (Rang, 1829)	x	x		x	x		x	
Diacria trispinosa (Blainville, 1821)	x	x		x	x			
Clio pyramidata (Linnaeus, 1767)	x	x		x	x	x		
Creseis clava (Rang, 1828)	x	x		x	x	x		
Hyalocylis striata (Rang, 1828)	x	x	x		x			
Styliola subula (Quoy and Gaimard, 1827)	x	x	x	x	x	x	x	x
Heliconoides inflata (d'Orbigny, 1834)		x		x	x		x	x
Limacina sp.						x		x
Limacina bulimoides (d'Orbigny, 1834)	x				x			
Limacina trochiformis (d'Orbigny, 1834)	x	x			x			
Peracle diversa (Monterosato, 1875)	x	x	x		x			x
Peracle reticulata (d'Orbigny, 1834)	x		x		x			

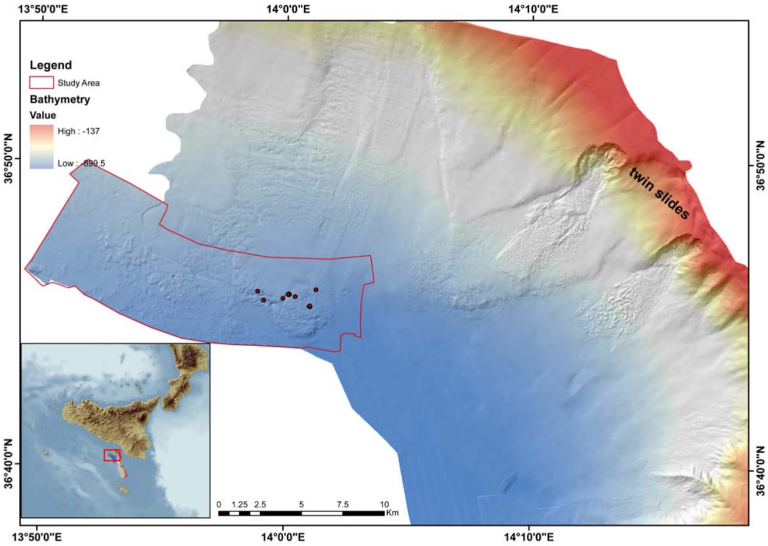
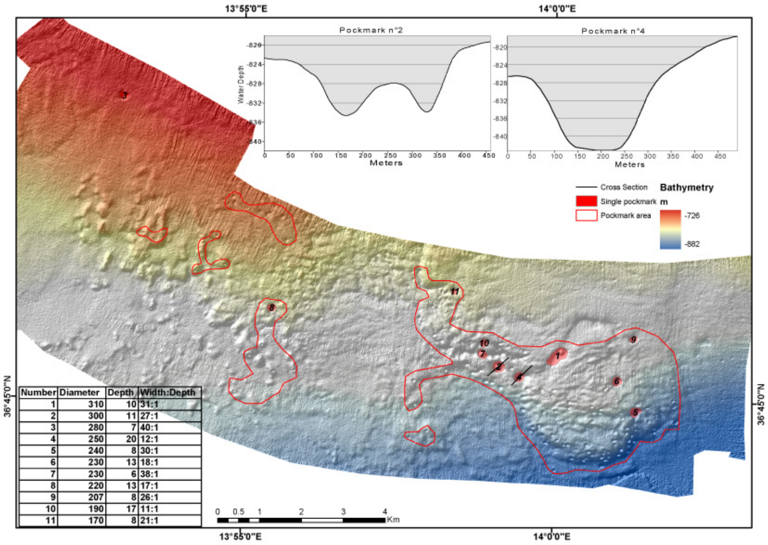


Fig. 1. Map showing the shaded relief Digital Terrain Model (DTM of 20 m resolution with 10× vertical exaggeration) of the Gela Basin in the Strait of Sicily. The figure illustrates the location of the pockmarks field discussed in this article (red spots represents major pockmarks); inset, the Mediterranean basin with rectangle showing the same area magnified in the figure.



Number	Diameter	Depth	Width:Depth
1	310	10	31:1
2	300	11	27:1
3	280	7	40:1
4	250	20	12:1
5	240	8	30:1
6	230	13	18:1
7	230	6	38:1
8	220	13	17:1
9	207	8	26:1
10	190	17	11:1
11	170	8	21:1

Fig. 2. Shaded relief DTM of the study area (5 m resolution and 10× vertical exaggeration) showing the complex, rough topography punctuated by many sub-circular depressions interpreted as pockmarks. The 11 major pockmarks, with diameter greater then 200 m, are numbered from maximum to minimum dimension. Their geo-morphometric characteristics are listed in the table; the bathymetric profiles show the cross sections of two main pockmarks showing the different internal geometry, respectively U-shaped and V-shaped with internal positive relief. Furthermore, the image reveal that the major pockmark (Number 1) is formed by two partly coalescent depressions.

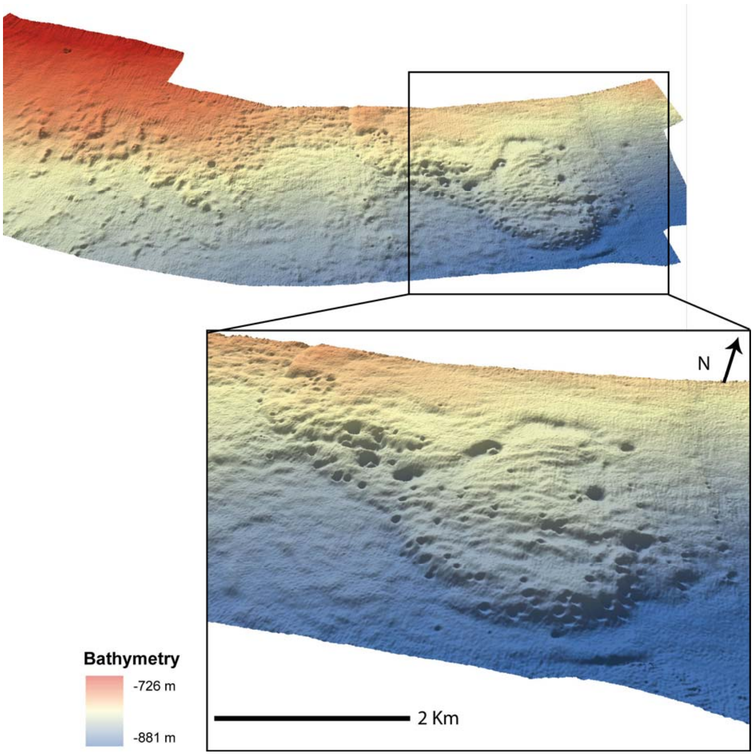


Fig. 3. Perspective view of the shaded relief DTM (resolution 5 m and 10× vertical exaggeration) of the study area showing the distribution of the pockmarks and their geometries; the inset shows a magnification of the highest density pockmarks area with more then 40 pockmarks with variable dimensions (8 of the major ones and up to 30 minor features)

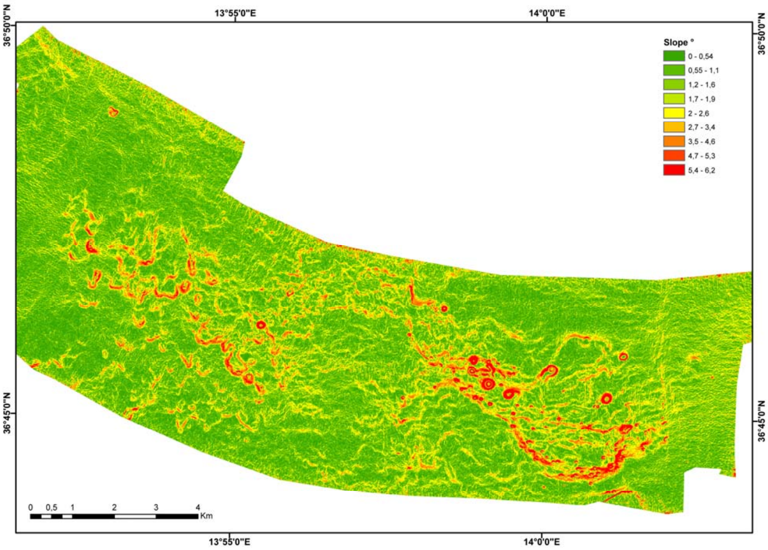


Fig. 4. Slope map of the study areas, calculated from the DTM, showing clearly the difference between the side slope of the pockmarks reaching the maximum of 16° and the regional surrounding slope about 2–3°.

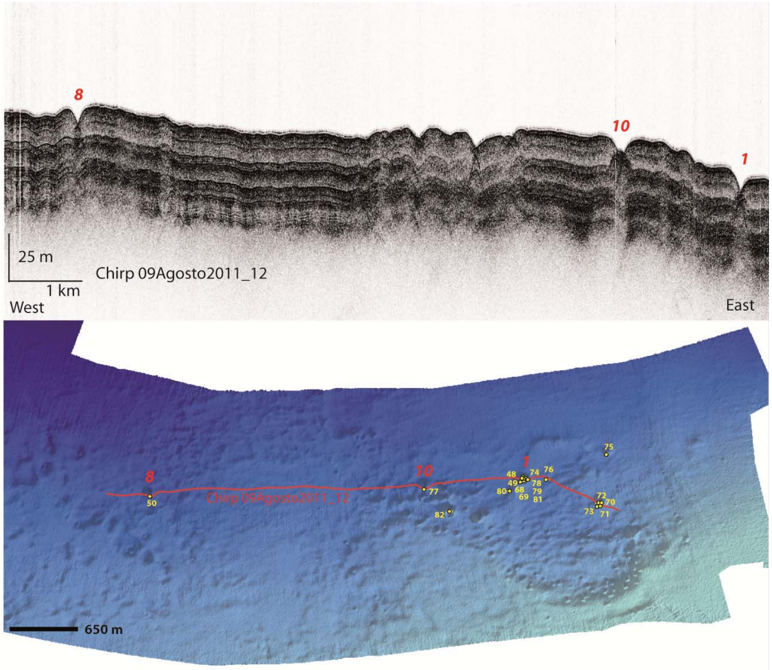


Fig. 5. (A) Chirp profile showing the subsurface stratigraphy of the pockmark area; **(B)** 3-D perspective view of the DTM shows the location of the chirp profile and the sample locations.; MEDCOR samples yellow, DECORS samples red.

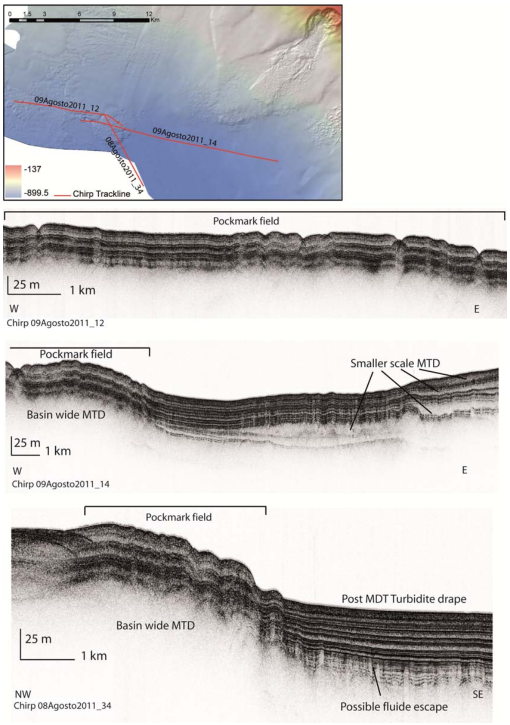


Fig. 6. Chirp sonar profiles across the pockmark-hosting morphologic bulge at the base of the slope showing the top of the last basin-wide mass-transport event (Gela slide?) and the thinning of plane-parallel reflectors (basin-plain fine-grained turbidites and hemipelagites) toward the bulge. Where thinner, this unit is likely easier to breach by the ascending fluids than in other areas.

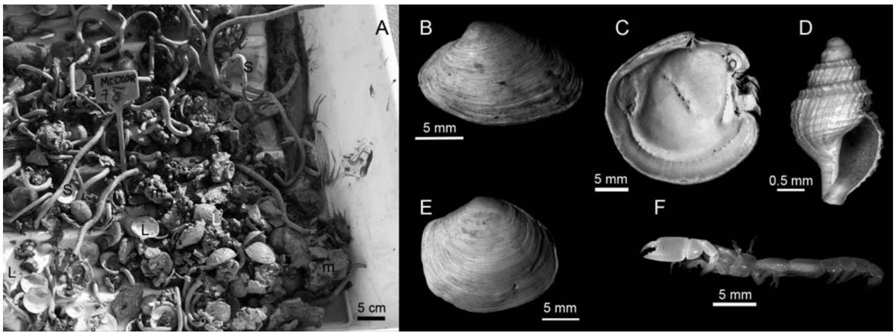


Fig. 7. Chemosymbiotic metazoans recovered from the GBPF: **(A)** haul whole catch of station MEDCOR 78 (pockmark #1) showing chemosymbiotic bivalves, tubeworms, and carbonate concretions mixed with non-seep fauna and anthropogenic litter; **(B)** *Isorropodon perplexum* from st. MEDCOR71 , **(C)** *Lucinoma kazani*, theratological shell from st. MEDCOR78, **(D)** *Taranis moerchi* from st. MEDCOR69, **(E)** *Myrtea amorpha* from st. MEDCOR78, **(F)** *Calliax* sp. from st. MEDCOR71.

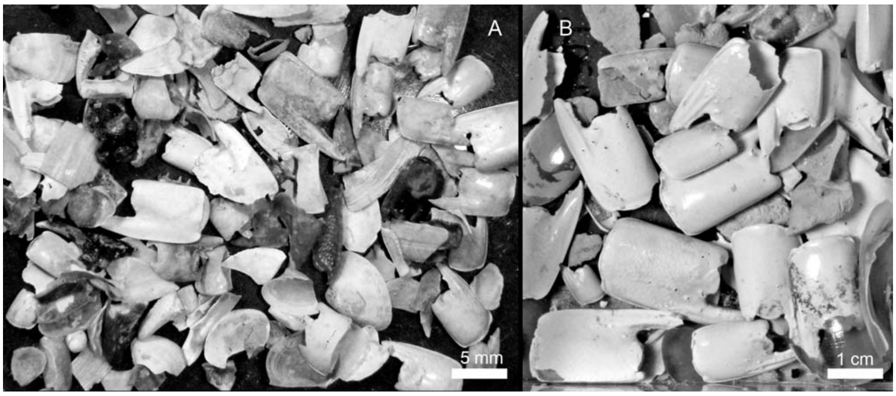


Fig. 8. DECAMOL skeletal assemblage; **(A)** coarse sand fraction; **(B)** hash fraction, all from st. MEDCOR69.

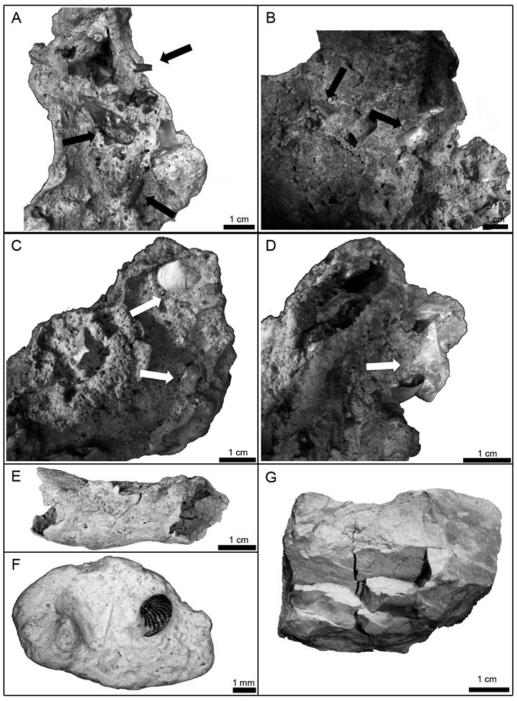


Fig. 9. Carbonates from the GBPF: **(A–D)** authigenic concretions (cemented matrix) embedding skeletal biosomes of seep-related metazoans, all from st. MEDCOR78: **(A–B)** *Calliax*, **(C–D)** *Isorropodon*; **(E)** indurated callianassid? burrow, armoured with chemosymbiotic-organisms bioclasts; **(F)** cemented matrix embedding a reworked black-stained shallow-water foraminifer (*Elphidium crispum*); **(G)** cemented mudstone layer at 210–230 cm in core MEDCOR70.

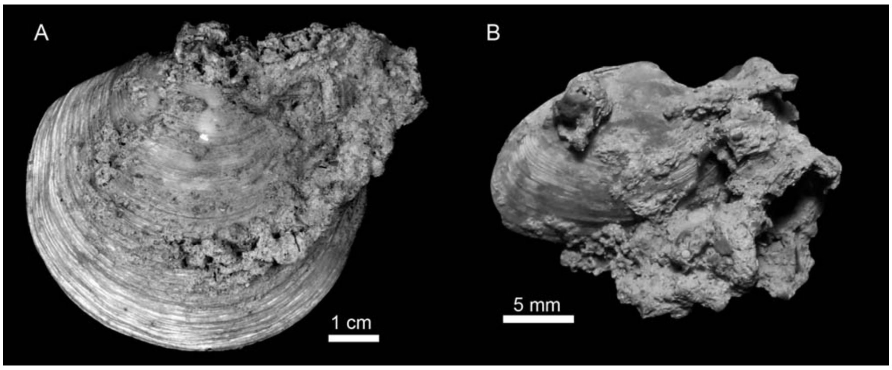


Fig. 10. Incipient methane-driven cementation of matrix on valves of chemosymbiotic bivalves from GBPF, precursors of seep-limestones: **(A)** *Lucinoma kazani* encrusted by carbon-depleted concretion (δ13C–37.57 ‰ PDB, see text), **(B)** *Isorropodon perplexum*, almost completely embedded.

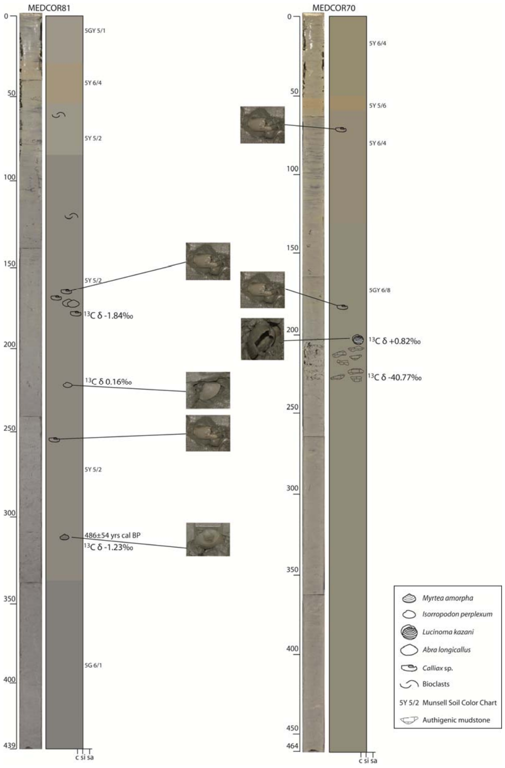


Fig. 11. Sedimentary cores MEDCOR81 (pockmark #1), and MEDCOR70 (pockmark #6): photographic (left) and (right) lithostratigraphic logs reporting main chronological, petrographic, isotopic and faunal features.

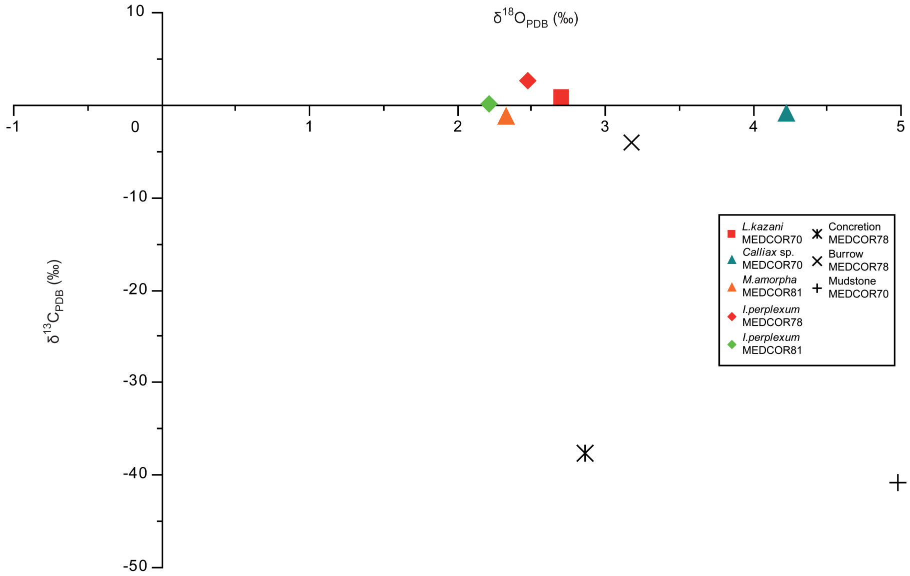


Fig. 12. Stable isotope compositions of bivalve shells (core MEDCOR 81), callianassid claw and authigenic carbonates all from st. MEDCOR70 and MEDCOR78 expressed in the conventional δ notation relative to the PDB reference standard.