Cold Seep Systems

Silvia Ceramicola, Stéphanie Dupré, Luis Somoza and John Woodside

Abstract 'Cold' seeps (or cold vents) are seafloor manifestations of fluid migration through sediments from the subsurface to the seabed and into the water column, and may reach the atmosphere. They are an important but not fully understood process in our oceans that has important repercussions on human society and on the climate. Modern sonar systems can obtain seafloor images of cold seep features from tens to thousands of meters wide with metric resolution, providing key information on the formation and evolution of the various seabed expressions of cold seeps. In this chapter we attempt to address cold seep systems with an emphasis on their origin, evolution, form, and occurrence, approaching them primarily from their morphologies and the acoustic character of the seafloor and near bottom erupted sediments. We address morphological characteristics of mud volcanoes, pockmarks, carbonate-related structures including MDAC, AOM and giant carbonate mounds and ridges, offering various examples mainly from recent discoveries in Mediterranean region which are among the most spectacular and most frequently cited examples. Detailed focus on topics such as acoustic backscatter, brine pools, etc. have been described in separate gray boxes of text with the aim to highlight their particular significance. Finally, gaps in knowledge and key research questions on cold seep studies have been outlined with the aim of orienting young researchers

---

S. Ceramicola (✉)
Istituto Nazionale di Oceanografia e di Geofisica Sperimentale—OGS,
Borgo Grotta Gigante 42/c, 34010 Sgonico, Trieste, Italy
e-mail: sceramicola@inogs.it

S. Dupré
IFREMER Laboratoire Aléas géologiques et Dynamique Sédimentaire
Centre Bretagne, ZI de la Pointe du Diable—CS, 10070-29280 Plouzané, France

L. Somoza
Marine Geology Dv, Geological Survey of Spain—IGME,
Ríos Rosas 23, 28003 Madrid, Spain

J. Woodside
Lyngby Marine Geophysical Research, Mgr. Nolenslaan 5,
1181 VL Amstelveen, The Netherlands

A. Micallef et al. (eds.), *Submarine Geomorphology*, Springer Geology,
DOI 10.1007/978-3-319-57852-1_19

and students towards those topics that deserve the highest attention as they are still unresolved.

Box 1: Acoustic Backscatter Data

Backscatter signal differs from acoustic reflection as it includes acoustic energy returned (in many different directions) from reflectors within the sediments to a depth dictated by the frequency and energy of the acoustic source. It therefore can provide information about the upper sediments on the seafloor. Backscatter data is used to detect active seepage at the seafloor because of the carbonate crusts and rough surface around seeps and the volume scatterers (rock fragments in mud breccia, gas, broken carbonate crust, etc.) in the upper seep sediments. The strong acoustic impedance contrast (reflectivity) between the sediments and both gas and crusts causes a stronger backscatter signal from these spots than from the normal seafloor sediments (e.g. Volgin and Woodside 1996; Zitter et al. 2005). On the other hand, brine pools appear as areas of practically no backscatter because most of the sonar energy is dispersed away from the sensors by specular reflection at the density interface between brine and normal sea water (e.g. Woodside and Volgin 1996), except for vertical incidence sonar signals. Both multibeam echosounders and side scan sonars (hull mounted or deep towed) can be used to collect acoustic backscatter data.

Box 2: Anaerobic Oxidation of Methane (AOM)

Methane is a powerful greenhouse gas with a greater influence than CO_2. If all the methane coming from deep submarine reservoirs emitted into the water column, through cold seeps systems, were to reach the atmosphere, it would have a significant impact on the climate change of the Earth. Therefore, anaerobic oxidation of methane (AOM) is considered an important filter and sink for methane, preventing its expulsion into the water column and ultimately into the atmosphere. AOM is mainly mediated by a consortium of anaerobic methanotrophic (ANME) archaea and sulfate reducing bacteria (SRB) (e.g. Boetius et al. 2000). The sulfate is made available from seawater infiltrating the upper seafloor sediments. Bicarbonate is a by-product of the reactions involved and can result in the deposition of authigenic carbonates (see Box 3).

Box 3: Methane-Derived Authigenic Carbonates

Methane-derived authigenic carbonates (MDACs) are formed as a by-product of the AOM described in the previous grey box. As results of the symbiosis between ANME and SRB, high amounts of Fe-enriched carbonates may form around cold seeps. The depth and the type of carbonates of MDACs depends basically on the rate of flux of the methane in the seeps (e.g. Magalhaes et al. 2012). Therefore, in seeps with high flux rates of methane, MDACs can be generated at the sediment-seawater interface forming pavements or crusts composed mainly of aragonite. In contrast, in seeps with low flux rates of methane, MDACs are formed below seafloor by cementation along the fluid conduits or pre-existing channels within the sedimentary column, forming chimney-like pipe structures mainly composed of dolomites. Extensive fields of the these carbonates forming chimneys, crusts, pavements or slabs are found offshore in areas like the Gulf of Cádiz, South China Sea, New Zealand and Costa Rica, and other areas of with extensive cold seep emissions (e.g. Díaz del Río et al. 2003). In anoxic bottom waters, such as the Black Sea, microbial consortia fuelled by methane seeps generate MDACs chimneys that form in the subsoil and rise several meter in height in the water column.

Box 4: Hydrothermal Vents

Cold seeps differ from hydrothermal vents occurring at mid oceanic ridges as the temperatures of vents are lower than 100 °C in contrast to 'hot' hydrothermal fluids that may reach temperatures of 200–400 °C. Generally, temperatures of cold seeps are warmer than the surrounding seawater reflecting the geothermal gradient of the seeping material, whether it comes from deep or shallow sediments.

Box 5: Brine Pools

In the Mediterranean region a thick layer up to 3 or 4 km of evaporitic deposits resulted from a late Miocene (~5 Ma, Messinian stage) desiccation of the sea (Hsu et al. 1973). Salt underlies a large part of the Messinian Mediterranean Basin. Water released from sediments below the salt creates a salty brine during its ascent through the salt to the seafloor. The brines are denser than the sea water and form pools in depressions on the seafloor. Often these depressions are pockmarks created by the fluid seeps, but they can also be formed by sedimentary deformation (e.g. along the Mediterranean Ridge, sediments folded during compression between the European and African plates south of Greece). The pools appear bizarrely as seafloor lakes.

1 Introduction

‘Cold’ seeps (or cold venting) are seafloor manifestations of fluid migration through sediments from the subsurface to the seabed and into the water column until they may reach the atmosphere. They may be generated by the activity of microbes in shallow sediments or by processes occurring deeper in the sediments (thermogenic). They are widespread natural processes found mostly (and in their most active state) on portions of land and seabed that are (or have been) characterised by the expulsion of free or hydrated gas (methane and higher hydrocarbons), oil (asphalt), water (salt brines, fresh or mixed waters) and sediments (mud breccia) in different proportions according to the processes that are responsible for their formation and the depth at which they have been generated. On land seepage has been known since ancient times by our ancestors (e.g. Romans, Native Americans, Azeris) who used the extruded material for curative purposes or for their everyday life. Some of these sites gained religious or cultural significance (e.g. Azerbaijan ‘eternal flames’).

Discoveries of submarine seeps occurred in the sixties when deep sea exploration achieved the first great discoveries. After that they have been recognised on the seafloors of all oceans (Fig. 1) including inland seas such as the Mediterranean and Black Seas (Judd and Hovland 2007), where some of the most diverse and

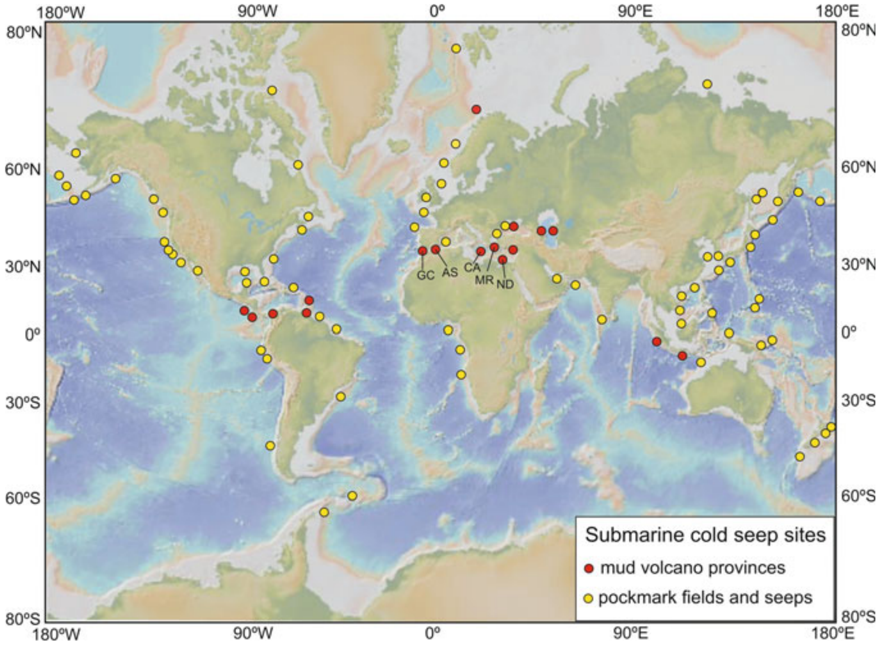

Fig. 1 Map showing distribution of cold seeps in the world (Modified from Milkov 2000; Kopf 2002). *GC* Gulf of Cádiz; *AS* Alboran Sea; *CA* Calabrian Arc; *MR* Mediterranean Ridge; *ND* Nile Delta Deep Sea Fan

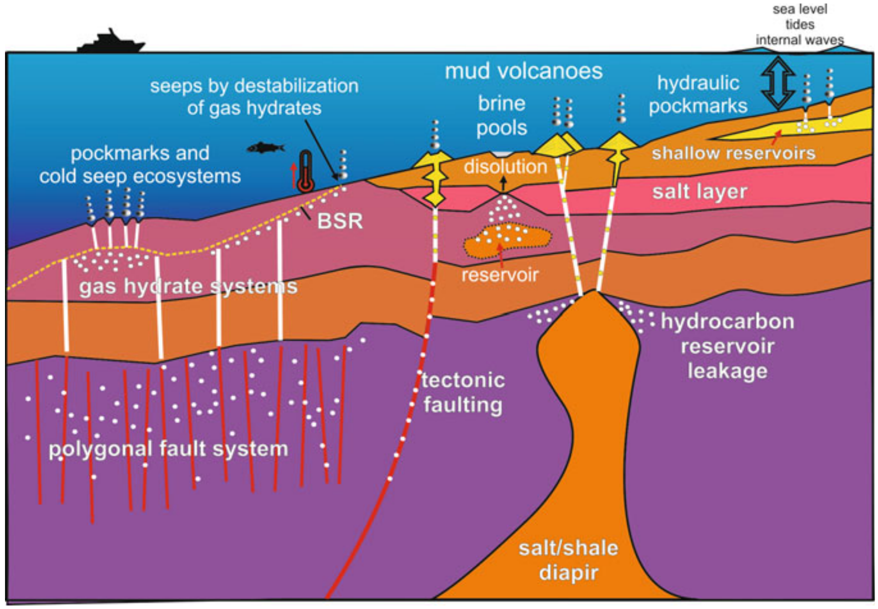

Fig. 2 Sketch of a portion of a continental margin affected by circulation of fluids (Modified from Berndt 2005)

spectacular examples have been discovered during the last 20 years (Ceramicola et al. 2014; Dupré et al. 2007, 2008, 2010, 2014; Huguen et al. 2005; Mascle et al. 2014; Woodside et al. 1996; Somoza et al. 2002, 2003; Zitter et al. 2005).

Seabed fluid flows have been identified on both active and passive continental margins in areas affected by compressional tectonics (e.g. subduction zones), or in deltaic environments characterised by rapid sediment deposition associated with high subsidence (e.g. Nile delta); however, they may occur as well in areas where the geothermal gradient is high or when thermogenic hydrocarbon reservoirs reach their final stages of natural gas generation (Fig. 2).

The great advances in underwater technology developed to explore the seafloor (ROVs, AUVs) since the end of the last century have greatly improved the capabilities of observing cold seep morphologies from a close distance, revealing their near bottom characteristics at metric resolution. This knowledge was key in unraveling important aspects of cold seep activity, resulting in better models of their formation and explanations of their spatio-temporal evolution.

Cold seeps are associated with a number of different seafloor structures such as mud volcanoes (including gryphons), pockmarks, diapirs, carbonate-related constructions (mounds, chimneys, crusts, plates), brine pools, oil and gas vents. In the present chapter the diverse seafloor geomorphologies of cold seeps, and how these are indicative of their formation, functioning, and evolution in time, will be touched upon and their most typical characteristics illustrated.

Cold venting can host important ecosystems (e.g. Sibuet and Olu 1998; Olu et al. 2004) and act as hotspots for geo-biosphere interactions. It is also important to be aware of their occurrence on the seafloor of continental margins as they may represent hazards for marine infrastructures (communication cables, oil drilling platforms, pipelines). Fluid and gas circulation in sediments is able to modify sediment pore pressure and thus favour the inception of failures and/or other types of slope erosion (i.e. gullies, canyons). Cold seeps expel methane and other greenhouse gases, so being able to quantify the global occurrence of submarine methane emissions in the global carbon budget and their impact on climate is of great relevance.

2 Methods to Detect Cold Seeps Systems

Long-range side scan sonars were used in the 1980s to obtain the first large scale bathymetric/morphological maps of the ocean floor. The GLORIA (Geological LOng Range Inclined Asdic) side scan sonar was one of the first sonars operated by UK and US to detect and investigate the continental margins worldwide. Sound source and receivers were built into a “fish” that was towed about 200 m behind a ship.

Knowledge of cold seeps greatly advanced thanks to the widespread use of modern echo-sounders capable of recording both bathymetry (depth) and reflectivity (backscatter) of the seafloor, as well as acoustic anomalies in the water column. Integrating these three types of acoustic information is key in characterising cold seep morphologies and activity at the seafloor. Seafloor bathymetry acquired using low frequency sounders (resolutions tens of meters), is particularly important as it allows large scale mapping and thus identification of the occurrence of large (kilometer scale) seafloor morphologies (i.e. multiple cones, large calderas, domes, pies, etc.). High frequency sounders allow higher-resolution (meter scale) bathymetry. These seabed maps are used to reveal details of cold seep morphologies such as striations along the lobes of mud flows, circular rims around the calderas, fractures in the carbonatic pavement, providing evidence to reconstruct their activity through time. High-resolution bathymetry maps can be used to differentiate ‘fresher’ morphologies of younger mud flows from older ones buried under marine sediments. This information combined with the locations of high reflectivity patches of the seafloor is used to guide the sampling of mud flow sediment. This is particularly important in determining the timing of the different flows and thus the different seep events.

150 circular to subcircular high-backscatter patches were recognised on the shallow inner part of the Mediterranean Ridge and Calabrian accretionary complexes, during extensive surveying by the GLORIA system in the Eastern and Central Mediterranean (Fusi and Kenyon 1996). Some of these patches were interpreted as evidence of mud volcanoes and mud ridges already identified by Cita

et al. (1981), and provided some of the first geophysical evidences of cold seeps in the Mediterranean sea (Limonov et al. 1996).

Bathymetric maps acquired from Autonomous Underwater Vehicles (AUV) and Remotely Operated Vehicles (ROV), which are able to fly closer to the seafloor, show details as small as one meter across. These are among the most detailed maps ever made of the deep seafloor (Dupré et al. 2008; Sen et al. 2016).

Because bathymetry alone cannot be used to infer activity at the seafloor, backscatter (see Box 1) is used to reveal active or recently active cold seep structures (depending on the penetration of the sounding device used to investigate the seafloor sediments). Multibeam sonars are also able nowadays to record the anomalies in the water column due to gas bubbles (hydroacoustic flares), another indication of activity at a cold seep which is the source of the bubbles.

When surveying a new portion of the seafloor in search of cold seeps, the integrated use of the above described acoustic methods, including subbottom profiler data (Ceramicola et al. 2014), can be very effective (Fig. 3). However ground truthing information with near-bottom visual surveys, together with core sampling (gravity, piston, mini cores) remain the only methods able to prove mud

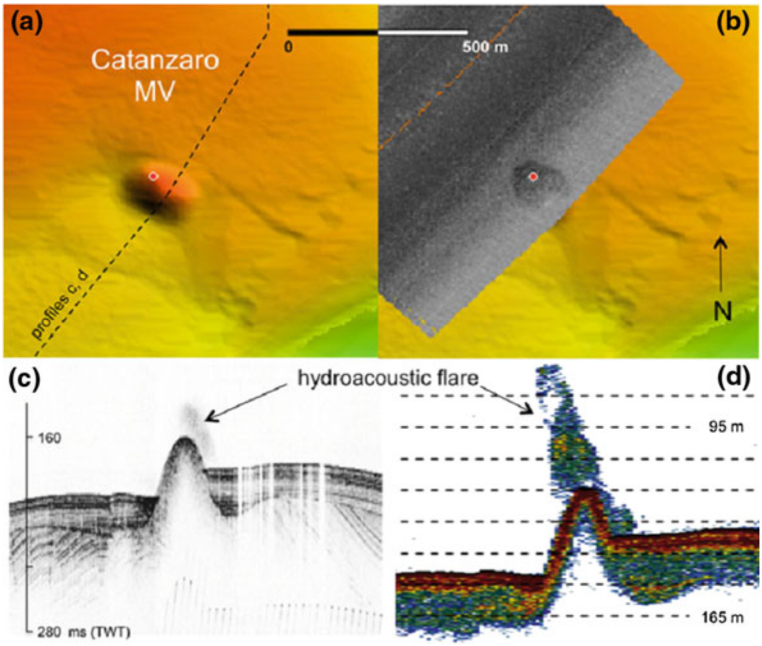

Fig. 3 Integrated acoustic methods to detect active seepage at the Catanzaro mud volcano (Ionian margin). **a** Multibeam bathymetry; **b** backscatter mosaic superimposed on bathymetry data; **c** subbottom data showing an acoustic flare in the water column; **d** echo sounder single beam data showing the flare in the water column above the mud volcano. The Catanzaro mud volcano has not been proven by coring or visual imaging yet. However, the combination of four different geophysical characteristics strongly suggests that this is a mud volcano (Ceramicola et al. 2014)

extrusion (e.g. mud breccia) on the seafloor. Core sediments are used to define the age of the different mud flows and when possible, to determine how long the cold seep structure has been active. Submersibles and ROVs equipped with cameras are commonly used to observe whether life is present at active or recently active cold seeps, to collect samples, to make measurements (e.g. temperature), and sometimes to further insonify the seafloor with acoustic signals.

3 Geomorphological Indicators of Cold Seeps

Fluid seepage through seafloor sediments is ubiquitous. For example, the rolling topography of sediment drape over a rough seafloor basement is related to loss of water due to compaction and differential subsidence, often along fine fractures in the sediment. In this chapter we restrict ourselves to more obvious structures on the seafloor that form in response to localised and concentrated fluid fluxes. These structures comprise mud volcanoes and mud flows, pockmarks (depressions) and brine pools, methane-derived carbonate structures (mounds, chimneys, sheets, etc.), and methane hydrates with their related structures (Fig. 2). On the scale of oceans, these structures are small but they can form large local landforms and fields of them.

3.1 Mud Volcanoes

Mud volcanoes are in no way 'volcanic' in the strict sense but derive their name from their similar shape and manner of formation by extrusion or eruption of material from below onto the surface above. They differ from mud diapirs in that the material forming them has actually breached the seafloor, which is not the case for mud or shale diapirs.

Mud volcanoes are generally the largest of these seafloor landforms: often sub-circular in plan view, with diameters of up to a few kilometers and typical heights of up to about 200 m. They are formed by eruption onto the seafloor of sediments from over-pressured formations on the order of kilometers deep (Fig. 4). There is thus a central feeder channel (sometimes with several branches) through which major eruptions occur and fluids (often rich in methane) seep continuously, or intermittently with lower intensity during the dormant phase. The driving pressure can be the result of compressional tectonics (e.g. at subduction zones or thrusts) or sedimentary pressure (e.g. on the Nile deep sea fan). Often, the sediments forming the surface of a mud volcano support a variety of clasts from indurated sediment below; thus, combined with methane-derived carbonate structures, they may form a rough surface and contain rocks and sediment very much older than the normal seafloor sediments. These deposits forming the mud volcano are known as mud breccia (Cita et al. 1981) and are responsible for the volume

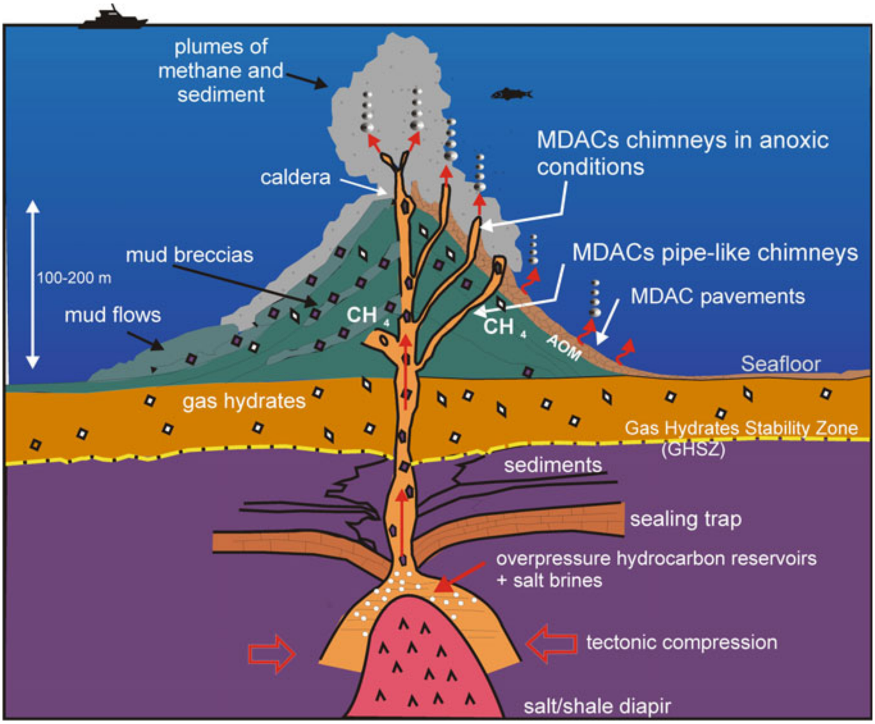

Fig. 4 Scheme showing the general functioning of mud volcanoes (Not all these features may be present)

backscattering of acoustic energy that makes them visible to sidescan sonar and multibeam mapping systems.

A more detailed discussion of the driving mechanism of mud volcanoes can be found in Chapter "Drivers of Seafloor Geomorphic Change" of this book.

Mud volcanoes have different morphologies that reflect their origins and structure (Fig. 5). These forms vary from broad flat mud pies such as those on the Nile Deep Sea Fan, to conical forms resembling volcanoes (such as Ginsburg Mud Volcano in the Gulf of Cadiz), but they are found mostly in the shape of an inverted bowl (such as the Mercator and Napoli mud volcanoes; e.g. Mascle et al. 2014). Sometimes they are composed of multiple conical shaped edifices, such as the twin cones of the Madonna dello Ionio or the Venere MV in the fore-arc basin of the Calabrian arc, one adjacent to the other sharing similar shapes and morphologies (Praeg et al. 2009), or the double cone at Chephren Mud Volcano on the Nile Deep sea Fan (Dupre et al. 2014; Mascle et al. 2014). The flat mud pies on the Nile Fan are located above broad 'gas chimneys'. They are kilometre scale wide but not high (typically about 50 m), and have distinctive concentric ridges and valleys of a few metres relief across the relatively flat summit (Fig. 5a).

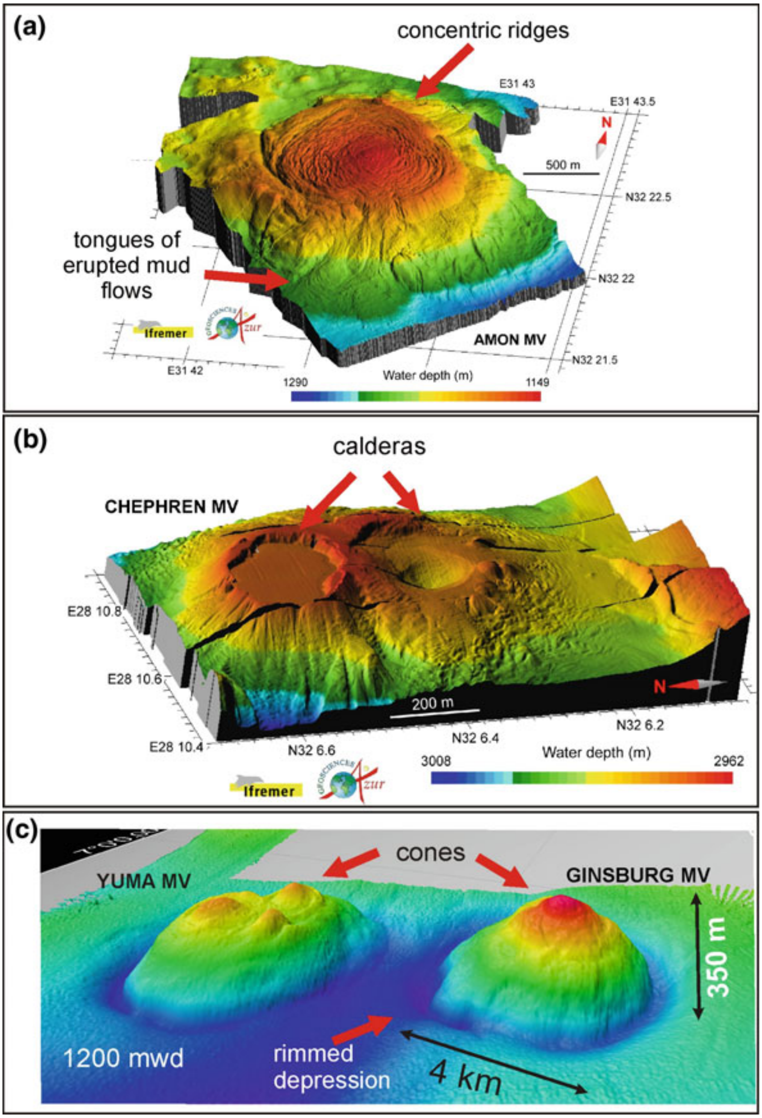

Fig. 5 Examples of mud volcanoes with different morphologies: Mud volcanoes with a central caldera such as **a** Amón and **b** Chephren MVs from Nile Deep Sea Fan (Dupré et al. 2008); and **c** mud volcanoes formed by an accumulation of cones and surrounded by a depression, like the Yuma and Ginsburg MVs from the Gulf of Cádiz (Modified from Toyos et al. 2016)

The ridges may show striations indicative of mud flow extrusion from the centre (Dupré et al. 2007) (see Fig. 5a). Activity occurs commonly near the centre of the volcano, however it may take place also locally closer to the rim. The physical consistency of erupted material is responsible for the shape of the edifice and the steepness of the its slope (Fig. 5b).

When collapse affects only the summit of the mud volcano, probably as a result of a fresh eruption of low consistency mud, a sag depression is formed resembling a volcanic caldera (e.g. Amsterdam, Madonna dello Ionio, Mercator, and Napoli MVs). Often the different tongues of erupted mud flows are visible down the flanks of the mud volcano and in some cases out onto the surrounding sea floor (e.g. Amsterdam, Sartori MVs). Depending on the consistency of the mud breccia, these mud flows and lobes can in some cases be as thick as 300 m, as at Amsterdam (Woodside et al. 1998) or Mercator MV (Somoza et al. 2003; Toyos et al. 2016). The Amsterdam mud volcano also shows a well developed caldera where the south rim has been breached resulting in massive flows. The flows themselves can bury some seafloor topography such as the anticlines and synclines formed by folding of the compressional accretionary prism at subduction zones, thus modifying the geomorphology.

In contrast, eruptions of higher consistency flows tend to build up circular to elongated cone-like mud volcanoes like Ginsburg MV (Fig. 5c) in the Gulf of Cádiz (e.g. Toyos et al. 2016). Sometimes, the upper cones of the mud volcanoes are formed by two or three cones as occurs at Yuma MV (Fig. 5c). At their base, most of these mud volcanoes show rimmed depression as the Hespérides or Anastasya MVs (Somoza et al. 2003), and scarps interpreted as flank failures developed by collapse, faulting and compaction processes.

Gryphons and salsas, common on land mud volcanoes, as in Azerbaijan (e.g. Mazzini et al. 2009) or the LUSI mud volcano in Indonesia (Mazzini et al. 2007), are also found associated with underwater mud volcanoes. The salsas can form pools on the summit of mud volcanoes (e.g. Napoli and Cheops mud volcanoes; e.g. Mascle et al. 2014) if the fluid is denser than the surrounding sea water, like salt rich brines (see below). Gryphons, steep-sided cones generally shorter than 3 m extrude fluid mud in active sub-centres of the mud volcano (features described onshore but identified also offshore). One gryphon on the west side of Amsterdam Mud Volcano rises to about 90 m (Zitter et al. 2005) and is therefore more of a parasitic cone than a gryphon.

Caldera morphologies are related to more fluid-rich seeps mainly associated with passive margins, whereas cones are more typical of mud volcanoes in compressional tectonic environments where eruptions result from buildup and release of pressure below; however both types may be present in either environment.

The age and duration of mud volcanic activity probably has a lot to do with the geological setting. In the Anaximander Mountains, examination of mud flows on Kula mud volcano suggest the occurrence of eruptions at a 5–10 kyr interval (Lykousis et al. 2009), although this need not be standard for all mud volcanoes. To the west, on the Mediterranean Ridge and the Calabrian accretionary prism, sediment cores and 12 kHz backscatter signatures from hundreds of mud volcanoes indicate the occurrence of mud breccias within a few metres of seabed, implying at least one eruption over the last 60 ka, i.e. the last glacial-interglacial cycle (Rabaute and Chamot-Rooke 2007; Ceramicola et al. 2014). However, many mud volcanoes may have been active over much longer timescales. Scientific drilling of Napoli and Milano mud volcanoes on the Mediterranean Ridge show them to have been in operation for more than 1 million years (Robertson and Kopf 1998). On the Calabrian prism, seismic reflection investigations of the Madonna dello Ionio and Pythagoras MVs suggest they have operated over the last 3 Ma (Praeg et al. 2009). In the Alborán Sea, complex mud volcanoes formed with multiple cones are the longest living mud volcanoes, constructed by at least six extrusion episodes since the mid-Pliocene 3.3 million years ago. In the Gulf of Cádiz, the largest mud volcanoes, Ginsburg and Yuma MVs (Fig. 5e), initiated in the Messinian (5.3 million years ago) after the tectonic emplacement of the Betic-Rifean Arc onto the Atlantic margin (Toyos et al. 2016).

3.2 Pockmarks

Pockmarks are depressions on the seafloor resulting from collapse of the sediments upon upward migration of overpressured fluids (Judd and Hovland 2007; King and MacLean 1970). Pockmarks form where seeps occur without eruption of deep sediments, although they can occur on mud volcanoes (Dimitrov and Woodside 2003). The fluids involved in the formation of pockmarks are mostly gases, more specifically methane, of microbial or thermogenic in origin. However, submarine water seeps may occur e.g. groundwater releases (Whiticar 2002) and dewatering of sediments (Harrington 1985; Loncke et al. 2015). Where the fluids have passed through salt formations, as in many parts of the Mediterranean Sea, dense brines (water saltier than the surrounding seawater) may fill the pockmarks, forming seafloor brine pools (Huguen et al. 2005) or lakes (Dupré et al. 2014) (see brine lake gray box).

Pockmarks are widespread in the marine environment from shallow water areas like estuaries (Garcia-Gil 2003), continental shelves (King and MacLean 1970; Ingrassia et al. 2015) and slopes (Bøe et al. 1998; Pilcher and Argent 2007), to deep water basins (Bayon et al. 2009; Gay et al. 2006; Marcon et al. 2014).

Driving mechanisms for pockmark formation and/or reactivation especially in the shallower examples are seismic activity, tidally driven hydraulic pumping (over the short-term time scale) and variation in hydrostatic pressure driven by sea level changes (over large-time scale) (Fig. 2). More information can be found in Chapter "Drivers of Seafloor Geomorphic Change" of this book.

The morphology of the pockmarks can be easily inferred from bathymetry if the resolution of the sonar is higher than the size of the pockmark. Combined with multi-frequency seafloor backscatter, the bathymetry may provide key information with regard to the detection and characterization of the pockmarks. A high amplitude of the backscatter signal may indicate the presence of methane-derived authigenic carbonates (MDACs), debris or coarse sediments within the pockmark.

The morphology and the spatial distribution of pockmarks are important guides in marine exploration with regard to their detection but also to the processes involved. They may provide information on the nature of the fluids involved (gas, hydrates, water, brines), the conditions of pockmark formation and evolution (the relative age, fluxes) and indications of the occurrence of post-formation processes (hydrodynamism, sedimentation rates).

Pockmarks and seafloor pools are commonly circular to oval (Fig. 6a, b, d) and can be 1–10s of meters across, and they may merge to form even larger structures up to several hundreds of m across (Ingrassia et al. 2015; Somoza et al. 2012). Their depths are usually up to about 10 m but may be greater than 200 m. Giant pockmarks may reach diameters >500 m and up to 1–1.5 km across (León et al. 2014; Pilcher and Argent 2007; Sultan et al. 2010; Somoza et al. 2003).

Pockmarks may be isolated, arranged in clusters or coalescent. They may form strings or chains in relation to fault traces (Soter 1999) or buried paleochannels (Gay et al. 2003). Widespread pockmarks may reach densities of over a few thousands per km^2 (Judd and Hovland 2007; Baltzer et al. 2014), and occupy wide surface areas, e.g. 30% of the seabed in the North Sea is scattered with pockmarks (Judd and Hovland 2007).

The pockmark shape can be asymmetric, e.g. due to slumping, or elongate, e.g. in relation to erosive features and the removal of sediments by bottom currents (Bøe

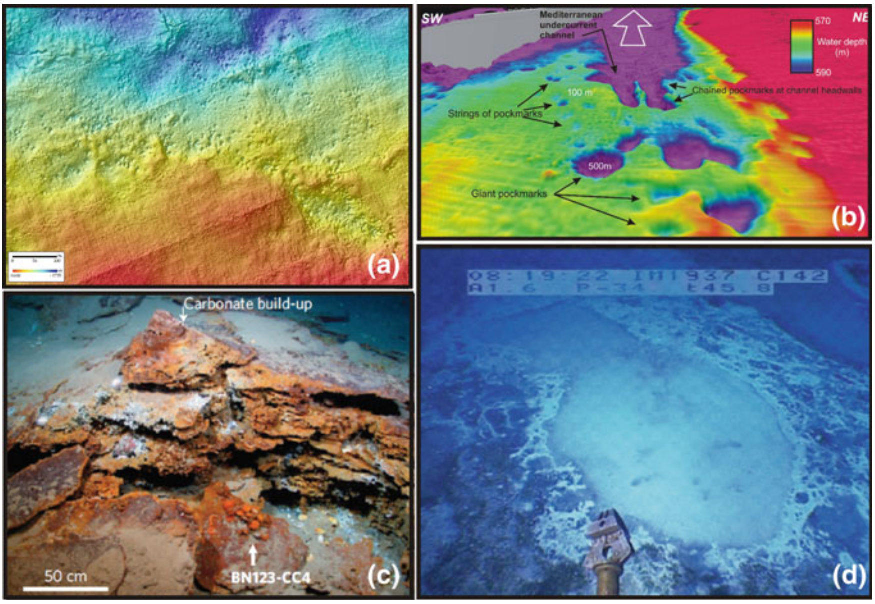

Fig. 6 Multibeam bathymetry and submarine images of pockmarks. **a** Field of pockmarks in the Nile Deep Sea Fan. **b** Chains of pockmarks in the Gulf of Cádiz. **c** Submarine image of methane-derived authigenic carbonates forming in a pockmark. **d** Submarine image of a pockmark filled with brine

et al. 1998; Josenhans et al. 1978). Pockmarks may be filled and associated with MDAC structures (Bayon et al. 2009) and fauna (Baltzer et al. 2014; Sen et al. 2016) or sediments deposited post-formation. Hydrate-bearing pockmarks are much more irregular depressions as a result of the formation and decomposition of gas hydrates in underlying sediments (Riboulot et al. 2016; Sultan et al. 2010).

The size of the pockmarks may be controlled by the fluid fluxes (Roberts 2001), by the underlying lithology (King and MacLean 1970) and by the thickness and architecture of near bottom sediments (Baltzer et al. 2014).

3.3 Carbonate-Related Structures

Most methane and other hydrocarbons associated with cold seeps are transformed into Methane-Derived Authigenic Carbonates (MDACs) due to the symbiotic activity of microbial-mediated consortia of archaea and bacteria (see grey boxes). The transformation of cold seep fluids to carbonates tends to strengthen structures such as mud volcanoes or pockmarks by providing both a hard framework and protective patches resistant to erosion (Fig. 6c).

3.3.1 Methane-Derived Authigenic Carbonates (MDACs)

The MDACs may form tubular chimneys (when oxidation of methane took place within the subsurface plumbing system) or build-ups of pavements or slabs when they occur near the surface of cold seeps (Fig. 6c). MDAC chimneys are typically cylindrical pipes with a central orifice up to 10 cm across and straight, tortuous, ramified or helical tubes showing a wide range of sizes (5–30 cm in diameter and 0.15–1.5 m in length). The central orifice acts as the seep conduit for methane and is thus the location of the AOM process (see gray box) which progressively cements the walls of the tubes with MDACs. The rate of cementation within the methane conduits is unknown. Some carbonate MDACs are associated with gas hydrate destabilization within mud volcanoes or seeps (Aloisi et al. 2000; Roberts 2001) (Fig. 4).

3.3.2 "Forest" of Carbonate Chimneys

Some of the most intriguing features we can observe rising from the seafloor of our continental margins, or lying on their side if collapsed, are seep-associated carbonate chimneys. Vast "forests" of these carbonate chimneys related to hydrocarbon-enriched fluid seepage have been reported in modern oceans as in the Kattegat (Jørgensen 1992), in the Gulf of Cádiz (Díaz-del-Río et al. 2003), in the

Adriatic Sea (Angeletti et al. 2015), in the Monterey Bay in California (Stakes et al. 1999), in the Campos basin off Brazil (Wirsig et al. 2012), in the Congo deep sea fan (Haas et al. 2010), in the Black Sea (Peckmann et al. 2001), in the Gulf of Mexico (Roberts 2001), off the Otago Peninsula in New Zealand (Orpin 1997), in the Dongsha area in the South China Sea (Han et al. 2013), and in the Cascadia subduction zone, offshore Oregon (Bohrmann et al. 1998). Some spectacular examples of forests of carbonate chimneys are observed in the Gulf of Cádiz. Here, carbonate mounds appear as irregular shaped clusters with a diameter of up to 6 km or clusters forming ridges up to 20 km long as in the Diasom chimney field (Somoza et al. 2003). The Diasom field is a prominent structural high with steep slopes between 25° and 35° and irregular crests formed by cone-shaped mounds rising 250 m above the seabed, such as the Cornide or Coruña Mounds. Observations from underwater camera revealed that these mounds are composed of large numbers of cylindrical pipe-like carbonate chimneys, pavements and crusts. Isotopic values from the chimneys show moderate to low depletion of $\delta^{13}C$ values (−20 to −40‰), reflecting that they were formed by AOM from a mixed source of biogenic and thermogenic gases (Díaz-del-Río et al. 2003).

The ramified pattern of the chimneys as observed in underwater photos indicates that they were formed by AOM (see Box 3) around the conduits that fed submarine cold seeps, and are now exposed probably as a result of winnowing by the strong Mediterranean outflow undercurrent (Díaz del Río et al. 2003). At the same time large vertical carbonate walls up to 50 m high, resulting from fissure-like seeps, may also have been exposed. In this way, giant carbonate mounds may form hard-rock morphological barriers that are able to channel strong deep water currents like the Mediterranean Outflow Water into the Atlantic Ocean.

The formation of vast expanses of MDACs around cold seeps also provides a hard substratum for growing seabed benthic organisms. Especially important are those forming reefs from what are known as cold-water corals (CWC), most of them belonging to the Scleractinia family as *Lophelia Pertusa* or *Madrepora Oculata*. These corals are able to live at water depths between 800 and 1200 m without the occurrence of light for photosynthesis. The deep water corals may grow around and above dormant cold seeps, being able to build up mounds (up to 50 m high) and/or linear ridges (up to 5 km long). The term CWC "reefs" is only used when the mounds or ridges are formed by living corals. The largest CWC reefs have been reported from the Porcupine, Rockall Trough (van Weering et al. 2003). There is strong scientific debate however as to whether the corals are fuelled by cold seeps or simply grow on cold seeps where a hard substrate is available and where there is upwelling food for them possibly related also to turbulence created by the formation of AOM carbonates. Further information may be found in Chapter "Cold-Water Carbonate Bioconstructions" in this book.

4 Geohazards and Ecosystem Habitats

Fluids at continental margins are major players in numerous geological, bio-chemical and oceanographic processes that may be associated with marine geohazards and can substantially alter the seafloor geomorphology. Some of the most dramatic hazards in which fluids may be involved are (i) sedimentary slope instabilities, (ii) association with earthquakes, and (iii) sudden methane release into the ocean. Fluids may thus be the predisposing or triggering factor, the geohazard itself, or a consequence of the geohazards. Developing large scale seafloor mapping programmes to acquire a good knowledge of the occurrence and distribution of active cold seep systems along continental margins, as well as understanding the processes that regulate venting and their implications regarding geohazards, are key to the security of the submarine nearshore, offshore, and coastal infrastructures. Hazards related to cold seeps may be natural or triggered by human activity (e.g. hydrocarbon spill, shallow gas blow-out). Monitoring the ocean floors at sites of venting using seabed observatory (EMSO, FluSO etc.…) represents an important scientific challenge. Detailed discussion of some of these topics can be found in Chapters “Submarine Canyons and Gullies”, “Submarine landslides” and “Applied Geomorphology and Geohazard Assessment for Deepwater Development” in this book.

On the other hand, cold seeps provide benefits to the marine environment by favouring life in deep water and hosting important ecosystems. Cold seeps areas hosting such vulnerable ecosystems should receive the attention of European and international regulations aimed at protecting and preserving these singular deep sea habitats for chemosynthetic organisms.

5 Gaps in Knowledge and Key Research Questions

The purpose of this subchapter is to highlight gaps in knowledge and key research questions on cold seep studies as a guide for young researchers and students to those topics that deserve the highest attention for future investigations.

Despite the growing interest in cold seep research and the many recent discoveries, the study of cold seep systems remains a relatively recent research topic. For this reason, processes and mechanisms regulating extrusion at seabed and their evolution in space and time are still largely unknown. Thus, the identification and analysis of the key questions represent an important scientific challenge.

Seabed morphology is an important tool that is able to reveal key information regarding the regulation of cold seep activity and the driving mechanisms. Microbathymetry maps, repeated multibeam acquisition of the same features in time, equalised backscatter analyses to reconstruct activity through time and the search for hydroacoustic anomalies in the water column are some of the modern tools that should be used to fill this gap in knowledge.

Some of the key research questions that deserve attention and specific investigation are:

1. How does the morphological variability of seeps relate to their specific driving processes? Different cold seep morphologies (e.g. mud pie, conic edifices, gryphons) are often observed adjacent to each other, occurring in a similar lithological and geological setting, and it is not clear on what this variability is dependant.
2. What is the timing of dormant versus active phases, the episodicity, and recurrence times?
3. How much gas is emitted into the water column, and what consequently is the impact of the gas released into the atmosphere on the global carbon cycle?
4. What is the impact of fluid release along faults during earthquakes, and what is their influence on geohazards?

Acknowledgements Because this chapter is based on the research of so many colleagues and projects, it is difficult to single out individual scientists and funding agencies for acknowledgment. This in no way diminishes the debt of thanks we have for their ground-breaking work. The names of a few of the many are to be found in the list of references. Reviewer G.G. Akhmanov is thanked for his positive and supporting comments on the chapter.

References

Aloisi G, Pierre C, Rouchy JM, Foucher JP, Woodside J (2000) Methane-related authigenic carbonates of eastern Mediterranean Sea mud volcanoes and their possible relation to gas hydrate destabilisation. Earth Planet Sc Lett 184:321–338

Angeletti L, Canese S, Franchi F, Montagna P, Reitner J, Walliser EO, Taviani M (2015) The "chimney forest" of the deep Montenegrin margin, south-eastern Adriatic Sea. Mar Petrol Geol. doi:10.1016/j.marpetgeo.2015.04.001

Baltzer A, Ehrhold A, Rigolet C, Souron A, Cordier C, Clouet H, Dubois S (2014) Geophysical exploration of an active pockmark field in the Bay of Concarneau, southern Brittany, and implications for resident suspension feeders. Geo-Mar Lett 34(2–3):215–230

Bayon G, Loncke L, Dupré S, Caprais JC, Ducassou E, Duperron S, Etoubleau J, Foucher JP, Fouquet Y, Gontharet S, Henderson GM, Huguen C, Klaucke I, Mascle J, Migeon S, Olu-Le Roy K, Ondréas H, Pierre C, Sibuet M, Stadnitskaia A, Woodside J (2009) Multi-disciplinary investigation of fluid seepage on an unstable margin: the case of the Central Nile deep sea fan. Mar Geol 261(1–4):92–104

Berndt C (2005) Focused fluid flow in passive continental margins. Philos T R Soc A 363 (1837):2855–2871

Bøe R, Rise L, Ottesen D (1998) Elongate depressions on the southern slope of the Norwegian Trench (Skagerrak): morphology and evolution. Mar Geol 146(1–4):191–203

Boetius A, Ravenschlag K, Schubert CJ, Rickert D, Widdel F, Gieseke A, Amann R, Jørgensen BB, Witte U, Pfannkuche O (2000) A marine microbial consortium apparently mediating anaerobic oxidation of methane. Nature 407:623–626

Bohrmann G, Greinert J, Suess E, Torres M (1998) Authigenic carbonates from the Cascadia subduction zone and their relation to gas hydrate stability. Geology 26(7):647–650

Ceramicola S, Praeg A, Cova D, Accettella M, Zecchin M (2014) Seafloor distribution and last glacial to postglacial activity of mud volcanoes on the Calabrian accretionary prism, Ionian Sea. Geo-Mar Lett 34:11–129

Cita MB, Ryan WFB, Paggi I (1981) Prometheus mud breccia: an example of shale diapirism in the western Mediterranean ridge. Annales Géologiques des Pays Helleniques 3:543–570

Díaz-del-Río V, Somoza L, Martínez-Frías J, Mata MP, Delgado A, Hernández-Molina FJ, Lunar R, Martin-Rubí JA, Maestro A, Fernández-Puga MC, León R, Llave E, Medialdea T, Vázquez JT (2003) Vast fields of hydrocarbon-derived carbonate chimneys related to the accretionary wedge/olistostrome of the Gulf of Cadiz. Mar Geol 195(1–4):177–200

Dimitrov L, Woodside J (2003) Deep sea pockmark environments in the eastern Mediterranean. Mar Geol 195:263–276

Dupré S, Woodside J, Foucher J-P, De Lange G, Mascle J, Boetius A, Mastalerz V, Stadnitskaia A, Ondréas H, Huguen C, Harmegnies F, Gontharet S, Loncke L, Deville E, Niemann H, Omoregie E, Olu-Le Roy K, Fiala-Medioni A, Dählmann A, Caprais J-C, Prinzhofer A, Sibuet M, Pierre C, Sinninghe Damsté J, NAUTINIL Scientific Party (2007) Seafloor geological studies above active gas chimneys off Egypt (Central Nile Deep Sea Fan). Deep Sea Res P I 54(7):1146–1172

Dupré S, Buffet G, Mascle J, Foucher J-P, Gauger S, Boetius A, Marfia C, the AsterX AUV Team, The Quest ROV Team, the BIONIL Scientific Party (2008) High-resolution mapping of large gas emitting mud volcanoes on the Egyptian continental margin (Nile Deep Sea Fan) by AUV surveys. Mar Geophys Res 29(4):275–290. doi:10.1007/s11001-009-9063-3

Dupré S, Woodside J, Klaucke I, Mascle J, Foucher J-P (2010) Widespread active seepage activity on the Nile Deep Sea Fan (offshore Egypt) revealed by high-definition geophysical imagery. Mar Geol 275(1–4):1–19. doi:10.1016/j.margeo.2010.04.003

Dupré S, Mascle J, Foucher J-P, Harmegnies F, Woodside J, Pierre C (2014) Warm brine lakes in craters of active mud volcanoes, Menes caldera off NW Egypt: evidence for deep-rooted thermogenic processes. Geo-Mar Lett 34(2–3):153–168. doi:10.1007/s00367-014-0367-1

Fusi N, Kenyon NH (1996) Distribution of mud diapirism and other geological structures from long-range sidescan sonar (GLORIA) data, in the Eastern Mediterranean Sea. Mar Geol 132:21–38

Garcia-Gil S (2003) A natural laboratory for shallow gas: the Rías Baixas (NW Spain). Geo-Mar Lett 23(3):215–229

Gay A, Lopez M, Cochonat P, Sultan N, Cauquil E, Brigaud F (2003) Sinuous pockmark belt as indicator of a shallow buried turbiditic channel on the lower slope of the Congo Basin, West African margin. Geol Soc Spec Publ Subsurf Sediment Mobil 216:173–189

Gay A, Lopez M, Ondreas H, Charlou JL, Sermondadaz G, Cochonat P (2006) Seafloor facies related to upward methane flux within a Giant Pockmark of the Lower Congo Basin. Mar Geol 226(1–2):81–95

Haas A, Peckmann J, Elvert M, Sahling H, Bohrmann G (2010) Patterns of carbonate authigenesis at the Kouilou pockmarks on the Congo deep-sea fan. Mar Geol 268:129–136

Han XQ, Yang KH, Huang YY (2013) Origin and nature of cold seep in north-eastern Dongsha area, South China Sea: evidence from chimney-like seep carbonates. Chin Sci Bul. 30:3689–3697

Harrington PK (1985) Formation of pockmarks by pore-water escape. Geo-Mar Lett 5(3):193–197. doi:10.1007/bf02281638

Hsü KJ, Ryan WBF, Cita MB (1973) Late Miocene desiccation of the Mediterranean. Nature 242:240–244

Huguen C, Mascle J, Woodside J, Zitter T, Foucher JP (2005) Mud volcanoes and mud domes of the Central Mediterranean Ridge: Near-bottom and in situ observations. Deep-Sea Res P I 52 (10):1911–1931

Ingrassia M, Martorelli E, Bosman A, Macelloni L, Sposato A, Chiocci FL (2015) The Zannone Giant Pockmark: first evidence of a giant complex seeping structure in shallow-water, central Mediterranean Sea, Italy. Mar Geol 363:38–51

Jørgensen NO (1992) Methane-derived carbonate cementation of marine sediments from Kattegat, Denmark: geochemical and geological evidence. Mar Geol 103:1–13

Josenhans HW, King LH, Fader GB (1978) A side-scan sonar mosaic of pockmarks on the Scotian Shelf. Can J Earth Sci 15:831–840

Judd A, Hovland M (2007) Seabed fluid flow: the impact on geology, biology and the marine environment. Cambridge University Press, Cambridge

Kopf AJ (2002) Significance of mud volcanism. Rev Geophys 40(2-1-2-52):1005

King LH, MacLean B (1970) Pockmarks on the Scotian Shelf. Geol Soc Am Bull 81:3142–3148

León R, Somoza L, Medialdea T, González FJ, Giménez-Moreno CJ, Pérez-López R (2014) Pockmarks on either side of the Strait of Gibraltar: formation from overpressured shallow contourite gas reservoirs and internal wave action during the last glacial sea-level lowstand? Geo-Mar Lett 34(2–3):131–151

Limonov AF, Woodside JM, Cita MB, Ivanov MK (1996) The Mediterranean Ridge and related mud diapirism: a background. Mar Geol 132:7–19

Loncke L, Maillard A, Basile C, Roest WR, Bayon G, Gaullier V, Pattier F, Mercier de Lépinay M, Grall C, Droz L, Marsset T, Giresse P, Caprais JC, Cathalot C, Graindorge D, Heuret A, Lebrun JF, Bermell S, Marcaillou B, Sotin C, Hebert B, Patriat M, Bassetti MA, Tallobre C, Buscail R, Durrieu de Madron X, Bourrin F (2015) Structure of the Demerara passive-transform margin and associated sedimentary processes. Initial results from the IGUANES cruise. Geological Society, London, Special Publications 431. doi:10.1144/sp431.7

Lykousis V, Alexandri S, Woodside J, de Lange G, Daehlmann A, Perissoratis C, Heeschen K, Chr Ioakim, Sakellariou D, Nomikou P, Rousakis G, Casas D, Ballas D, Ercilla G (2009) Mud volcanoes and gas hydrates in the Anaximander mountains (Eastern Mediterranean Sea). Mar Petrol Geology 26:854–872

Magalhães VH, Pinheiro LM, Ivanov MK, Kozlova E, Blinova V, Kolganova J, Vasconcelos C, McKenzie J, Bernasconi SM, Kopf AJ, Díaz-del-Río V, González FJ, Somoza L (2012) Formation processes of methane-derived authigenic carbonates from the Gulf of Cadiz. Sedimen Geol 243–244(1):155–168

Marcon Y, Ondreas H, Sahling H, Bohrmann G, Olu K (2014) Fluid flow regimes and growth of a giant pockmark. Geology 42(1):63–66. doi:10.1130/g34801.1

Mascle J, Mary F, Praeg D, Brosolo L, Camera L, Ceramicola S, Dupré S (2014) Distribution and geological control of mud volcanoes and other fluid/free gas seepage features in the Mediterranean Sea and nearby Gulf of Cadiz. Geo–Mar Lett 34:89–110

Mazzini A, Svensen H, Planke S, Guliyev I, Akhmanov GG, Fallik T, Banks D (2009) When mud volcanoes sleep: insight from seep geochemistry at the Dashgil mud volcano, Azerbaijan. Mar Petrol Geol 26(9):1704–1715

Mazzini A, Svensen H, Akhmanov GG, Aloisi G, Planke S, Malthe-Sorenssen A, Istadi B (2007) Triggering and dynamic evolution of the LUSI mud volcano, Indonesia. Earth Planet Sc Lett 261(3–4):375–388

Milkov AV (2000) Worldwide distribution of submarine mud volcanoes and associated gas hydrates. Mar Geol 167(1):29–42

Olu-Le Roy K, Sibuet M, Fiala-Medioni A, Gofas S, Salas C, Mariotti A, Fouche JP, Woodside J (2004) Cold seep communities in the deep eastern Mediterranean Sea: composition, symbiosis and spatial distribution on mud volcanoes. Deep-Sea Res PT I 51(12):1915–1936

Orpin AR (1997) Dolomite chimneys as possible evidence of coastal fluid expulsion, uppermost Otago continental slope, southern New Zealand. Mar Geol 138:51–67

Peckmann J, Reimer A, Luth U, Luth C, Hansen BT, Heinicke C, Hoefs J, Reitner J (2001) Methane-derived carbonates and authigenic pyrite from the northwestern Black Sea. Mar Geol 177(1–2):129–150

Pilcher R, Argent J (2007) Mega-pockmarks and linear pockmark trains on the West African continental margin. Mar Geol 244(1–4):15–32

Praeg D, Ceramicola S, Barbieri R, Unnitha V, Wardell N (2009) Tectonically-driven mud volcanism since the late Pliocene on the Calabrian accretionary prism, central Mediterranean Sea. Mar Petrol Geol 26:1849–1865

Rabaute A, Chamot-Rooke N (2007) Quantitative mapping of active mud volcanism at the western Mediterranean Ridge-backstop contact. Mar Geophys Res 28:271–293

Riboulot V, Sultan N, Imbert P, Ker S (2016) Initiation of gas-hydrate pockmark in deep-water Nigeria: geo-mechanical analysis and modelling. Earth Planet Sci Lett 434:252–263. doi:10.1016/j.epsl.2015.11.047

Roberts HH (2001) Fluid and gas expulsion on the northern Gulf of Mexico continental slope: Mud-prone to mineral-prone responses. In: Natural gas hydrates: occurrence, distribution, and detection, vol 124. Geophysical monograph series. AGU, Washington, DC, pp 145–161. doi:10.1029/GM124p0145

Robertson AHF, Kopf A (1998) Origin of clasts and matrix within the Milano and Napoli mud volcano, Mediterranean Ridge accretionary prism. In: Robertson AHF, Emeis KC, Richter C, Camerlenghi A (eds), Proceedings of the ODP, scientific reports, vol 160. College Station, TX (Ocean Drilling Program), pp 575–596

Sen A, Ondréas H, Gaillot A, Marcon Y, Augustin JM, Olu K (2016) The use of multibeam backscatter and bathymetry as a means of identifying faunal assemblages in a deep-sea cold seep. Deep Sea Res PI 110:33–49. doi:10.1016/j.dsr.2016.01.005

Sibuet M, Olu K (1998) Biogeographic biodiversity and fluid dependence of deep-sea cold-seep communities at active and passive margins. Deep-Sea Res P II 45(1–3):517–567

Somoza L, Gardner JM, Díaz-del-Río V, Vázquez T, Pinheiro L, Hernández-Molina FJ, TASYO/ANASTASYA Shipboard Scientific Parties (2002) Numerous methane gas related seafloor structures identified in the Gulf of Cádiz. Eos Transactions of the American Geophys Union 47:541–547

Somoza L, Diaz-del-Rio V, Leon R, Ivanov M, Fernández-Puga MC, Gardner JM, Hernández-Molina FJ, Pinheiro LM, Rodero J, Lobato A, Maestro A, Vázquez JT, Medialdea T, Fernández-Salas LM (2003) Seabed morphology and hydrocarbon seepage in the Gulf of Cadiz mud volcano area: acoustic imagery, multibeam and ultra-high resolution seismic data. Mar Geol 195(1–4):153–176

Somoza L, Medialdea T, León R, Ercilla G, Vázquez JT, Farran M, Hernández-Molina FJ, González FJ, Juan C, Fernández-Puga MC (2012) Structure of mud volcano systems and pockmarks in the region of the Ceuta Contourite Depositional System (Western Alborán Sea). Mar Geol 332–334:4–26

Soter S (1999) Macroscopic seismic anomalies and submarine pockmarks in the Corinth-Patras rift, Greece. Tectonophysics 308(1–2):275–290. doi:10.1016/S0040-1951(99)00090-6

Stakes DS, Orange D, Paduan JB, Salamy KA, Maher N (1999) Cold-seeps and authigenic carbonate formation in Monterey Bay, California. Mar Geol 159(1–4):93–109

Sultan N, Marsset B, Ker S, Marsset T, Voisset M, Vernant AM, Bayon G, Cauquil E, Adamy J, Colliat JL, Drapeau D (2010) Hydrate dissolution as a potential mechanism for pockmark formation in the Niger delta. J Geophys Res-Sol Ea 115 (B8):n/a–n/a. doi:10.1029/2010jb007453

Toyos MH, Medialdea T, León R, Somoza L, Gonzalez FJ, Meléndez N (2016) Evidence of episodic long-lived eruptions in the Yuma, Ginsburg, Jesús Baraza and Tasyo mud volcanoes, Gulf of Cádiz. Geo-Mar Lett. doi:10.1007/s00367-016-0440-z

Van Weering TJ, de Haas H, Akhmetzamov AM, Kenyon NH (2003) Giant carbonate mounds along the Porcupine and SW Rockall Trough margins. In: Mienert J, Weaver P (eds) European margin sediment dynamics, side-scan sonar and seismic images. Springer, Berlin, pp 211–216

Volgin AV, Woodside JM (1996) Sidescan sonar images of mud volcanoes from the Mediterranean Ridge: causes of variation in backscatter intensity. Mar Geol 132(1–4):39–53

Whiticar MJ (2002) Diagenetic relationships of methanogenesis, nutrients, acoustic turbidity, pockmarks and freshwater seepages in Eckernforde Bay. Mar Geol 182(1–2):29–53. doi:10.1016/s0025-3227(01)00227-4

Wirsig C, Kowsmann RO, Miller DJ, de Oliveira Godoy JM, Mangini A (2012) U/ Th-dating and post-depositional alteration of a cold seep carbonate chimney from the Campos Basin offshore Brazil. Mar Geol 329–331:24–33

Woodside JM, Ivanov MK, Limonov AF, Shipboard Scientists of the Anaxiprobe Expeditions (1998) Shallow gas and gas hydrates in the Anaximander Mountains regions, eastern Mediterranean Sea. In: Henriet JP, Mienert J (eds) Gas hydrates: relevance to world margin stability and climate change, vol 137. Geological Society, London, Special Publications, pp 177–193

Woodside JM, Volgin AV (1996) Brine pools associated with Mediterranean Ridge mud diapirs: an interpretation of echo-free patches in deep two sidescan sonar data. Mar Geol 132(1–4):55–61

Zitter TAC, Huguen C, Woodside JM (2005) Geology of mud volcanoes in the Eastern Mediterranean from combined sidescan and submersible surveys. Deep-Sea Res Pt I 52 (3):457–475