Deep Sea Research Part I: Oceanographic Research Papers
July 2007, Volume 54, Issue 7, Pages 1146-1172
http://dx.doi.org/10.1016/j.dsr.2007.03.007

Seafloor geological studies above active gas chimneys off Egypt (Central Nile Deep Sea Fan)

Stéphanie Dupré[a, *], John Woodside[a], Jean-Paul Foucher[b], Gert de Lange[c], Jean Mascle[d], Antje Boetius[e], Vincent Mastalerz[c], Alina Stadnitskaia[f], Hélène Ondréas[b], Caroline Huguen[g], François Harmégnies[b], Swanne Gontharet[h], Lies Loncke[i], Eric Deville[j], Helge Niemann[e], Enoma Omoregie[e], Karine Olu-Le Roy[k], Aline Fiala-Medioni[l], Anke Dählmann[c], Jean-Claude Caprais[k], Alain Prinzhofer[j], Myriam Sibuet[k], Catherine Pierre[h], Jaap Sinninghe Damsté[f] and the NAUTINIL Scientific Party

[a] Sedimentology and Marine Geology Department, Faculty of Earth and Life Sciences, Vrije Universiteit, Amsterdam, The Netherlands
[b] Département Géosciences Marines, Ifremer, Brest Centre, Plouzané, France
[c] Geosciences Department, Universiteit Utrecht, The Netherlands
[d] Géosciences Azur, Villefranche sur Mer, France
[e] Max Planck Institute for Marine Microbiology, Bremen, Germany
[f] NIOZ, Texel, The Netherlands
[g] Université de Perpignan, France
[h] UPMC, LOCEAN, Paris, France
[i] Université d'Amiens, France
[j] Institut Français du Pétrole, Rueil-Malmaison, France
[k] Laboratoire Environnement Profond, Brest Centre, Plouzané, France
[l] UPMC, Observatoire Océanologique de Banyuls, France

*: Corresponding author : Dupré S., email address : stephanie.dupre@locean-ipsl.upmc.fr

Abstract:

Four mud volcanoes of several kilometres diameter named Amon, Osiris, Isis, and North Alex and located above gas chimneys on the Central Nile Deep Sea Fan, were investigated for the first time with the submersible Nautile. One of the objectives was to characterize the seafloor morphology and the seepage activity across the mud volcanoes. The seepage activity was dominated by emissions of methane and heavier hydrocarbons associated with a major thermal contribution. The most active parts of the mud volcanoes were highly gas-saturated (methane concentrations in the water and in the sediments, respectively, of several hundreds of nmol/L and several mmol/L of wet sediment) and associated with significantly high thermal gradients (at 10 m below the seafloor, the recorded temperatures reached more than 40 °C). Patches of highly reduced blackish sediments, mats of sulphide-oxidizing bacteria, and precipitates of authigenic carbonate were detected, indicative of anaerobic methane consumption. The chemosynthetic fauna was, however, not very abundant, inhibited most likely by the high and vigorous fluxes, and was associated mainly with carbonate-crust-covered seafloor encountered on the southwestern flank of Amon. Mud expulsions are not very common at present and were found limited to the most active emission centres of two mud volcanoes, where slow extrusion of mud occurs. Each of the mud volcanoes is fed principally by a main narrow channel located below the most elevated areas, most commonly in the centres of the structures. The distribution, shape, and seafloor morphology of the mud volcanoes and associated seeps over the Central Nile Deep Sea Fan are clearly tectonically controlled.

Keywords: Nile fan; Fluid seepage; Mud volcanoes; Mud breccia; Gas chimneys; Authigenic carbonate precipitation; Methane; Seafloor morphology

1. Introduction

Marine research has greatly benefited over the last decades from sea technology development. Examples of this are the introduction of submersibles and underwater remotely operated vehicles, investigations in deep water environments, and the acquisition of high resolution geophysical data as in seismic profiles or seafloor imaging. The newly acquired datasets have revealed, in particular, an intense seepage activity all over the globe (e.g., Kopf, 2002; Mazurenko and Soloviev, 2003; Milkov, 2000). Seep-related structures, until recently poorly known, were commonly associated with gas emission (methane and higher hydrocarbon gases), mud volcanism, precipitation of authigenic carbonate and chemosynthetic life.

Mud volcanoes originate from under-compacted and over-pressured clay-rich sedimentary layers. They develop at convergent margins, e.g., onshore and offshore Trinidad (Deville *et al.*, 2003) and along the Hellenic subduction zone (Camerlenghi *et al.*, 1995; Camerlenghi *et al.*, 1992; Cita *et al.*, 1981; Cronin *et al.*, 1997; Huguen *et al.*, 2004; Limonov *et al.*, 1996), and at rifted continental margins, for example, in the Gulf of Mexico (Neurauter and Bryant, 1989; Sager *et al.*, 2003; Sassen *et al.*, 1993), the Gulf of Guinea (Heggland and Nygaard, 1998; Heggland *et al.*, 1996), and the Nile Deep Sea Fan (Loncke *et al.*, 2004; Mascle *et al.*, 2001), wherever tectonic forces and high sedimentation rates contribute to the rapid subsidence and burial of uncompacted sediments. Similarly, some abyssal parts of inland seas characterized by a thick sedimentary pile are associated with numerous submarine mud volcanoes (typically the Caspian and the Black Seas, Dimitrov, 2002; Woodside *et al.*, 1997; Yusifov and Rabinowitz, 2004).

Besides the strong interest of the exploration and petroleum industry (e.g., off Egypt, see Abdel *et al.*, 2001; Dolson *et al.*, 2001), the environmental effects of the gas (methane) release from offshore reservoirs into the uppermost sedimentary cover, the water column, and possibly even to the atmosphere derive increasing attention from public and governmental communities (IPCC, 2001). Moreover, sedimentary instability induced by high sedimentary fluid content or gas emissions, in some cases introduced together through dissociation of gas hydrates (Bouriak *et al.*, 2000), can cause slope failures and mass flows that can pose potentially serious hazards to society. Such events might have contributed to the destruction of the coastal city of Alexandria and the close surroundings in ancient times (Stanley *et al.*, 2004; Stanley *et al.*, 2001).

This paper focuses on four wide mud volcanoes located above gas chimneys in the upper slope domain of the Central Nile Deep Sea Fan. These structures, which lie between ~500 and 1200 metres water depth (Fig. 1 and Table 1) were observed *in situ* for the first time during the 2003 NAUTINIL campaign by the R/V *L'Atalante* with the French submersible *Nautile* (Dupré *et al.*, 2006). This expedition was carried out in the framework of the multidisciplinary ESF EUROCORES Euromargins Project Mediflux dedicated to an integrated study of seepage through the seabed of the Nile Deep Sea Fan. The large variety of data collected using the submersible, as well as multibeam data, CTD measurements and long piston cores coupled with thermal probes, revealed intense seepage activity. Ground-truth evidence for high fluid and gas emission systems is based on geological, (micro)biological, geochemical, and geophysical data (Dupré *et al.*, 2006).
The main objective of the exploratory dives was to investigate the seafloor morphology of the mud volcanoes to find direct evidence for fluid and gas emissions and compare the seepage activity across the mud volcanoes. Detailed seafloor geological maps were produced and are presented in this paper. We discuss the characteristics and relationships in the seafloor morphology, the nature and the spatial and temporal distribution of fluid venting structures, the biochemical processes at these seeps, the occurrence of benthic and chemosynthetic fauna, and the intensity of the seepage activity (fluid emission,

thermal fluxes). The development and functioning of the wide mud volcanoes located above gas chimneys in the Central Nile Deep Sea Fan are discussed in this context.

2. Background studies

2.1. Eastern Mediterranean Sea Geology

The complex tectonic history of the Eastern Mediterranean Sea started with the opening of the Tethys Ocean in Early/Late Triassic through Jurassic times (Biju-Duval *et al.*, 1978; Hirsch *et al.*, 1995). From Middle/Late Triassic through Early Cretaceous times, successive rifting episodes took place (Hirsch *et al.*, 1995) leading to the formation of NE-SW oriented marine sedimentary basins in northern Egypt (Dolson *et al.*, 2001). Subsequently in Cenomanian times, the Eastern Mediterranean experienced convergence between the African and Eurasian plates, initiating the progressive closure of the Tethys Ocean and the creation of the Alpine-Himalayan orogenic belt (McKenzie, 1970; Sage and Letouzey, 1990). The Nile Deep Sea Fan started to develop at the end of the Eocene (Salem, 1976) with the offshore deposition of a thick northwards prograding detrital series (Ross and Uchupi, 1977). In Late Miocene time, the Mediterranean Sea was isolated from the Atlantic Ocean, causing major evaporation and the deposition of evaporites in the deeper basins (Hsü *et al.*, 1973; Ryan, 1978; Sage and Letouzey, 1990). Associated with this drastic decrease in sea level (Ryan, 1978), large-scale canyons incised the proximal part of the margin with the development of several regional drainage networks (Abdel *et al.*, 2000; Dolson *et al.*, 2002). This Messinian salinity crisis was a major event for the subsequent tectonic evolution of the Mediterranean Basins, particularly in the region of the Egyptian Margin. A sea level rise in Pliocene time was followed by Plio-Pleistocene falls and progradation of the modern Nile Delta. Most of the Nile Deep Sea Fan was constructed since Late Miocene and corresponds at present to the most prominent sedimentary edifice along the Eastern Mediterranean margins, with sediments more than 9-10 km thick (Abdel *et al.*, 2001; Mascle *et al.*, 2003).
After the Messinian salinity crisis and subsequent deposition of thick sediments, salt tectonics off Egypt became very active with the downslope gravity spreading or gliding of the evaporites and the sedimentary overburden. Such thin-skinned syn-sedimentary deformation still strongly affects the middle and lower Nile Fan at present, especially in the western and eastern provinces, where the seafloor is shaped by numerous salt-tectonics-related features, such as growth faults, salt diapirs and crestal grabens (Fig. 1) (Gaullier *et al.*, 2000; Mascle *et al.*, 2001). In contrast, the Messinian evaporites are almost absent in the upper slope domain because of the downslope movements and are compensated with post-salt sediments up to 2.5 km thick (Loncke *et al.*, 2002; Loncke *et al.*, 2006).

The Egyptian offshore has proven to be a prolific domain for hydrocarbons (Dolson *et al.*, 2002). The main reservoirs are found in the Pliocene-Pleistocene deepwater channels and basin-floor turbidite sands and in the Upper Miocene sequences composed of fluvial or turbidite sands (Abdel *et al.*, 2001; Dolson *et al.*, 2001). The thick Messinian evaporites clearly played a significant role by sealing the maturing petroleum system below. The salt distribution over the deep sea fan matches roughly the oil discoveries province, whereas the shallower and more proximal former Messinian platform corresponds mainly to the gas province (Fig. 1). Related fluid leakage through faults contributes to the seepage activity recorded at the seabed, namely at the mud volcanoes located above gas chimneys, and examined in the present paper.

The seepage activity in the Eastern Mediterranean Sea is characterized by a wide distribution and diversity. Fluid venting structures and associated mud volcanoes mark parts of the seafloor on the Mediterranean Ridge accretionary wedge within and near the backthrust domain (Cita *et al.*, 1996; Cita *et al.*, 1981; Cronin *et al.*, 1997; Fusi and Kenyon, 1996; Hieke *et al.*, 1996; Huguen *et al.*, 2004; Huguen *et al.*, 2005b; MEDINAUT/MEDINETH Shipboard Scientific Party, 2000; MEDRIFF Consortium, 1995; Volgin and Woodside, 1996), in the complex deformation zone of the Anaximander Mountains between the Hellenic and Cyprus arcs (Woodside *et al.*, 1998; Zitter *et al.*, 2005) and along the Florence Rise (Woodside *et al.*, 2002). Seepage activity was also discovered along the rifted continental margin to the south, comprising from west to east the Herodotus Abyssal Plain, the Nile Deep Sea Fan and the Levant Basin (Bellaiche *et al.*, 2001; Coleman and Ballard, 2001; Loncke *et al.*, 2004; Mascle *et al.*, 2001).

2.2. Fluid escape structures on the Nile Deep Sea Fan

The Nile Deep Sea Fan can be divided into three main sedimentary and morphostructural domains: the Western, the Central and the Eastern Provinces (Bellaiche *et al.*, 2001; Bellaiche *et al.*, 1999; Loncke *et al.*, 2004; Mascle *et al.*, 2001) (Fig. 1). Based on multibeam data (bathymetry and backscatter), numerous potential fluid escape structures had been identified on the seafloor prior to NAUTINIL. These fluid venting structures are closely related to the fault network, encompassing either deep faults traced to deep-seated basement structures or shallow intra-sedimentary faults induced by salt tectonics or slope instabilities (Huguen *et al.*, 2006b; Loncke *et al.*, 2004; Mascle *et al.*, 2006). The Western Province, containing the Rosetta branch of the Nile River (Fig. 1), is dissected by abundant meandering distributary channels of various ages and is the most recently active part of the deep-sea fan. The seafloor there is scattered with numerous small cones and sub-circular depressions. These structures are formed by mud eruptions and fluid emissions along growth faults induced by sedimentary loading in the upper slope domain (Gaullier *et al.*, 2000). Some of the depressions are large morphologic features: the wide Menes Caldera lying in ~3000 metres of water is over 8 km in diameter (Huguen *et al.*, 2006a; Huguen *et al.*, 2005a). The Central Province is characterized by significant sedimentary instabilities along the continental slope (Bayon *et al.*, 2005; Loncke *et al.*, 2004). Debris flow layers are widespread in some parts of the uppermost sedimentary cover, and the seafloor is very disturbed by thousands of pockmarks with associated authigenic carbonate crusts (Loncke *et al.*, 2004). The Eastern Province corresponds to a wide zone of transtensive grabens with NNW-SSE oriented strike-slip faults and is clearly delimited from the Central Province by one of them (Fig. 1). This tectonic corridor was initially interpreted as the offshore prolongation of the Gulf of Suez (Mascle *et al.*, 2000). The seafloor morphology and the sedimentary depositional pattern result most likely from a combination of regional transtensional tectonics and the salt tectonic activity (Gaullier *et al.*, 2000), interacting with subsalt inherited basement faults (Loncke *et al.*, 2006). In the Eastern Province, the thick uppermost sedimentary cover, together with the underlying Messinian evaporites, is strongly disturbed by thin-skinned gravity tectonics. Downslope spreading and creep form numerous ridges and depressions, very well expressed on multibeam bathymetric maps (Fig. 1).

The large mud volcanoes located above gas chimneys are not restricted to one of these provinces, even if most of the structures identified so far are in the central part of the Nile Deep Sea Fan (Fig. 1) (Loncke *et al.*, 2004). These mud volcanoes are located along a relatively narrow belt at the edge of the present-day continental platform in the western (SIMED expedition in 2005) and the central parts of the Nile Deep Sea Fan (e.g., North Alex and Athon), or in a more distal position in water depth between 750 and 1200 metres on the former Messinian platform (e.g., Isis mud volcano) or close to it (e.g., Osiris and Amon mud volcanoes) (Fig. 1). Messinian evaporites are therefore absent around the mud volcanoes as a result of original non-deposition, erosion, or removal of evaporites by downslope spreading. However, in the case of the more distal Osiris and Amon, isolated salt bodies may remain nearby (see seismic profiles in Loncke *et al*., 2004). These mud volcanoes were first identified by multibeam swath mapping, a limited number of seismic lines, and sampling obtained during the FANIL expedition in 2000 (Loncke *et al.*, 2004; Sardou and Mascle, 2003). Zones of strong backscatter in multibeam acoustic imagery, commonly interpreted as potential active seepage areas, were observed mainly at the centres of the structures (Fig. 2). Seismic data, when available, have revealed wide and deep seismically transparent columns beneath the surface of the mud volcanoes, attributed to gas-saturated sediments (Abdel *et al.*, 2000; Loncke *et al.*, 2004) forming so-called gas chimneys. One piston core in the centre of Osiris carried out during the FANIL cruise exhibited 2 metres of structureless muddy sediments, enriched in hydrogen sulfide (H_2S) and methane (CH_4), and containing some clasts.

3. Nautile submersible surveys

3.1. Targets

Five exploration dives with the *Nautile* submersible were dedicated to investigate four of the ten then known wide mud volcanoes in the Central Nile Deep Sea Fan (Fig. 1 and Table 1). A few additional dives were made to obtain specific sedimentological, geochemical and microbiological samples.

The North Alex mud volcano is located in the gas province in the western part, just north of the Rosetta Canyon, at the limit of the present-day continental platform, and it is the shallowest (500 metres water depth) and most proximal structure explored (~50 km from the coast line). Isis, Osiris and Amon mud volcanoes are located on the Messinian platform in the eastern part of the Central Nile Deep Sea Fan, west of the major NNE-SSW trending fault zone (~100 km away from the coast line) (Figs 1 and 3). These latter are at the frontier between the gas/condensate province and the oil discoveries province, north of the main area of exploitation wells and at the southern limit of the northeast Mediterranean Deepwater Block (Fig. 1) (Abdel *et al.*, 2001). The exploration dive surveys attempted to cover the maximum surface of the mud volcanoes with an emphasis on the strongest backscatter areas interpreted as favourable sites for seepage.

3.2. Tools

For all the dives, the *Nautile* submersible was equipped with a variety of sensors, cameras and sampling devices. The most importance of which were: A pressure sensor and a sounder which calculated with great accuracy both the immersion depth of the submersible and its altitude above the seafloor. The bathymetry was therefore estimated with less than one metre error, providing detailed information on the morphology of the explored mud volcanoes. Enhanced methane concentrations in the water column were detected qualitatively with a CAPSUM METS sensor. The temperature of the water column was continuously measured, and subsequently filtered within the first 2 metres above the seafloor, in order to compare thermal variations across the mud volcano, in particular between the active and inactive sites. In addition to this set of sensors, two remote arms were used to operate several types of tools for specific sampling and measurement. Biological and geological samples were thus easily grabbed at the seafloor. They included rock clasts, pieces of authigenic carbonate crust, and bivalve shells. Push cores 20 to 30 centimetres in length were collected for sedimentological, biological, and geochemical purposes. A thermal probe (Micrel) to measure heat flux in the first tens of centimetres of sediments and two titanium bottles to sample water and gas under maintenance of *in situ* pressure were also utilized. The seafloor observations and sampling operations during the dives were recorded with digital and analogue cameras together with two video cameras. Four laser beams, integrated with these cameras, created four points of light with a fixed distance of ~20 centimetres between them for use in estimating the size of observed objects and the scale of seafloor relief, which was especially useful in analysing video images. In addition to the submersible surveys, the following operations were conducted from the mother ship *L'Atalante*: long piston coring of the mud volcano sediments coupled with thermal flux measurement using outrigger thermal probes, CTD rosette water/fluid sampling above the inferred main emission centres of the mud volcanoes (Mastalerz *et al.*, 2007), and multibeam acquisition with the Simrad EM12-Dual (MediMap Group *et al.*, 2005). The Adelie software developed by Ifremer and based on ArcMap GIS software was used to perform dive analyses together with previously available multibeam datasets acquired during the FANIL (2000) expedition.

4. Large mud volcanoes above gas chimneys

4.1. Tectonic control

The distribution of mud volcanoes and associated seeps on the Nile Deep Sea Fan (Loncke *et al.*, 2004), together with the overall shape of the mud volcanoes and their seafloor morphology, are clearly tectonically controlled. The gas chimneys on the Nile Deep Sea Fan, sometimes located over Messinian canyons (Loncke *et al.*, 2006), are commonly above or near reactivated deep-seated faults together with shallower faults (Loncke *et al.*, 2004; Mascle *et al.*, 2006) (Fig. 1). A fault network was identified on seismic profiles, 3D seismic coherency and bathymetry maps (Abdel *et al.*, 2001; Loncke, 2002; Loncke *et al.*, 2004; Sardou and Mascle, 2003). Two major fault trends dissect the Egyptian margin, the NW-SE Temsah trend and the NE-SW to ENE-WSW Rosetta trend (Abdel *et al.*, 2001) (Fig. 1).

Although the sub-circular mud volcanoes are slightly elongated in the slope direction (e.g., SSE/NNW for Osiris and Isis mud volcanoes, see Figs 5 and 6) because of sedimentary creep or slumping at their northern side, the overall shape of the mud volcanoes is mainly tectonically controlled (Dupré *et al.*, 2006). Clearly, the most tectonically disturbed seafloor (i.e., with numerous faults, ridges, escarpments, instabilities, steepest and most variable slopes and surrounding relief) is associated with the most irregular shaped mud volcanoes, namely Amon and Osiris (Fig. 3). The carbonate crust field on the southwestern side of the Amon mud volcano faces the major transpressive fault zone initially activated in transtension (Fig. 3) (Loncke *et al.*, 2006) and forms a broad linear band of very high backscatter parallel to the NW-SE southern fault (Loncke *et al.*, 2004); it is thus most likely related to seepage along a fault. In contrast, the radially symmetrical Isis mud volcano is located on the former Messinian platform with a much less disturbed and faulted surrounding seafloor and a uniform slope of 1.1º towards the north (Figs 3 and 6 and Table 1).

4.2. Seafloor morphology

The first-order morphology of the four studied mud volcanoes of the Central Nile Deep Sea Fan is cylindrical, with a diameter of several kilometres (1.5 to 4.6 km) and a height of less than 90 m (Table 1 and Figs 4 to 7). The surfaces of the mud volcanoes are almost flat (Fig. 8). Some of them have a slightly conical morphology, with a gentle uniform slope from the edges to the centre (e.g., Amon, Fig. 4) or a slightly elevated and restricted centre (e.g., Isis, Figs 6 and 8b). Osiris is distinguished by two separate elevated domes, one with a low conical shape in the southwestern quarter and a second flatter one located on the northeastern side (Figs 5 and 8a). Most of the expelled solid material is composed of relatively uniform mud breccia observed on the seafloor and partly covered with fine sediments (Figs 4a, 5a, 6a, 7a and 9). Neither edges of mud flows nor fluidized muds were visually identified at any of the four mud volcanoes.

The surfaces on Amon, North Alex and Isis exhibited a series of roughly concentric ridges and troughs up to about 3 metres in relief alternating with plateau areas (Fig. 8) uniformly covered with small decimetre-scale depressions and mounds. The ridges were often partly modified by mass flows along the steepest slope. Moreover, the seafloor was disturbed in places by microfaults, scarps, and related local tectonic features (Fig. 10d). Osiris had a much smoother surface, showing gentle depressions and mounds less than one metre high (Figs 5 and 10e). The seafloor in the most external areas, close to the outer edge of the mud volcanoes, was typically smooth and undisturbed (Fig. 10a). The outer flanks were fairly abrupt.

The centres of Amon, North Alex, and Isis and the southwestern dome of Osiris exhibited larger scale features, slightly more fractured, with marked morphological differences, however, from one mud volcano to another (Figs 4 to 7). Relatively flat and uniform on North Alex (Fig. 7), the seafloor was covered with decimetre-scale gentle depressions and mounds on Osiris (Fig. 5), and highly disturbed with higher topographic features on both Amon and Isis (Figs 4, 6, and 11a to 11e). The transition separating the concentric ridges and the centres of these latter two mud volcanoes was very sharp. In these centres, rough mud structures, several metres high (Fig. 11a), were juxtaposed with a smoother and hilly relief composed of depressions and mounds of decimetric scale, which were already modified by erosion and hemipelagic sedimentation (Fig. 11b). The flanks of these chaotic structures were generally abrupt, sometimes subvertical, and often fractured. Striations along these surfaces were often visible (Fig. 11e), regularly subvertical, indicating clearly that the mud breccia had been slowly extruded. This mud breccia was relatively uniform in texture and composed of fine clay particles enclosing rock clasts of various sizes. These restricted areas in the centres of Amon and Isis mud volcanoes were the only sites exhibiting relatively fresh mud breccia, corresponding therefore to the youngest mud extrusion events (Figs 4 and 6).

During the ascent of mud and gases towards the seabed, some fragments of rocks may be incorporated from the sedimentary strata through which the migration path forms and end up at the seafloor. Rock clasts of significant size, centimetric to decimetric, were relatively rare at the surface of the explored mud volcanoes. None of these were found lying on the seafloor on Osiris and North Alex, and only a few rock clasts were observed in the active centres of Isis and Amon mud volcanoes (Fig. 12d), corresponding to polygenic grey clayey limestones and more or less indurated clays, most likely originating from the mud source layer. The discrepancies between the different explored mud volcanoes may indicate that the last massive mud eruption on North Alex and Osiris is old, as corroborated by the absence of fresh mud breccia on these mud volcanoes (Fig. 5 and 7), unlike on Isis and Amon (Fig. 4 and 6).

4.3. Main gas emission centres

4.3.1. Emission centres associated with dark sediment patches

Nature and distribution of the gas seeps

Grey to black sediments were found in patches at the surface of the seafloor at the active emission centres of the mud volcanoes, where the environment is highly gas-saturated (Fig. 11f). The colour is a result of precipitation of iron with sulphide derived from microbial hydrocarbon-fueled sulfate reduction (Boetius *et al.*, 2000; Orphan *et al.*, 2002). Samples from the black patches generally show high concentrations of sulfides and gas.

Presumably the black seeps develop where methane reaches the sulfate-penetrated surface sediments supporting high rates of anaerobic oxidation of methane (AOM) mediated by consortia of methanotrophic archaea and bacteria (Boetius *et al.*, 2000). *Ex situ* rates measured by incubation of sediments with ^{14}C-labeled methane or ^{35}S-labeled sulfate reach more than 20 mmol.m^{-2}.d^{-1} (Omoregie et *al.*, unpublished data). Both AOM and sulfate reduction are very active biogeochemical processes at these seeps (Gontharet *et al.*, 2006; Mastalerz *et al.*, 2007; Omoregie *et al.*, 2005). Hydrogen sulfide gas (H_2S) was easily detected with its strong smell during the opening of the cores. Additionally, carbonate precipitation from the oxidized methane-derived carbon led to the formation of small carbonate concretions observed within the sediments (Gontharet *et al.*, 2006).

The black sediment patches were concentrated principally on the highest areas of the mud volcanoes (Figs 4 to 7). These slightly elevated domes are located in the centre of the mud volcanoes except for Osiris, where the highest point is located in the southwestern quarter of the mud volcano (Figs 5 and 8a). The surface covered with these black sediments in the centre of North Alex was relatively wide in comparison with the centres of the other mud volcanoes (Fig. 7). The black patches were usually distributed over a relatively small sub-circular area (e.g., within a radius of ~25 m on Amon and Isis, Figs 4 and 6) and restricted to the smoothest parts (Fig. 11b). The rougher and raised structures encountered at the centres of Amon and Isis were not usually associated with black sediments and were composed almost exclusively of relatively fresh mud breccia (Figs 11a and 11c). The black sediment patches formed small isolated patches of various sizes, a few centimetres to a few metres wide at most. For instance, the centres of Amon and Isis were characterized by numerous black seeps from 10 centimetres up to 2 metres across (Fig. 11f). On the active southwestern dome of Osiris, the black sediment patches were much less abundant (Fig. 5) and were limited also in size (tens of centimetres).

Sedimentary descriptions of the most representative cores taken in the black sediments at the most active sites of the different mud volcanoes are summarized in Fig. 9. The black sediment patches were most abundant at the centres of Amon and Isis and presented similar visual aspects (Figs 9a, c). Most of them were covered with very bright white deposits composed of sulfur and bacterial filaments (Figs 11b, 11d, 11f and 12b). Clearly related to sulfide production, the white mats most commonly lay on the dark reduced sediments but were sometimes found around the edges of these black patches. In some places, the white mats covered most of the surface of the black sediment patches, particularly on Amon (Fig. 12b). The bacterial filaments, relatively dense on top of black sediments in the active centre of Amon, correspond to sulfide-oxidizing filamentous bacteria (presumably Beggiatoa). The uppermost centimetres of the mud breccia in the dark grey to black sediments on both Amon and Isis correspond to soft, homogenous and structureless material, sometimes with a relatively high terrigeneous admixture of silt and sand. The transition to the underlying dark grey more consolidated mud breccia is sharp. The matrix of the mud breccia in cores was very porous as a result of degassing, like that of the mud breccia surrounding the black patches. The mud breccia below the soft black sediments on Amon and Isis contains numerous millimetric rock clasts and occasionally others that are bigger, a few centimetres in size, and irregularly shaped. These clasts are commonly light to dark grey more or less indurated claystones. Moreover, geochemical analyses of the uppermost centimetres of the sedimentary cores, taken at the centres of Amon and Isis, revealed the presence of millimetric carbonate concretions with typical depleted ^{13}C isotopic signatures of methane-derived carbon (e.g., -17.69‰ on Amon) (Gontharet *et al.*, 2006). Carbonate concretions with similar negative stable carbon isotopic compositions, but much larger in size (up to several centimetres), characterize the mud breccia collected in the active centre of North Alex (Figs 9d and 12c). These carbonates form irregular-shaped tubular open or fully cemented concretions interpreted as gas escape conduits. The mud breccia sampled at the most active site on Osiris is much more uniform (Fig. 9b): dark grey, rather homogeneous, structureless, relatively porous (in cores) because of degassing, and containing many small rock clasts up to 2 centimetres in size. The thickness of the black top sediments, when there were any, was relatively thin. The presence of carbonate concretions was not observed on Osiris but is not excluded.

Thermal measurements

The main emission centres of the four explored mud volcanoes are the areas where the highest thermal gradients in the sediments were recorded (Table 1 and Figs 4b, 5b, 6b and 7b). Temperatures were extremely high in the active centres of Amon and Isis, reaching respectively 45 and 42ºC at 10 metres below seafloor. At equivalent depths on the most active areas of Osiris and North Alex, 20 to 22ºC were measured. For comparison, background thermal gradients measured in hemipelagic sediments away from seep-related activity sites (a few km away from the eastern edge of Isis) are much lower: 0.02ºC/m (T. Feseker, pers. comm.). Furthermore, an elevation of the temperatures of the near-bottom sea water above the main active emission centres was recorded for each of the four explored mud volcanoes. The temperature at the surface of Osiris, commonly at 13.6ºC, reached 13.75ºC on top of the southwestern dome. Similar but significantly higher was the increase in the water temperature in the centre of North Alex, equivalent to 0.25ºC with a maximum of 13.9ºC (Table 1).

Gas component

At the main emission centres of the four explored mud volcanoes, *in situ* evidence for gas saturation was observed, and saturation was confirmed by high gas concentrations measured in pore waters in the uppermost mud breccia layer and in the water near the seafloor (Mastalerz *et al.*, 2004, 2005, 2007; Prinzhofer *et al.*, 2005).

Long piston cores in the centres of the four investigated mud volcanoes recovered 5 to 10 metres of highly gas-saturated disturbed and relatively homogeneous dark grey mud breccia. Gas analyses of pore waters from sediment samples of the four studied mud volcanoes revealed a high content of methane, above the atmospheric equilibrium (0.9 mmol/L of wet sediment) (Mastalerz *et al.*, 2004, 2007). The highest value, 7.5 mmol/L of wet sediment, was recorded at the centre of Isis mud volcano, 5.3 metres below the seafloor (Mastalerz *et al.*, 2007). Besides methane, heavier hydrocarbon gases were also detected in the sediments: mainly ethane, propane and butane (C_2 to C_4), and exceptionally C_5 and C_6 at the centre of Isis (Mastalerz *et al.*, 2004, 2007).

The seafloor in the main active emission sites was disturbed by numerous small millimetric holes produced by the escaping gas (Figs 4 to 7 and 12a). The density and the size of these holes varied among the four explored mud volcanoes. Compared to the other mud volcanoes, the seabed on the slightly elevated dome of Osiris was much less perforated (Fig. 5). In contrast, the seafloor in the active centre of North Alex was strongly and relatively widely disturbed with numerous larger holes (Fig. 7), indicating that the degassing is probably more vigorous, as additionally indicated by the observed spontaneous degassing.

The visibility in the water column over the active centres was considerably reduced, with some moderation on Osiris. The water at the centre of Isis, for instance, was particularly cloudy because of turbidity induced by fluid expulsion, the presence of gas bubbles in the water column and the reworking of subsurface sediments (Figs 11d and 11f). Furthermore, any disturbance of the sediments by seabed contact of the submersible or by penetration with sampling and measurement tools almost instantly triggered the escape of gas bubbles into the water column (Fig. 11f). Gas bubbles were up to a few centimetres in diameter and escaped continuously for at least several minutes for the most vigorous degassing (e.g., in the centres of Isis and North Alex). Visual evidence for spontaneous degassing into the water column was observed only at the centre of North Alex (Fig. 7), possibly facilitated there by the lower water column pressure (5 MPa) compared to the other, deeper, mud volcanoes (e.g., 11 MPa on Amon). However, the methane sensor indicated the presence of such gas in the centre of each of the explored mud volcanoes and in their close periphery. Gas analyses in the water column above the most active areas of the four explored mud volcanoes revealed high methane concentrations (up to 660 nmol/L) within the first 50 to 100 metres above the seafloor (Table 1) (de Lange *et al.*, 2006), well above the concentration of methane in standard seawater (about 1 nmol/L). Furthermore, ethane and propane were detected above all the investigated mud volcanoes (Mastalerz *et al.*, 2004, 2005, 2007). The stable carbon isotopic compositions of methane, ethane and propane in the sediments and in the water are very similar, indicating a direct and relatively fast gas escape without isotopic alterations due to the predominant biogeochemical transformation (de Lange *et al.*, 2006; Mastalerz *et al.*, 2007). Noble gas analysis further supports such rapid migration (Prinzhofer *et al.*, 2005).

Stable carbon and hydrogen isotopic compositions of the hydrocarbon gases and noble gas analyses indicate that most of the gases released into the water column above the main emission centres of the mud volcanoes are principally of thermogenic origin (e.g., 65% of all collected hydrocarbon gases at Isis, Mastalerz *et al.*, 2007). These gases are clearly mature and derived from secondary gas (e.g., North Alex) or oil cracking (e.g., Isis, Osiris), with a level of maturity increasing significantly from North Alex to Isis and to Osiris (Mastalerz *et al.*, 2007; Prinzhofer *et al.*, 2005). Hydrocarbon gases at North Alex, located in the proximal domain of the Nile Deep Sea Fan, have different sources than the deeper mud volcanoes (Isis and Osiris) (Prinzhofer *et al.*, 2005), which are located at the frontier between the gas and oil province (marked with the green line boundary in Fig. 1).

Bioactivity

Chemosynthetic fauna

Methane and sulfide are used as energy sources by several seep-related biota such as tubeworms and bivalves, which have been previously found at many different seep settings (Olu-Le Roy *et al.*, 2002; Sibuet and Olu, 1998). However, chemosynthetic tube worms and bivalves were not observed in great abundance at the main emission centres of the four explored mud volcanoes on the Nile Deep Sea Fan. The gas-saturated black sediment patches on Isis and Amon were occasionally surrounded by apparently empty shells of molluscs and local scatterings of shell debris of bivalves (millimetre to centimetre in size). Small clusters of tubicolous polychaetes, presumably vestimentiferans, were found exceptionally in the active centre of North Alex. It is possible that we missed those chemosynthetic organisms that live mainly in the uppermost tens of cm of the sediments, for example Acharax, a deep dwelling Solemyid bivalve (Boetius and Suess, 2004). Generally, the limited sampling of infauna and fauna associated with the dark sediment patches revealed more bioactivity and diversity than was first inferred from the seafloor observations. Similarly to those found on the Mediterranean Ridge and the Anaximander Mountains (Olu-Le Roy *et al.*, 2002), the bivalves are of relatively small size. Push cores in the centres of Amon, Isis and North Alex recovered several specimens of living bivalves commonly found at seeps and belonging to three families: Lucinidae, Vesicomyidae and Mytilidae. These organisms often contain sulfide-oxidizing symbionts. A few specimens of a symbiotic lucinid clam resembling *Lucinoma kazani* found in the Anaximander Moutains (Salas and Woodside, 2002) and hosting bacteria performing autotrophy and sulfide oxidation were collected in the sediments at several mud volcanoes (North Alex, Amon, Isis) (Duperron *et al.*, 2006). Lucinidae, *Myrtea aff. amorpha*, were additionally found in the centre of North Alex, together with Mytilidae *Idas aff. modiolaeformis*, containing both methanotrophic and sulfur-oxidizing symbionts with a great diversity of symbiotic bacteria (S. Duperron. pers. comm.). Vesicomyidae specimens identified as *Isorropodon aff. perplexum* were found in the sediments at the centre of Isis.

Near-bottom fauna

Our observations with the *Nautile* indicate a relatively high bioactivity in the near-bottom water column with a large diversity and abundance of organisms, especially at the active emission centres of the mud volcanoes. Dense accumulations of larvae of crustaceans and fishes were present in the main seep areas on each explored mud volcano (Figs 10f and 11d). Together with suspended sedimentary particles and gas bubbles in the water column, these larvae contributed to a significant decrease in visibility over these parts of the mud volcanoes. Euphausiacea and Mysidacea shrimps together with Copepodea, Amphipodae and Thaliacea (Doliolida) organisms were identified in the water column (M. Segonzac, pers. comm.). We observed numerous macrofauna organisms composed mainly of fishes from various families, numerous Rajidae on North Alex and a few Sebastidae (Scorpaneiform), Merlucciidae (Gadiform) and Congridae on Osiris (R. Causse and S. Iglésias, pers. comm.) (Fig. 12a). A *Chaceon* crab (*C. mediterraneus*) in the centre of Amon resembles crabs encountered on Napoli and Amsterdam mud volcanoes (Olu-Le Roy *et al.*, 2002) (Fig. 12d). A few snake fishes, encountered in particular in the centre of Amon, probably belong to the Zoarcidae family, typically found in hydrothermal and seep environments (Biscoito *et al.*, 2002). Such a high concentration of living organisms potentially reflects the availability of food in relation to the activity of the mud volcano, but interestingly –although not based on quantitative data- seems to be inversely proportional to the intensity of the activity. Although Osiris was the quietest mud volcano with a small number of seeps (Fig. 5), a relatively lower methane concentration in the water column (Table 1) (de Lange *et al.*, 2006), and the smoothest topography, the bioactivity in the near-bottom water column above the main seep area appeared by far the highest of all the explored mud volcanoes.

4.3.2. Emission centres associated with carbonate crust

In addition to the precipitation of authigenic carbonate concretions within the sediments at the centres of the mud volcanoes, relatively thick authigenic carbonate crusts form on the seafloor. However, the only site identified so far on the four explored mud volcanoes is the southwestern flank of Amon (Fig. 4). Carbonate crusts form several types of structures principally outside the central active region. Parts of the seafloor at Amon were covered with relatively flat and low-relief carbonate crust in the form of sub-circular shields a few centimetres thick and a few decimetres wide, and larger fractured plates resembling turtle-backs. Most of these carbonate crust structures were partly covered with sediments. Carbonate mounds resembling conical chinese hats or mushroom-like structures and reaching a few decimetres to one metre high (Fig. 12e) were also observed. Furthermore, exceptionally massive and isolated deposits 1 to 2 metres high were found. Core penetration in the sediments surrounding the carbonate crust structures was limited undoubtedly by the presence of sub-seafloor carbonate crusts. Closer to the centre of the mud volcano and restricted apparently to much smaller surface area, fractured carbonate plates were almost completely covered with sediments together with a higher density of empty bivalve shells (Fig. 4).

Similar to the active emission centre, the temperatures of the near-bottom seawater in the region where carbonate crusts cover the seafloor were slightly elevated, by up to 0.15ºC relative to the 13.7ºC usually recorded above non-seep areas at the surface of Amon. Furthermore, enhanced methane concentrations were measured *in situ* in this region with the CAPSUM METS sensor. Additionally, sampling activity from the submersible fairly easily triggered the vigorous escape of gas bubbles. The composition and the origin of the gas were not analyzed. Geochemical analyses of the carbonates ($\delta^{13}C$ values), however, revealed a methane origin for the carbon (Bayon *et al.*, 2006; Gontharet *et al.*, 2006). The sampled carbonate crusts are dark grey, lithified, and cemented by a homogeneous fine-grained aragonite-rich matrix (Bayon *et al.*, 2006; Gontharet *et al.*, 2006), with oxidised surfaces varying in colour from dark brown/black to ochre due to the exposure to oxygen-rich bottom water. The crusts were systematically perforated by holes up to 5 millimetres in diameter through which fluids escape and some of which hosted tube worms. These latter have been identified as vestimentiferans (*Lamellibrachia* sp.), organisms known to rely on chemosynthetic symbiotic bacteria for their nutrition. Furthermore, relatively dense accumulations of bivalve shells (Lucinidae), however mostly empty, were scattered on the seafloor, although it is assumed that numerous living bivalves were buried within the sediments. The chemosynthetic fauna was comparably abundant in this region covered with authigenic carbonate crusts, in contrast to the scarcity at the other gas seeps encountered in the centre of the mud volcano.

In addition to the carbonate crusts and close to them, lineaments and sub-circular patches of consolidated and hard black material of a few cm to a few dm across cover the seafloor (Fig. 12 f). Their visual appearance resembles tars as found at asphalt seeps in the Gulf of Mexico (MacDonald *et al.*, 2004). Sampling could not be achieved because of the material's hardness, but would be required in future to confirm and define accurately its composition and origin. Bivalve fragments were completely embedded in the solidified black matter similarly to tubeworms in the massive asphalt flows discovered in the Campeche Knolls in the Gulf of Mexico (MacDonald *et al.*, 2004). Furthermore, the seep environment of Amon is similar to that of Campeche Knolls, with carbonate-crust-covered seafloor, active fluid venting associated with mature and thermogenic gas, and oil slicks at the sea surface. Amon is indeed located at the limit between the gas/condensate province and the oil province (Fig. 1) (Abdel *et al.*, 2001), where observations of oil slicks at the sea surface have been reported (Abdel *et al.*, 2000).

4.4. Secondary gas seeps

The seepage associated with dark sediment patches and gas-saturated mud breccia was not restricted to the active emission centres of the mud volcanoes. Numerous peripheral black sediment patches, here referred to as secondary seep sites, were discovered on the seafloor on the four explored mud volcanoes (Figs 4 to 8). These seeps were not sampled. In contrast with the black sediment patches in the centre of the mud volcanoes, these secondary seeps were not covered with bright white mats. They were most commonly relatively small in size, typically decimetre-scale, and were isolated or grouped in clusters of up to five patches, surrounded by mud breccia already covered with hemipelagic sediments. In areas where the seafloor morphology was slightly disturbed with metre-scale depressions and mounds, the secondary seeps preferentially appeared in the depressions. On Amon, the rare secondary seeps were observed exclusively in the southern half of the mud volcano (Fig. 4). On Osiris, the peripheral seeps were located in the northern part of the mud volcano, along the eastern and northern flanks of the northeastern dome (Figs 5 and 8a). On Isis and North Alex, the number of secondary seeps was significantly higher (Figs 6 and 7), and they were ubiquitous. The methane sensor detected gas release into the water column above such secondary seeps in the northeastern part of Isis (Fig. 6). In contrast with the central black sediment patches, the peripheral black seeps were often surrounded, when not covered, by the debris of bivalves, most likely relying on chemosynthesis. Small clusters of vestimentiferans resembling polychaetes Siboglinidae were found exceptionally close to an external active seep on Amon.

4.5. Low-fluid-flow areas

Large areas of the surface of the mud volcanoes appeared relatively quiet in terms of fluid emissions, as inferred from *in situ* visual observations (e.g., hemipelagic sediment cover) (Figs 4 to 7), and as also confirmed by low methane concentrations measured in the outer part of the main emission centre on either short push cores (20 cm length) collected with *Nautile* or long piston cores taken from the ship (typically Isis, Mastalerz *et al.*, 2007). Additionally, the thermal gradients measured in the sediments outside the main emission sites are comparably low, systematically below 100ºC/km (Figs 4b, 5b, 6b and 7b). Similarly to the distribution of the methane concentrations, long piston cores taken at various radial distances on Isis indicate a significant and rapid decrease in the temperature gradients from the centre to the peripheries (below 300 and 100ºC/km respectively at a distance of 200 and 600 metres away from the centre) (Feseker *et al.*, 2006). Additionally, the temperatures of the water close to the seafloor in these peripheral areas were relatively uniform, 13.6ºC on average on Osiris, the 'coldest' mud volcano, and 13.7ºC on Amon, Isis and North Alex.

The seafloor in these low-fluid-flow areas was composed of mud breccia partly covered with fine sediments (Figs 4a, 5a, 6a and 7a). This superficial sedimentary cover results from a combination of hemipelagic sedimentation and deposition of sedimentary particles suspended by fluid emission. In the most external areas of the mud volcanoes, the seafloor, flat and undisturbed, exhibited relatively light yellowish sediments, corresponding to the lowest activity. Most of the seafloor morphology in the low-fluid-flow areas was, however, relatively gentle with small-scale relief (dm to a few m high). The seafloor was systematically associated with traces of bioturbation represented by numerous small cones up to 30 cm high with usually darker (grey or brown) sediments on top (Figs 10b and 10e). Most of these cones had on their summits a small millimetre-size orifice, from which white tube worms have been observed coming out. These worm burrows are scattered over almost the entire surface of the four explored mud volcanoes, where the fluid flows are presumably low, with great density and uniformity. The responsible worms, polychaetes of decimetre size (D. Desbruyères, pers. comm.) are clearly related to the mud volcano seepage activity and indicate a rich organic matter substratum. The polychaetes avoid the lowest activity areas in the most external areas of the mud volcanoes as well as the (most) active seep areas where high concentrations of gases are present in the mud breccia and warmer fluids are released. In addition to these bioturbation features, the seafloor on Osiris -almost on the entire surface of the mud volcano- was covered with dense colonies of white sea fan polyps (Gorgonians, *Eunicella*) (Figs 5 and 10e). Benthic fauna, almost exclusively composed of a few specimens of fishes, was occasionally found in the low-activity areas of the mud volcanoes, contrasting with the greater abundance and variety at the main active sites.

5. Discussion

5.1. Seep distribution and feeder channels

Both the methane concentrations in the pore waters and the content of hydrocarbons decrease from the centres of the mud volcanoes to the peripheries, as demonstrated by a series of long piston cores taken at various radial distances on Isis (Mastalerz *et al.*, 2007). Following the same trend are the shallow and deeper thermal gradients obtained on the four mud volcanoes (Table 1 and Figs 4b, 5b, 6b and 7b) (for details from Isis see Feseker *et al.*, 2006). The current fluid seepage sites identified from the submersible on the surfaces of the mud volcanoes are limited in number and size, with the exception of the carbonate-crust-covered seafloor on the southwestern flank of Amon,

which occupies a larger surface area (~ 0.1 km^2 based on the high backscatter surface on the multibeam imagery map). The main active sites are themselves restricted to sub-circular areas of a few tens of metres in diameter on the highest areas of the mud volcanoes, on slightly elevated domes (Figs 4 to 8), where methane and higher hydrocarbon gas concentrations and temperatures both in the water and in the sediments are the highest (Table 1); the secondary seeps, although more numerous, are of much smaller size (dm^2) and isolated as scattered patches outside the narrow active emission centres. The transition between active and inactive areas is sharp, with clear changes in the water column, seafloor morphology and sedimentary environment. These *in situ* observations and measurements suggest that the fluids are not emitted into the water column uniformly at the seafloor. Although the conduit of the gas chimneys appears on seismic profiles (Loncke *et al.*, 2004) to be as wide as the mud volcanoes forming the surface expression at the seafloor, the gas concentrations in the uppermost sedimentary cover on top of the mud volcano do not appear equally distributed. The transparent seismic facies of the gas chimneys is probably caused by disrupted sedimentary structure and high gas content. The most vigorous fluid escape occurs in restricted areas on the most elevated domes of the mud volcanoes and is most likely fed through a single principal channel with a relatively narrow diameter of a few tens of metres. The secondary seeps, on the other hand, would be fed by subsidiary conduits that have channelled fluids out towards the periphery of the mud volcano. We infer that these secondary channels form away from the centre because of difficulty in reaching the seafloor between the centre and the periphery, where the ridges and grooves suggest compression of the mud. The flow through the principal central channel is strong enough to be maintained in time without major fluctuations or hiatuses, but the secondary channels are probably less robust. Between the two there can be a general but mild diffusive flux of fluids that is not strong enough to support chemosynthetic fauna by providing sufficient nutrients.
We propose that there exist 4 different time and space characteristics for fluxes at the mud volcanoes located above gas chimneys in the central area of Nile Deep Sea Fan:

(1) *Vigorous fluid emissions and mud expulsion over restricted areas*. This is found on the highest area of the mud volcano, over a narrow dome mainly located in the centre. On the Nile Deep Sea Fan mud volcanoes, methane and fluid fluxes apparently do not inhibit the diffusion of sulphate from the water column into the seafloor, nor the associated AOM activity as it is observed in places like the central area of Håkon Mosby mud volcano (de Beer *et al.*, 2006). Fluxes of methane and sulphate are high enough to support AOM communities which produce equally high amounts of sulphide during consumption of these gases. However, elevated methane concentrations in the water column provide evidence that some methane circumvents this microbial filter. Additionally, AOM promotes calcium carbonate precipitation leading to the formation of millimetre to centimetre concretions. Although gas fluxes are probably significant enough to form carbonate crust (Luff *et al.*, 2004), the unstable environment (e.g., mud extrusion) in the main active emission centre of the mud volcanoes most likely inhibits it. The environment may not be stable enough for chemosynthetic fauna to develop abundantly. Possible pulses of higher and stronger degassing from time to time are not excluded. Although the location of the main feeder channel below the centre of the mud volcano appears to be rather stable through time, it can shift in response to changing conduit conditions at depths and to tectonic activity. A good example is the Osiris mud volcano, which shows a significant displacement of the main emission centre from the northeastern dome to the now active southwestern dome (Figs 5 and 8a). Less obvious is the shift of the main emission area at the centre of Isis, where 3D seismic coherency maps at 5 and 35 ms TWT reveal a second and former buried emission centre located slightly northeast of the present one (Loncke, 2002).

(2) Less vigorous fluid emissions over broader areas and long periods of time as indicated by the formation of large and thick carbonate crust. The region covered with carbonate crusts is located on the southwestern flank of Amon, in a wide depression, and is clearly aligned and linked to NW-SE faults identified both in the south and in the north of the mud volcano (Figs 1 and 3). The methane fluxes there are sufficient to contribute to the precipitation of carbonate and particularly to the formation of large and relatively thick crusts. In similarity with the main active centres, the fluxes are not high enough to inhibit sulphate penetration into the seafloor and thus AOM. The continuity over a long period of time is required to develop thick carbonate crusts. The thicknesses of the carbonate crust structures outcropping at the seabed are potentially good temporal indicators for an estimate of the minimum duration of such an activity. The observed massive carbonate crust deposits on Amon are 1 to 2 metres high and would require on the order of 50 000 to 100 000 years to form at growth rates of 2 cm/ka, a value measured for carbonate crust sampled in the Central Province of the Nile Deep Sea Fan (Bayon et al., 2006).

(3) *Moderate to low fluid emissions at small scale seeps (< 1 metre) that are probably to some degree intermittent.* These seeps, here referred to as secondary seeps, are probably much less stable in time and position than the main seeps associated with black sediment patches and precipitation of authigenic carbonate. They are characterized by less vigorous fluxes and have most likely a shorter life span, but they may even support a viable chemosynthetic community. These secondary seeps are fed by numerous small channels connected at depth with very narrow conduits, not permanently supplied with gases, leading to the small dm scale dark sediment patches in the subsurface, as commonly encountered at North Alex and Isis. The secondary seeps are relatively rare, however, on Amon, where the activity is focused at two major emission sites through which most of the gas escapes: the centre fed by a narrow feeder channel and the carbonate crust field connected to a NW-SE fault.

(4) *Areas of low to absent fluxes.* Most of the surface and subsurface of the explored mud volcanoes exposes a low degree of seepage activity, at least in the uppermost investigated metres of sediments. The mud breccia in these areas is already covered with sediments, and the seafloor is characterized by numerous traces of bioturbation, indicators of a rich organic matter substratum. Neither dark sediment patches nor carbonate crusts are observed. Gas concentrations and thermal gradients in the sediments and the water column are, however, slightly elevated compared to background levels.

5.2. Development and functioning of the large mud volcanoes

The initiation of fluid emissions associated with the birth of the mud volcanoes is clearly related to the tectonic activity, along newly created or reactivated faults. This activity might be connected with significant slope instabilities or earthquakes. For example, off Makran in Pakistan, modern analogues of mud extrusions from several mud volcanoes occurred in correlation with earthquakes (e.g., the 8.5 magnitude earthquake on 27 November 1945, Delisle *et al.*, 2002). Off Egypt, the gas chimneys must have originated as the migration pathways were created by faulting through a well-developed deep-sea fan above an uncompacted clay layer. To date the beginning of the mud volcanism in the absence of accurate seismic and deep drilling on the sides of the mud volcanoes is rather difficult. Moreover, the carbonate crusts on Amon, which are a relatively recent development on an already existing mud volcano, are much younger. Estimate of their age, based on carbonate growth rate measured for authigenic carbonate crusts sampled in

pockmarks in the Central Province (Bayon *et al.*, 2006), provides an age of between 50 and 100 kyrs.
The gases released at the explored mud volcanoes on the Nile Deep Sea Fan are principally thermogenic, with therefore elevated temperatures required for their formation (up to 150-200ºC and even higher, Whiticar, 1994). This implies that they originate from deep sedimentary layers, potentially several kilometres. The pre-Messinian origin for the source layer proposed by Loncke *et al.* (2004) has been confirmed with dating of several carbonate clasts collected in the centre of Isis mud volcano. Nannofossil determination (C. Muller) indicates an early Serravillian age (Coccolithus pelagicus, Helicosphaera carteri, Reticulofenestra pseudoumbilica, Cyclicargolithus abisectus, Cyclococcolithus premacintyrei). However, this mud is younger than the widespread uncompacted clay layer of Oligocene age that was a good candidate suggested by Loncke (2002) for the source of the mud mobilised to build the wide mud volcanoes on the Nile Deep Sea Fan.

The present-day mode of functioning of the four explored mud volcanoes located above wide gas chimneys in the Central Nile Deep Sea Fan differs from that commonly inferred from the observations made for onshore and offshore mud volcanoes, in particular those of the Eastern Mediterranean.

The seismic, multibeam imagery and coherency data (Loncke *et al.*, 2002; Loncke *et al.*, 2004) do not support distinct mud expulsion events with the identification of clear mud outflows (see, e.g., Amsterdam and Kula mud volcanoes in the Anaximander Mountains, Zitter *et al.*, 2005). The rare mud flows identified from multibeam data (bathymetry and backscatter) in the area close to the mud volcanoes on the Central Nile Deep Sea Fan correspond most likely to gravity-driven debris flows (North Alex and Amon). Moreover, the acoustic imagery maps and the seafloor observations did not reveal any fluidized mud at the surfaces of these mud volcanoes nor mud flows emitted from subconical centres running down the flanks of the structures (see, e.g., mud volcanoes in the Appenines, Capozzi and Picotti, 2002; and in the Makran, Delisle *et al.*, 2002).

In contrast with the onshore mud volcanoes in Azerbaijan (Etiope *et al.*, 2004) or the offshore Moscow mud volcano on the Mediterranean Ridge (Ivanov *et al.*, 1996), for example, none of those on the Nile Deep Sea Fan seem to have recently experienced episodic and catastrophic eruptions. Furthermore, the volumes of solid material extruded at the seafloor from the four explored mud volcanoes are relatively low (estimated from multibeam bathymetry to be between 0.5 and 3.5 km^3, Table 1). The differences in the mode of eruption and the volume of expelled mud are most likely linked and are strongly related to the tectonic setting (Woodside *et al.*, 2006; Woodside *et al.*, 2005). Although large volumes of material are expelled at mud volcanoes in compressive environment (typically Amsterdam mud volcano in the Anaximander Mountains), the mud volcanism in an extensive regime, for example in deltaic environments, is certainly characterized by more continuous emissions with possibly fewer big eruptions.

The present day seepage activity is clearly dominated by gas emissions. *In situ* observations and measurements revealed intense seepage activity, with methane and higher hydrocarbon gases entering the water column. Gases within a suitable range of fluxes promote chemosynthesis together with the precipitation of carbonate through crusts or small concretions within the sediments. The amount of expelled solid material, mud breccia and rock clasts is comparatively small at present. Indeed, the most recently expelled mud breccia is very much limited in volume, covering only a small surface area of the seafloor, and corresponding to relatively slow and subvertical mud extrusion leading to rough and chaotic mud structures, and in turn to the construction of the narrow dome. These most recent mud extrusion events occurred in the highly active central domes of Amon and Isis, where fresh mud, not yet covered with sediments, outcrops. The latest mud extrusions of North Alex and Osiris are much older, as shown by a much gentler seafloor morphology, already smoothed by erosion and shaped by sedimentation.

6. Conclusions

1. *Intense seepage activity*. Numerous gas seeps characterize the seafloor on the four investigated mud volcanoes, Amon, Isis, Osiris and North Alex, located in the Central Nile Deep Sea Fan. The activity is clearly dominated at present by gas emissions. The main emission centres whose the seafloor is covered with numerous black sediment patches are associated with a high turnover of sulfate and methane (resulting in the production of hydrogen sulphide) as well as with the precipitation of millimetre to decimetre scale carbonate concretions within the sediments. Another type of environment associated with a high level of seepage activity characterizes parts of the seafloor, exclusively observed on the southwerstern flank of Amon, and corresponds to large and relatively thick authigenic carbonate crust deposits. Almost all of the seafloor at the upper surface of the mud volcanoes is disturbed directly or indirectly by the seepage activity, respectively by gas and carbonate-crust-related seeps and bioturbation features.

2. *High gas and thermal fluxes*. The active sites associated with black sediments and carbonate crusts are both highly gas saturated. High gas concentrations in the water column (methane on the order of hundreds of nmol/L) and in the sediments (methane on the order of several mmol/L of wet sediment) characterize the main emission centres located on the highest area of the mud volcanoes, on a slightly elevated dome. Similarly, the thermal gradients in the sediments there are significantly high, with a maximum temperature of 45ºC recorded at 10 metres below the seafloor at Amon. Additionally, a slight increase in the water temperature, 0.15 to 0.25ºC, above the main seep areas (black sediment patches and carbonate crusts) is systematically observed in comparison with the rest of the mud volcano in the water column near the seafloor. The methane fluxes are not so high that they would inhibit anaerobic oxidation of methane; however, they are high enough to promote, via the AOM activity, the precipitation of authigenic calcium carbonates. Moreover, the high fluxes in the main emission centres of the mud volcanoes where the seafloor is covered with black sediment seeps, together with the unstable environment (e.g., mud extrusion), prevent the chemosynthetic organisms to develop abundantly.

3. *Slowly extruded mud*. Fresh mud breccia characterizes only the most active emission centres where the gas and thermal fluxes are very high, and it is furthermore restricted to a few tens of m^2. The mud is slowly subvertically extruded upon high differential pressure and corresponds therefore to relatively low volume. At the surface of the mud volcanoes, it appears that mud flows do not correspond to emitted outflows but rather to gravity destabilized sediments. Additionally, the seafloor in the main active emission centres is not covered with numerous and big rock clasts. The most recent mode of eruption of the four explored mud volcanoes on the Central Nile Deep Sea Fan is unlikely to be explosive.

4. *Narrow and limited feeder channels*. The mud volcanoes are fed by a main single channel most commonly located below the centre of the mud structure. Indeed, the highest seepage activity is concentrated and restricted to a narrow and slightly elevated dome, although numerous but small seeps associated with lower fluxes dot the entire surface of the mud volcanoes. Moreover, the seafloor morphology changes drastically from the main emission centre towards the external parts of the mud volcanoes, together with significant decreases in the size and numbers of seeps, temperatures and gas concentrations in the sediments and in the water.

5. *Tectonic control*. The distribution of the mud volcanoes in the upper slope domain of the Central Nile Deep Sea Fan and associated seeps on and close to the mud volcanoes, together with the overall shape of the mud volcanoes, are clearly tectonically controlled. The main emission centres of the mud volcanoes through which the mud is expelled are

most likely more stable in space and in time in the less tectonically active seafloor surroundings. Faults reaching the seabed are potential pathways for fluid escapes. Long-term gas releases along these faults contribute to the formation of relatively thick carbonate crust and the associated chemosynthetic fauna (typically the carbonate-crust-covered seafloor on the southwestern flank of Amon located in a depression and aligned with the NW-SE southern fault).

6. *Deep sources*. The mud and the gases mainly composed of methane and higher hydrocarbons (ethane, propane and up to C_6) originate from deep layers as indicated by the pre-Messinian dating of mud fragments and the significant thermal contribution to the emitted gases. Emitted hydrocarbons are predominantly related to known reservoirs at depth, possibly the distal turbidites within the Serravillian to Tortonian sequences, the Oligocene sands and older formations from the Cretaceous and Jurassic (Abdel *et al.*, 2001).

Acknowledgments

We would like to express many thanks to the scientists who participated in the NAUTINIL expedition, the crews from the R/V L'Atalante, the team operating the *Nautile* submersible, and the European Science Foundation, which is promoting the Mediflux Project between the Netherlands, France and Germany. The Netherlands Organisation for Scientific Research is thanked for the Dutch financial support of the Mediflux Program through NWO/ALW contract 855.01.031.

References

Abdel, A.A., El Barkooky, A., Gerrits, M., Meyer, H., Schwander, M., Zaki, H., 2000. Tectonic evolution of the eastern Mediterranean Basin and its significance for hydrocarbon prospectivity in the ultradeepwater of the Nile Delta. The Leading Edge 19 (10), 1086-1102.

Abdel, A.A., El Barkooky, A., Gerrits, M., Meyer, H.J., Schwander, M., Zaki, H., 2001. Tectonic evolution of the eastern Mediterranean Basin and its significance for the hydrocarbon prospectivity of the Nile Delta deepwater area. GeoArabia (Manama) 6 (3), 363-384.

Bayon, G., Henderson, G.M., Pierre, C., Bohn, M., 2006. Temporal activity of fluid seepage on the Nile deep-sea fan inferred from U-Th dating of authigenic carbonates. CIESM Workshop Monograph. Fluids seepages / mud volcanism in the Mediterranean and adjacent domains 29, 111-114.

Bayon, G., Loncke, L., Dupré, S., Gontharet, S., Migeon, S., Caprais, J.-C., Huguen, C., Mascle, J., Pierre, C., Foucher, J.-P., the Nautinil and Mimes Scientists, 2005. Active pockmarks, mounds and slope instabilities on the Nile margin: In situ observations, geophysical, sedimentological and geochemical evidence. General Assembly 2005, European Geosciences Union. Geophysical Research Abstracts, Vienna, Austria. 24-29 April 2005, p. 6953.

Bellaiche, G., Loncke, L., Gaullier, V., Mascle, J., Courp, T., Moreau, A., Radan, S., Sardou, O., 2001. Le cône sous-marin du Nil et son réseau de chenaux profonds; nouveaux résultats (campagne Fanil). Comptes Rendus de l'Académie des Sciences, Série II. Sciences de la Terre et des Planètes 333 (7), 399-404.

Bellaiche, G., Zitter, T., Droz, L., Gaullier, V., Mart, Y., Mascle, J., Prismed Equipe Scientifique France, 1999. Le Cône sous-marin profond du Nil; principaux résultats de la campagne PRISMED II du N.O. l'Atalante. Comptes Rendus de l'Académie des Sciences, Série II. Sciences de la Terre et des Planètes 329 (10), 727-733.

Biju-Duval, B., Letouzey, J., Montadert, L., 1978. Variety of margins and deep basins in the Mediterranean. AAPG Memoir 29, 293-317.
Biscoito, M., Segonzac, M., Almeida, A.J., Desbruyères, D., Geistdoerfer, P., Turnipseed, M., van Dover, C., 2002. Fishes from the hydrothermal vents and cold seeps - An update. Cahiers de Biologie Marine 43, 359-362.
Boetius, A., Ravenschlag, K., Schubert, C.J., Rickert, D., Widdel, F., Gieseke, A., Amann, R., Jorgensen, B.B., Witte, U., Pfannkuche, O., 2000. A marine microbial consortium apparently mediating anaerobic oxidation of methane. Nature 407 (6804), 623-626.
Boetius, A., Suess, E., 2004. Hydrate Ridge; a natural laboratory for the study of microbial life fueled by methane from near-surface gas hydrates. Chemical Geology 205, 291-310.
Bouriak, S., Vanneste, M., Saoutkine, A., 2000. Inferred gas hydrates and clay diapirs near the Storegga Slide on the southern edge of the Voring Plateau, offshore Norway. Marine Geology 163 (1-4), 125-148.
Camerlenghi, A., Cita, M.B., Della, V.B., Fusi, N., Mirabile, L., Pellis, G., 1995. Geophysical evidence of mud diapirism on the Mediterranean Ridge accretionary complex. Marine Geophysical Researches 17 (2), 115-141.
Camerlenghi, A., Cita, M.B., Hieke, W., Ricchiuto, T., 1992. Geological evidence for mud diapirism on the Mediterranean Ridge accretionary complex. Earth and Planetary Science Letters 109 (3-4), 493-504.
Capozzi, R., Picotti, V., 2002. Fluid migration and origin of a mud volcano in the Northern Apennines (Italy); the role of deeply rooted normal faults. Terra Nova 14 (5), 363-370.
Cita, M.B., Ivanov, M.K., Woodside, J.M., 1996. The Mediterranean Ridge diapiric belt. Elsevier, Amsterdam, Netherlands.
Cita, M.B., Ryan, W.B.F., Paggi, L., 1981. Prometheus mud breccia; an example of shale diapirism in the Western Mediterranean Ridge. Annales Geologiques des Pays Helleniques 30, 543-570.
Coleman, D., Ballard, R., 2001. A highly concentrated region of cold hydrocarbon seeps in the southeastern Mediterranean Sea. Geo-Marine Letters 21 (3), 162-167.
Cronin, B.T., Ivanov, M.K., Limonov, A.F., Egorov, A., Akhmanov, G.G., Akhmetjanov, A.M., Kozlova, E., TTR Shipboard Scientific Party, 1997. New discoveries of mud volcanoes on the eastern Mediterranean Ridge. Journal of the Geological Society of London 154 (2), 173-182.
de Beer, D., Sauter, E., Niemann, H., Kaul, N., Foucher, J.-P., Witte, U., Schlüter, M., Boetius, A., 2006. In situ fluxes and zonation of microbial activity in surface sediments of the Håkon Mosby Mud Volcano. Limnology and Oceanography 51 (3), 1315-1331.
de Lange, G., Mastalerz, V., Dählmann, A., Haese, R., Mascle, J., Woodside, J.M., Foucher, J.-P., Lykousis, V., Michard, A., 2006. Geochemical composition and origin for fluid and gas fluxes at Eastern Mediterranean mud volcanoes. CIESM Workshop Monograph. Fluids seepages / mud volcanism in the Mediterranean and adjacent domains 29, 103-110.
Delisle, G., von Rad, U., Andruleit, H., von Daniels, C.H., Tabrez, A.R., Inam, A., 2002. Active mud volcanoes on- and offshore eastern Makran, Pakistan. International Journal of Earth Sciences 91 (1), 93-110.
Deville, E., Battani, A., Griboulard, R., Guerlais, S., Herbin, J.P., Houzay, J.P., Muller, C., Prinzhofer, A., 2003. The origin and processes of mud volcanism; new insights from Trinidad. Geological Society Special Publications 216, 475-490.
Dimitrov, L.I., 2002. Mud volcanoes--the most important pathway for degassing deeply buried sediments. Earth-Science Reviews 59 (1-4), 49-76.
Dolson, J.C., Boucher, P.J., Dodd, T., Ismail, J., 2002. Petroleum potential of an emerging giant gas province, Nile Delta and Mediterranean Sea off Egypt. Oil and Gas Journal 100 (20), 32-37.
Dolson, J.C., Shann, M.V., Matbouly, S., Harwood, C., Rashed, R., Hammouda, H., 2001. The petroleum potential of Egypt. AAPG Memoir 74, 453-482.
Duperron, S., Fiala-Médioni, A., Caprais, J.-C., Olu, K., Sibuet, M., 2006. Evidence for chemoautotrophic symbiosis in a Mediterranean cold seep clam (Bivalvia: Lucinidae):

comparative sequence analysis of bacterial 16S rRNA, APS reductase and RubisCO genes. FEMS Microbiology Ecology 59, 64-70.
Dupré, S., Woodside, J.M., Klaucke, I., Mascle, J., Foucher, J.-P., the NAUTINIL & MIMES Scientific Parties, 2006. Multi-scale seafloor mapping of active seep-related structures, offshore Egypt. CIESM Workshop Monograph. Fluids seepages / mud volcanism in the Mediterranean and adjacent domains 29, 65-71.
Etiope, G., Feyzullayev, A., Baciu, C.L., Milkov, A.V., 2004. Methane emission from mud volcanoes in eastern Azerbaijan. Geology 32 (6), 465-468.
Feseker, T., Dählmann, A., Foucher, J.-P., 2006. Thermal and geochemical evidence for episodic mud eruptions at a mud volcano? The Isis mud volcano case. CIESM Workshop Monograph. Fluids seepages / mud volcanism in the Mediterranean and adjacent domains 29, 115-122.
Fusi, N., Kenyon, N.H., 1996. Distribution of mud diapirism and other geological structures from long-range sidescan sonar (GLORIA) data, in the Eastern Mediterranean Sea. Marine Geology 132 (1-4), 21-38.
Gaullier, V., Mart, Y., Bellaiche, G., Mascle, J., Vendeville, B.C., Zitter, T., Benkhelil, J., Buffet, G., Droz, L., Ergun, M., Huguen, C., Kopf, A., Levy, R., Limnov, A., Shaked, Y., Volkonskaia, A., Woodside, J.M., Prismed II Second Leg Scientific Party France, 2000. Salt tectonics in and around the Nile deep-sea fan; insights from the PRISMED II cruise. Geological Society Special Publications 174, 111-129.
Gontharet, S., Pierre, C., Blanc-Valleron, M.-M., Rouchy, J.-M., Fouquet, Y., Bayon, G., Foucher, J.-P., Woodside, J., Mascle, J., the Nautinil Scientific Party, 2006. Methane-related carbonates and associated authigenic minerals from the Eastern Mediterranean Sea. CIESM Workshop Monograph. Fluids seepages / mud volcanism in the Mediterranean and adjacent domains 29, 97-102.
Heggland, R., Nygaard, E., 1998. Shale intrusions and associated surface expressions; examples from Nigerian and Norwegian deepwater areas. 30th annual offshore technology conference 1, 111-124.
Heggland, R., Nygaard, E., Gallagher, J.W., 1996. Techniques and experiences using exploration 3D seismic data to map drilling hazards. Proceedings of the 28th annual Offshore technology conference 1, 119-127.
Hieke, W., Werner, F., Schenke, H.W., 1996. Geomorphological study of an area with mud diapirs south of Crete (Mediterranean Ridge). Marine Geology 132 (1-4), 63-93.
Hirsch, F., Flexer, A., Rosenfeld, A., Yellin, D.A., 1995. Palinspastic and crustal setting of the eastern Mediterranean. Journal of Petroleum Geology 18 (2), 149-170.
Hsü, K.J., Cita, M.B., Ryan, W.B.F., 1973. The origin of the Mediterranean evaporites. Initial Reports of the Deep Sea Drilling Project 13 Part 2, 1203-1231.
Huguen, C., Foucher, J.-P., Mascle, J., Loncke, L., Ondréas, H., Thouement, M., the NAUTINIL Scientific Party, 2006a. Mud/brine expulsions on the Nile Deep Sea Fan: Geophysical characterization and in situ dive observations of mud mounds in the Menes Caldera. CIESM Workshop Monograph. Fluids seepages / mud volcanism in the Mediterranean and adjacent domains 29, 73-77.
Huguen, C., Foucher, J.-P., Mascle, J., Ondréas, H., Thouement, M., Loncke, L., the NAUTINIL Scientific Party, 2005a. The Nile Deep Sea Fan Mud Mounds: First “in situ” evidences for active brine seepage (NAUTINIL Cruise, 2003). General Assembly 2005, European Geosciences Union. Geophysical Research Abstracts, Vienna, Austria. 24-29 April 2005, p. 7332.
Huguen, C., Mascle, J., Chaumillon, E., Kopf, A., Woodside, J., Zitter, T., 2004. Structural setting and tectonic control of mud volcanoes from the Central Mediterranean Ridge (Eastern Mediterranean). Marine Geology 209 (1-4), 245-263.
Huguen, C., Mascle, J., Loubrieu, B., Chamot-Rooke, N., Loncke, L., Woodside, J.M., Zitter, T., Benkhelil, J., Tahchi, E., 2006b. Regional distribution and tectonic control of mud volcanoes in the Eastern Mediterranean Sea: evidence from regional swath bathymetry, backscatter records, and seismic data. CIESM Workshop Monograph. Fluids seepages / mud volcanism in the Mediterranean and adjacent domains 29, 27-33.

Huguen, C., Mascle, J., Woodside, J., Zitter, T., Foucher, J.P., 2005b. Mud volcanoes and mud domes of the Central Mediterranean Ridge: Near-bottom and in situ observations. Deep Sea Research Part I: Oceanographic Research Papers 52 (10), 1911-1931.
IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Ivanov, M.K., Limonov, A.F., van Weering, T.C.E., 1996. Comparative characteristics of the Black Sea and Mediterranean Ridge mud volcanoes. Marine Geology 132 (1-4), 253-271.
Kopf, A.J., 2002. Significance of mud volcanism. Reviews of Geophysics 40(2), 1005, doi:10.1029/2000RG000093.
Limonov, A.F., Woodside, J.M., Cita, M.B., Ivanov, M.K., 1996. The Mediterranean Ridge and related mud diapirism; a background. Marine Geology 132 (1-4), 7-19.
Loncke, L., 2002. Le delta profond du Nil: structure et évolution depuis le Messinien, Thèse de doctorat de l'Université P. et M. Curie (Paris 6).
Loncke, L., Gaullier, V., Bellaiche, G., Mascle, J., 2002. Recent depositional patterns of the Nile deep-sea fan from echo-character mapping. AAPG Bulletin 86 (7), 1165-1186.
Loncke, L., Gaullier, V., Mascle, J., Vendeville, B., Camera, L., 2006. The Nile deep-sea fan: An example of interacting sedimentation, salt tectonics, and inherited subsalt paleotopographic features. Marine and Petroleum Geology 23 (3), 297-315.
Loncke, L., Mascle, J., Fanil Scientific Parties, 2004. Mud volcanoes, gas chimneys, pockmarks and mounds in the Nile deep-sea fan (eastern Mediterranean); geophysical evidences. Marine and Petroleum Geology 21 (6), 669-689.
Luff, R., Wallmann, K., Aloisi, G., 2004. Numerical modeling of carbonate crust formation at cold vent sites; significance for fluid and methane budgets and chemosynthetic biological communities. Earth and Planetary Science Letters 221 (1-4), 337-353.
MacDonald, I.R., Bohrmann, G., Escobar, E., Abegg, F., Blanchon, P., Blinova, V., Brueckmann, W., Drews, M., Eisenhauer, A., Han, X., Heeschen, K., Meier, F., Mortera, C., Naehr, T., Orcutt, B., Bernard, B., Brooks, J., de Farago, M., 2004. Asphalt volcanism and chemosynthetic life in the Campeche Knolls, Gulf of Mexico. Science 304 (5673), 999-1002.
Mascle, J., Benkhelil, J., Bellaiche, G., Zitter, T., Woodside, J., Loncke, L., Prismed II Cruise Shipboard Scientific Party France, 2000. Marine geologic evidence for a Levantine-Sinai Plate; a new piece of the Mediterranean puzzle. Geology 28 (9), 779-782.
Mascle, J., Camera, L., Chamot-Rooke, N., Costis, C., Gaullier, V., Loncke, L., Nielsen, C., Operto, S., Ribodetti, A., Sage, F., Sallares, V., L. Schenini, L., Skharinov, S., 2003. New constraints on the deep structure of the Eastern Mediterranean Sea from new MCS seismic reflection data. In: EGS-AGU-EUG Joint Assembly. Geophysical Research Abstracts, Nice, France. 06-11 Avril 2003, p. 9172.
Mascle, J., Loncke, L., Camera, L., 2006. Les sorties de fluides "grand fond" de la marge du Nil: Cadre géologique et contrôle structural. 10th Congrès Français de Sédimentologie. 10th Congrès Français de Sédimentologie, Livre n°51 Résumés, Presqu'île de Gien, France. 25-30 April 2004.
Mascle, J., Zitter, T., Bellaiche, G., Droz, L., Gaullier, V., Loncke, L., Prismed Scientific Party France, 2001. The Nile deep sea fan; preliminary results from a swath bathymetry survey. Marine and Petroleum Geology 18, 471-477.
Mastalerz, V., Dählmann, A., de Lange, G.J., the NAUTINIL and ANAXIMANDER Scientific Parties, 2004. Methane venting at mud volcanoes from the East Mediterranean Ridge and the Nile Deep-Sea Fan. 1st General Assembly, European Geosciences Union. Geophysical Research Abstracts, Nice, France. 25-30 April 2004, p. 422.
Mastalerz, V., Dählmann, A., de Lange, G.J., the NAUTINIL and ANAXIMANDER Scientific Parties, 2005. Gas emission and composition from mud volcanoes in the eastern Mediterranean: Nile and Anaximander areas. General Assembly 2005, European Geosciences Union. Geophysical Research Abstracts, Vienna, Austria. 24-29 April 2005, p. 5265.

Mastalerz, V., de Lange, G., Dählmann, A., 2007. Venting at Isis mud volcano, offshore Egypt: origin and migration of hydrocarbons as inferred from their stable carbon and hydrogen isotopic composition. Submitted to Chemical Geology.
Mazurenko, L.L., Soloviev, V.A., 2003. Worldwide distribution of deep-water fluid venting and potential occurrences of gas hydrate accumulations. Geo-Marine Letters 23 (3 - 4), 162-176.
McKenzie, D.P., 1970. Plate tectonics of the Mediterranean region. Nature 226 (5242), 239-243.
MediMap Group, Loubrieu, B., Mascle, J., 2005. Morpho-bathymetry of the Mediterranean Sea, CIESM/Ifremer special publication, Atlases and Maps, 2 maps at 1 / 2 000 000.
MEDINAUT/MEDINETH Shipboard Scientific Party, 2000. Linking Mediterranean brine pools and mud volcanism. Eos, Transactions, American Geophysical Union 81 (51), 625, 631-632.
MEDRIFF Consortium, 1995. Three brine lakes discovered in the seafloor of the eastern Mediterranean. Eos, Transactions, American Geophysical Union 76 (33), 313, 318.
Milkov, A.V., 2000. Worldwide distribution of submarine mud volcanoes and associated gas hydrates. Marine Geology 167 (1-2), 29-42.
Neurauter, T.W., Bryant, W.R., 1989. Gas hydrates and their association with mud diapir/ mud volcanoes on the Louisiana continental slope. In: Key, J. (Ed.), 21st annual offshore technology conference. Offshore Technology Conference, [Dallas, TX], United States, pp. 599-607.
Olu-Le Roy, K., Sibuet, M., Fiala-Médioni, A., Gofas, S., Salas, C., Mariotti, A., Foucher, J.-P., Woodside, J., 2002. Cold seep communities in the deep eastern Mediterranean Sea: composition, symbiosis and spatial distribution on mud volcanoes. Deep Sea Research Part I: Oceanographic Research Papers 51, 1915-1936.
Omoregie, E., Niemann, H., Boetius, A., the Mediflux team, 2005. Anaerobic oxidation of methane and sulfate reduction in the Nile Deep Sea Fan. General Assembly 2005, European Geosciences Union. Geophysical Research Abstracts, Vienna, Austria. 24-29 April 2005, p. 8535.
Orphan, V.J., House, C.H., Hinrichs, K.-U., MacKeegan, K.D., Delong, E.F., 2002. Multiple archaeal groups mediate methane oxidation in anoxic cold seep sediments. Proceedings of the National Academy of Sciences of the United States of America 99 (11), 7663-7668.
Prinzhofer, A., Deville, E., Foucher, J.-P., Caprais, J.-C., Mascle, J., 2005. Geochemistry of gas emanations from mud volcanoes and pockmarks from offshore Egypt. 2005 AAPG International Conference and Exhibition. Paris 2005 AAPG International Conference and Exhibition; abstracts, Paris, France. 11-14 September 2005.
Ross, D.A., Uchupi, E., 1977. Structure and sedimentary history of southeastern Mediterranean Sea-Nile Cone area. AAPG Bulletin 61 (6), 872-902.
Ryan, W.B.F., 1978. Messinian badlands on the southeastern margin of the Mediterranean Sea. In: Cita, M.B., Ryan, W.B.F. (Eds.), Messinian erosional surfaces in the Mediterranean. Elsevier, Amsterdam, Netherlands, pp. 349-363.
Sage, L., Letouzey, J., 1990. Convergence of the African and Eurasian Plate in the eastern Mediterranean. Petroleum and tectonics in mobile belts; proceedings of the IFP exploration and production research conference, 49-68.
Sager, W.W., MacDonald, I.R., Hou, R., 2003. Geophysical signatures of mud mounds at hydrocarbon seeps on the Louisiana continental slope, northern Gulf of Mexico. Marine Geology 198 (1-2), 97-132.
Salas, C., Woodside, J., 2002. Lucinoma kazani n. sp. (Mollusca: Bivalvia): evidence of a living benthic community associated with a cold seep in the Eastern Mediterranean Sea. Deep Sea Research Part I: Oceanographic Research Papers 49 (6), 991-1005.
Salem, R., 1976. Evolution of Eocene-Miocene sedimentation patterns in parts of northern Egypt. AAPG Bulletin 60 (1), 34-64.
Sardou, O., Mascle, J., 2003. Cartography by multibeam echo-sounder of the Nile deep-sea Fan and surrounding areas (2 sheets). Special publication CIESM, Monaco.

Sassen, R., Brooks, J.M., MacDonald, I.R., Kennicutt, M.C., II, Guinasso, N.L.J., Requejo, A.G., 1993. Association of oil seeps and chemosynthetic communities with oil discoveries, upper continental slope, Gulf of Mexico. In: Rosen Norman, C., Sartin, A., Barrett, M. (Eds.), Gulf Coast Association of Geological Societies; transactions of the 43rd annual convention. Gulf Coast Association of Geological Societies, New Orleans, LA, United States, pp. 349-355.

Sibuet, M., Olu, K., 1998. Biogeography, biodiversity and fluid dependence of deep-sea cold-seep communities at active and passive margins. Deep Sea Research Part II: Topical Studies in Oceanography 45 (1-3), 517-567.

Stanley, J.D., Goddio, F., Jorstad, T.F., Schnepp, G., 2004. Submergence of ancient Greek cities off Egypt's Nile Delta; a cautionary tale. GSA Today 14 (1), 4-10.

Stanley, J.D., Goddio, F., Schnepp, G., 2001. Nile flooding sank two ancient cities. Nature 412 (6844), 293-294.

Volgin, A.V., Woodside, J.M., 1996. Sidescan sonar images of mud volcanoes from the Mediterranean Ridge: possible causes of variations in backscatter intensity. Marine Geology 132 (1-4), 39-53.

Whiticar, M.J., 1994. Correlation of natural gases with their sources. In: Magoon Leslie, B., Dow Wallace, G. (Eds.), The petroleum system; from source to trap. American Association of Petroleum Geologists, Tulsa, OK, United States, pp. 261-283.

Woodside, J., Lykousis, V., Foucher, J.-P., Dupré, S., Alexandri, S., de Lange, G., Mascle, J., Zitter, T., and the Scientists of the ANAXIMANDER, MEDIFLUX, MEDINAUT projects, 2006. Seafloor fluid emissions in the eastern Mediterranean: variety as a function of environment. Geological Processes on Deep-Water European Margins. International Conference and 15th Anniversary Training Through Research Post-Cruise Meeting Programme and abstract book, 101.

Woodside, J.M., Ivanov, M.K., Limonov, A.F., 1997. Neotectonics and fluid flow through seafloor sediments in the eastern Mediterranean and Black seas; preliminary results of geological and geophysical investigations during the ANAXIPROBE/ TTR-6 cruise of R/ V Gelendzhik, July-August 1996; Part II, Black Sea, Paris, International.

Woodside, J.M., Ivanov, M.K., Limonov, A.F., 1998. Shallow gas and gas hydrates in the Anaximander Mountains region, eastern Mediterranean Sea. Geological Society Special Publications 137, 177-193.

Woodside, J.M., Lykousis, V., Foucher J.-P., Dupré, S., Alexandri, S., de Lange G., Mascle, J., Zitter, T., the scientists of the ANAXIMANDER, MEDIFLUX and MEDINAUT projects, NAUTINIL and MIMES shipboard scientific parties, 2005. Comparative Eastern Mediterranean mud volcanology. VIII International Conference on Gas in Marine Sediments abstracts, 3-6.

Woodside, J.M., Mascle, J., Zitter, T.A.C., Limonov, A.F., Ergun, M., Volkonskaia, A., 2002. The Florence Rise, the Western Bend of the Cyprus Arc. Marine Geology 185 (3-4), 177-194.

Yusifov, M., Rabinowitz, P.D., 2004. Classification of mud volcanoes in the South Caspian Basin, offshore Azerbaijan. Marine and Petroleum Geology 21 (8), 965-975.

Zitter, T.A.C., Huguen, C., Woodside, J.M., 2005. Geology of mud volcanoes in the eastern Mediterranean from combined sidescan sonar and submersible surveys. Deep Sea Research Part I: Oceanographic Research Papers 52 (3), 457-475.

Tables

Number of additionnal sampling dives		1	0	1	0
Centre longitude (E)		31º 42.6'	31º 35.5'	31º 23.4'	30º 8.20'
Centre latitude (N)		32º 22.2'	32º 19.7'	32º 21.7'	31º 58.2'
Water depth above the summit	m	1118	747	991	501
Height of the mud volcano	m	90	90	50	50
Diameter range of the mud volcano	km	2.6-2.8	3.0-4.6	3.2-3.7	1.5-2.0
Slope of surrounding seafloor	º	1,9	0,9	1,4	2,6
Estimated volume of extruded mud breccia	km^3	1,5	3,5	1,3	0,5
Temperature in the sediments 10 metres bsf at the active summit	ºC	45.3	20.3	41.7	21.8
Temperature in the near bottom water column at the active summit	ºC	13.85	13.75	13.8	13.9
Max [CH_4] above the active summit [1]	nmol/L	510	270	660	250
Location of main black sediment seeps		central dome	SW dome	central dome	central dome
Location of main carbonate crust seeps		SW side	none	none	none
Relative level of seepage activity in September 2003		very high	medium	very high	high

Table 1
Main characteristics of the four explored mud volcanoes located above gas chimneys on the Central Nile Deep Sea Fan. [1](De Lange et al., 2006; Mastalerz et al., 2007).

Fig. 1

Nile Deep Sea Fan shaded morphology map (Abdel *et al.*, 2000; Abdel *et al.*, 2001; Loncke *et al.*, 2002; Loncke *et al.*, 2006; Loncke *et al.*, 2004; Sardou and Mascle, 2003). The offshore Nile fan is composed of three distinct morpho-structural provinces with, in particular, significant variations in the sedimentary supply from the Nile River and in the gravity-driven sedimentary deformations induced by salt tectonics (Gaullier *et al.*, 2000; Loncke *et al.*, 2004). Gas and condensate are found principally in the Central Nile Deep sea Fan, while oil discoveries have been made in the western and eastern parts of the offshore delta (Abdel *et al.*, 2000). The studied mud volcanoes located above the gas chimneys (North Alex, Isis, Osiris and Amon) belong to the Central Nile Deep Sea Fan and were explored with the submersible *Nautile* during the NAUTINIL expedition in 2003. The Nile Deep Sea Fan mud volcanoes are systematically above or nearby reactivated deep-seated faults (Loncke *et al.*, 2004; Mascle *et al.*, 2006), sometimes also connected to Messinian canyons (Loncke *et al.*, 2006). See Table 1 for summary of the main morphological characteristics of each of these mud volcanoes.

Fig. 2

Backscatter imagery of North Alex mud volcano and close surroundings obtained with the Simrad EM12 multibeam echosounder during the NAUTINIL expedition (resolution of 50 metres). The track of the dive is indicated with a white line. Different levels of backscatter amplitude characterize the seafloor there. 1) A low and uniform backscatter characterizes most of the surface of the mud volcano with an amplitude similar to that of normal hemipelagic sediments and is primarily caused by a relatively homogeneous mud breccia containing rare big clasts and already covered with hemipelagic sediments. 2) Medium level backscatter seafloor located outside the mud volcano north of it is attributed to mud breccia gravity flows partly covered with hemipelagic sediments (see Fig. 7). 3). *In situ* observations have confirmed that the high backscatter restricted in the centre of the mud volcano to the highest and narrow slightly elevated dome corresponds to a high level of seepage activity. Free gas emission in the water column and highly gas-saturated mud breccia characterize the seafloor there. This high backscatter zone is sub-circular and is elongated in the seafloor slope direction (SSE-NNW). In addition to the high backscatter at the centre of the mud volcano, strong but much smaller sub-circular backscatter patches identified outside the mud volcano are most likely relatively recent and thick carbonate crust deposits as well as now active seeps.

Fig. 3

3D bathymetric block of the eastern part of the Central Nile Deep Sea Fan revealing the seafloor morphology (Sardou and Mascle, 2003) and focused in three large mud volcanoes: Isis, Osiris and Amon (VE, vertical exaggeration of 15). These mud volcanoes located above wide gas chimneys are clearly tectonically controlled (see Fig. 1). Numerous faults are expressed on the seafloor, disturbing it, particularly along the major N010-020 fault zone where Osiris and Amon are located. Many of these faults identified on the bathymetry are connected with Messinian canyons (Fig. 1) and growth faults associated with salt tectonics.

6.1. Fig. 4

a) Seafloor geological map of Amon mud volcano based on *in situ* observations made during the dives with the submersible *Nautile* during the Nautinil expedition (2003). The

seafloor morphology and the seep distribution are reported. See Figs 1 and 3 for exact location and Table 1 for mud volcano characteristics. Contour lines are in metres below sea level (Sardou and Mascle, 2003). From the external towards the middle parts of the most active centres, the seafloor exhibits a rougher morphology and younger mud deposits (t3: relatively old mud breccia already covered with thin hemipelagic sediments; t2: smooth mud breccia structures most often associated with dark sediment patches as partly covered with hemipelagic sediments; and t1: most recent mud extrusion-related structures associated with a chaotic seafloor). The main gas emission sites associated with dark sediment patches are located in the centre of the mud volcanoes or slightly shifted from it (Osiris, Fig. 5a), although the secondary seeps correspond to distal locations from the centre. One major and unique site with carbonate-crust-covered seafloor is located on the southwestern side of Amon, and here referred to as a main active emission site.
b) The sampling and measurement stations of the dives are reported on the bathymetric map of the mud volcano. Thermal gradient values are in °C/km and correspond to the uppermost sediments (first tens of centimetres).

Fig. 5

a) Seafloor geological map of Osiris mud volcano and b) Sampling and measurement stations map. A, B and C are point locations reported along the microbathymetric profile in Fig. 8a. See legend in Fig. 4.

Fig. 6

a) Seafloor geological map of Isis mud volcano and b) Sampling and measurement stations map. A, B, C, D and E are point locations reported along the microbathymetric profile in Fig. 8b. See legend in Fig. 4.

Fig. 7

a) Seafloor geological map of North Alex mud volcano and b) Sampling and measurement stations map. See legend in Fig. 4 and acoustic signature of the mud volcano subsurface and surroundings in Fig. 2.

Fig. 8

Microbathymetric profiles (with a resolution of better than one metre) along the tracks of the dives on a) Osiris and b) Isis. See location of the reference points (A, B, C, D and E) on the seafloor maps in Figs. 5 and 6. These mud volcanoes are wide, up to 4.6 km in diameter for the largest mud volcano (i.e., Osiris), with a very low relief of 50 to 90 metres (see Table 1 for more detail). The height of the mud volcanoes was previously overestimated because of the lower resolution (50 metres) of the multibeam echosounder data. Note the vertical exaggeration is x29. The mud volcanoes are extremely flat structures, with a slightly elevated dome most commonly located in the centre where most of the activity associated with black sediment seeps is concentrated (typically Isis). The main emission centre on Osiris is located in the southwest part of the mud volcano with, however, a lower level of activity. The rare and only secondary seeps on this mud volcano are located along the northern flank of a secondary dome. The seepage activity is more widely spread on Isis. See Figs 5 and 6 for detail on the seafloor morphology and seep distribution along the tracks. Furthermore, the overall shape of the mud volcanoes, clearly tectonically controlled, differs significantly from Isis, surrounded by a relatively undisturbed seafloor, to Osiris, located in a more active tectonic setting (Fig. 3). In contrast with Osiris (a), the seafloor morphology on Isis mud volcano (b) is radially symmetrical as indicated by the two microbathymetric profiles in the SE-NW and SW-NE directions, which are surprisingly similar and differ only within a few metres elevation.

Fig. 9

Cores from the uppermost sediments collected during the submersible dives at the four explored mud volcanoes (cm b.s.f. stands for centimetres below seafloor). The lithology is typical of the sediments present at the main active emission sites on the slightly elevated dome, located most commonly in the centre of the mud volcanoes. These sites were all gas saturated, and the seafloor there was scattered with millimetric holes caused by escaping gas bubbles (Fig. 12a), especially on North Alex (Fig. 7a). The sampling triggered gas bubble ascent in the water column (Fig. 11f) when spontaneous degassing was not already observed at the seafloor (typically the centre of North Alex). Piston cores - short and long- were all characterized by the strong smell of hydrogen sulfide (H_2S), a clear indication of active sulfate reduction. Core descriptions are for a) the active centre of Amon, where the surfaces of the black sediment patches were typically covered with sulfide-oxidizing bacteria (presumably Beggiatoa) forming dense filaments (Fig. 12b), b) the southwestern dome of Osiris, c) the active centre of Isis (Fig. 11f), and d) the main emission centre at North Alex, where numerous centimetric carbonate concretions precipitate in the sediments (Fig. 12c).

Fig. 10

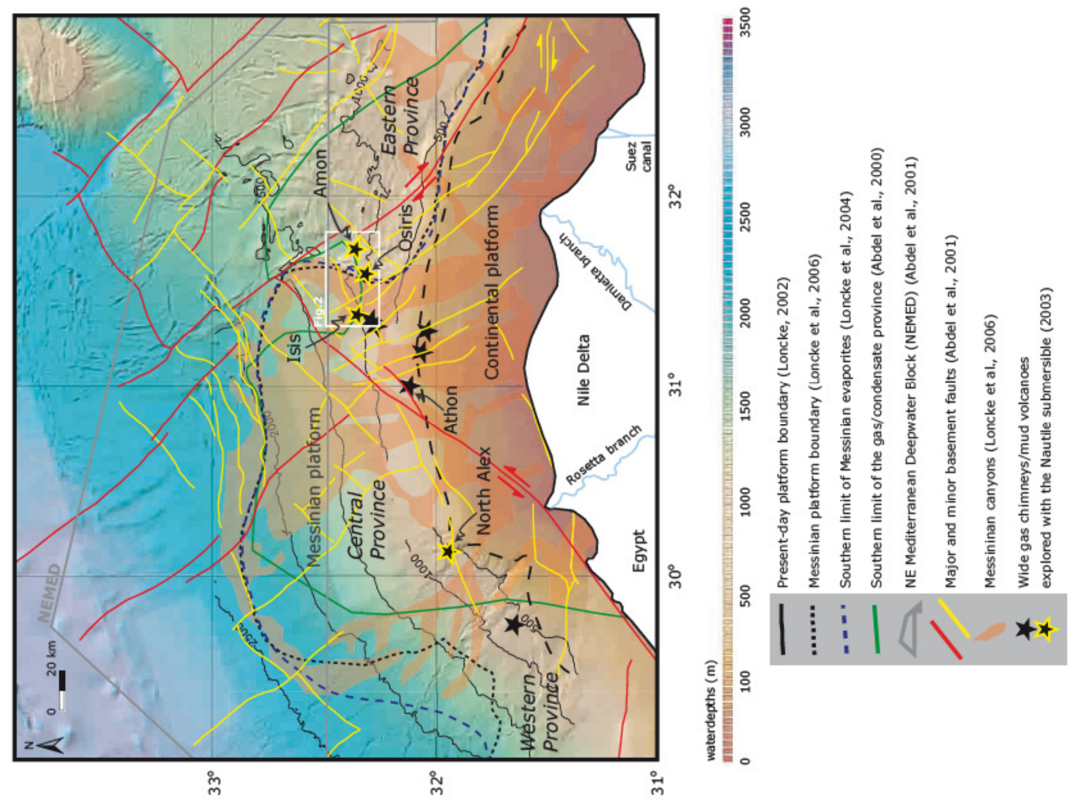
Seafloor pictures taken from the submersible *Nautile* at the four explored mud volcanoes (the white scale bar stands for 20 cm). a) Flat and undisturbed seafloor covered with fine sediments. The movement of the submersible together with sampling activity easily triggered a small turbidity current (North Alex). b) Bioturbation features built by white polychaete tube worms (Osiris). c) Gentle seafloor morphology on Amon associated with small scale ridges and mass flows. d) Superficial fracture on Isis. e) Smooth seafloor morphology with depressions and mounds, systematically associated with colonies of white gorgonias (Eunicella), exclusively encountered on Osiris (Fig. 5a). f) High density of larvae in the water column (North Alex).

Fig. 11

Seafloor pictures taken from the submersible *Nautile* at the four explored mud volcanoes (the white scale bar stands for 20 cm). a) Rough topography in the active centre of Amon. b) Smooth seafloor morphology with black sediment patches covered with white mats composed partly of sulfide oxidizing bacteria (presumably Beggiatoa) in the active centre of Amon. c) Fractured mud breccia in the active centre of Amon. d) Rough topography in the main emission centre of Isis, where the visibility was significantly reduced by the high density of benthic organisms in the water column. e) Subvertical striations along recently extruded mud breccia in the active centre of Amon. f) Free gas emission triggered by sampling activity above an active black sediment seep in the centre of Isis.

Fig. 12

Seafloor pictures taken from the submersible *Nautile* at the four explored mud volcanoes (the white scale bar stands for 20 cm with the exception of the figure c). a) Seafloor scattered with holes through which gas most probably escapes. The benthic fauna was relatively abundant at the surface of the mud volcanoes with numerous types of fishes. A few specimens from the Sebastidae family were observed at the surface of Osiris: *Helicolenus dactylopterus dactylopterus* (Scorpaneiform) (R. Causse and S. Iglésias, pers. comm.). b) Black sediment patches covered with thick white mats of organic or bacterial in origin in the active centre of Amon. c) Centimetric carbonate concretions within the sediments in the active emission centre of North Alex. d) Rough and disturbed seafloor in the active centre of Amon close to an active black sediment seep. Note the presence of a *Chaceon* crab (*C. mediterraneus*). e) Carbonate crust chimney on the southwestern flank of Amon, where the sediments were highly gas saturated and the seafloor scattered with relatively dense concentrations of Lucinidae chemosynthetic bivalves (Fig. 4a). f). Asphalt seep with numerous bivalves embedded in the solidified tar, located on the carbonate-crust-covered seafloor on Amon (Fig. 4a).



NEMED
Western Province
Central Province
Eastern Province
Messinian platform
Continental platform
Isis
Amon
Osiris
Athon
North Alex
Nile Delta
Egypt
Rosetta branch
Damietta branch
Suez canal
Fig.2
0 20 km
30°
31°
32°
33°
waterdepths (m)
0 100 500 1000 1500 2000 2500 3000 3500
Present-day platform boundary (Loncke, 2002)
Messinian platform boundary (Loncke et al., 2006)
Southern limit of Messinian evaporites (Loncke et al., 2004)
Southern limit of the gas/condensate province (Abdel et al., 2000)
NE Mediterranean Deepwater Block (NEMED) (Abdel et al., 2001)
Major and minor basement faults (Abdel et al., 2001)
Messininan canyons (Loncke et al., 2006)
Wide gas chimneys/mud volcanoes explored with the Nautile submersible (2003)

Figure 1

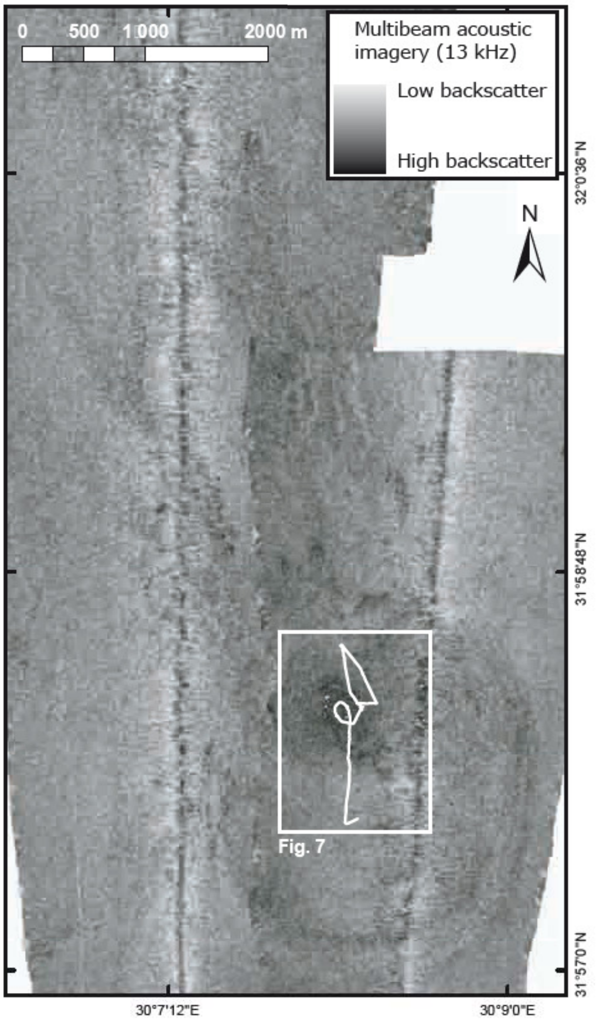

0 500 1 000 2000 m
Multibeam acoustic imagery (13 kHz)
Low backscatter
High backscatter
N
Fig. 7
32°0'36"N
31°58'48"N
31°57'0"N
30°7'12"E
30°9'0"E

Figure 2

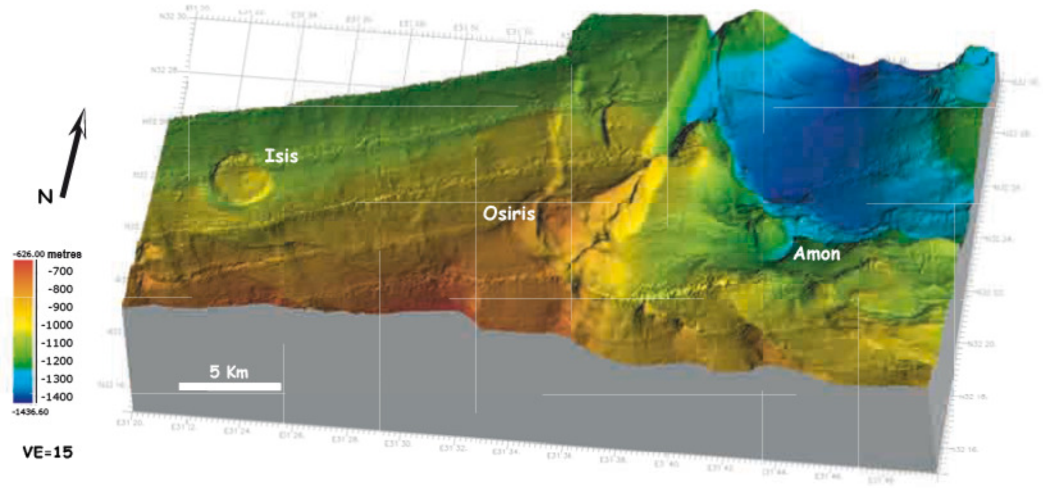

Isis
Osiris
Amon
N
-626.00 metres
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1436.60
5 Km
VE=15

Figure 3

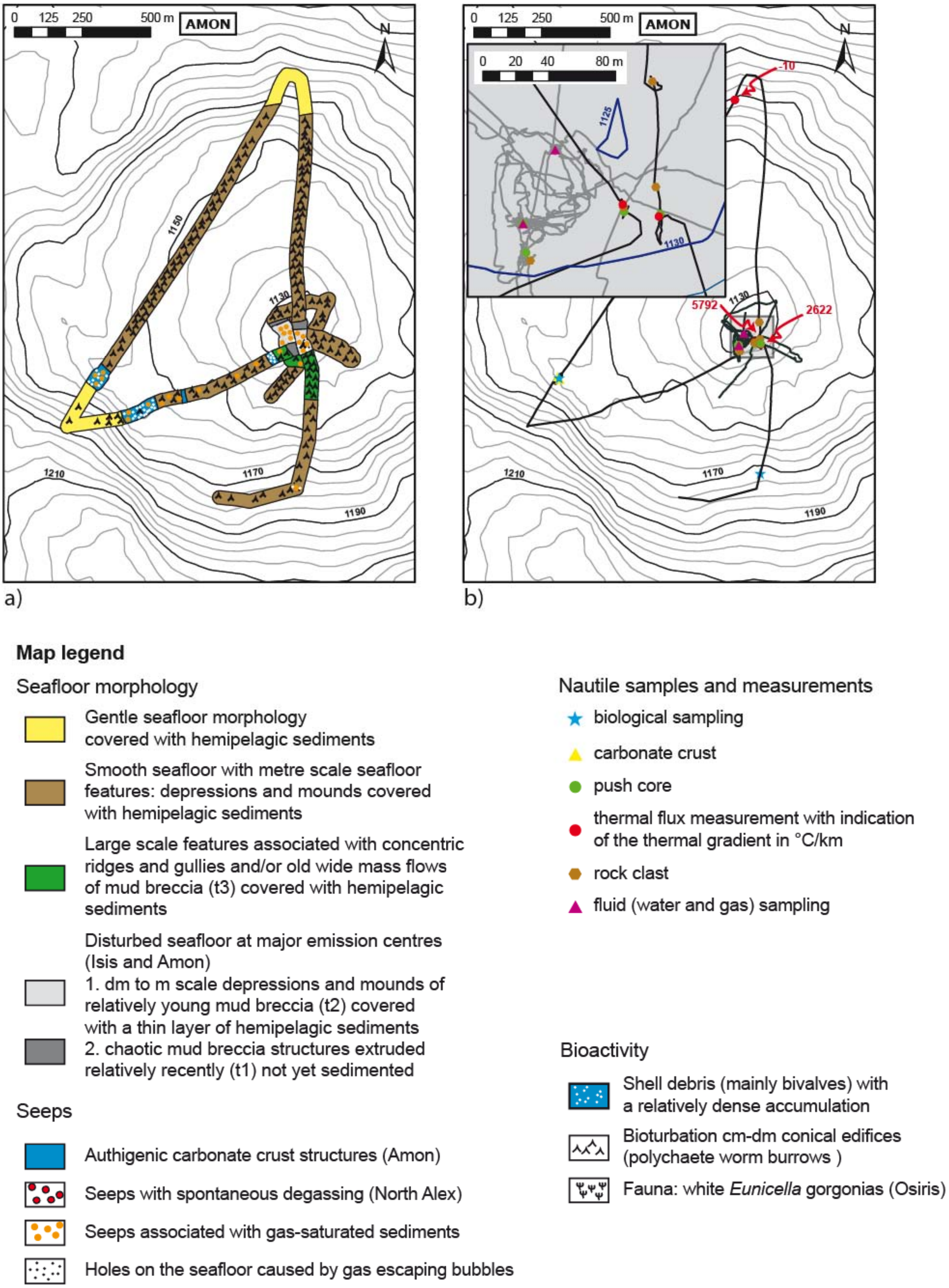
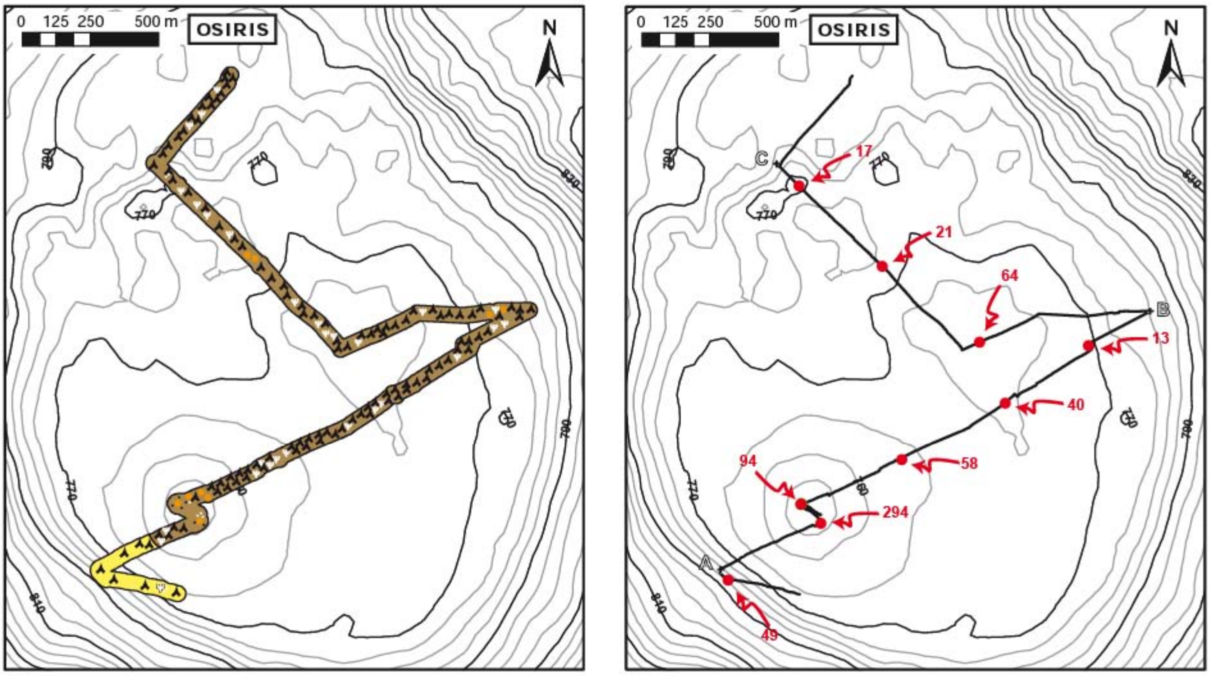

0 125 250 500 m
AMON
N
1150
1130
1170
1190
1210
a)
0 125 250 500 m
AMON
N
0 20 40 80 m
1125
1130
-10
5792
2622
1170
1190
1210
b)
Map legend
Seafloor morphology
Gentle seafloor morphology covered with hemipelagic sediments
Smooth seafloor with metre scale seafloor features: depressions and mounds covered with hemipelagic sediments
Large scale features associated with concentric ridges and gullies and/or old wide mass flows of mud breccia (t3) covered with hemipelagic sediments
Disturbed seafloor at major emission centres (Isis and Amon)
1. dm to m scale depressions and mounds of relatively young mud breccia (t2) covered with a thin layer of hemipelagic sediments
2. chaotic mud breccia structures extruded relatively recently (t1) not yet sedimented
Seeps
Authigenic carbonate crust structures (Amon)
Seeps with spontaneous degassing (North Alex)
Seeps associated with gas-saturated sediments
Holes on the seafloor caused by gas escaping bubbles
Nautile samples and measurements
biological sampling
carbonate crust
push core
thermal flux measurement with indication of the thermal gradient in °C/km
rock clast
fluid (water and gas) sampling
Bioactivity
Shell debris (mainly bivalves) with a relatively dense accumulation
Bioturbation cm-dm conical edifices (polychaete worm burrows)
Fauna: white *Eunicella* gorgonias (Osiris)

Figure 4



0 125 250 500 m
OSIRIS
N
770
790
830
840
A
B
C
17
21
64
13
40
58
94
294
49

a) b)

Figure 5

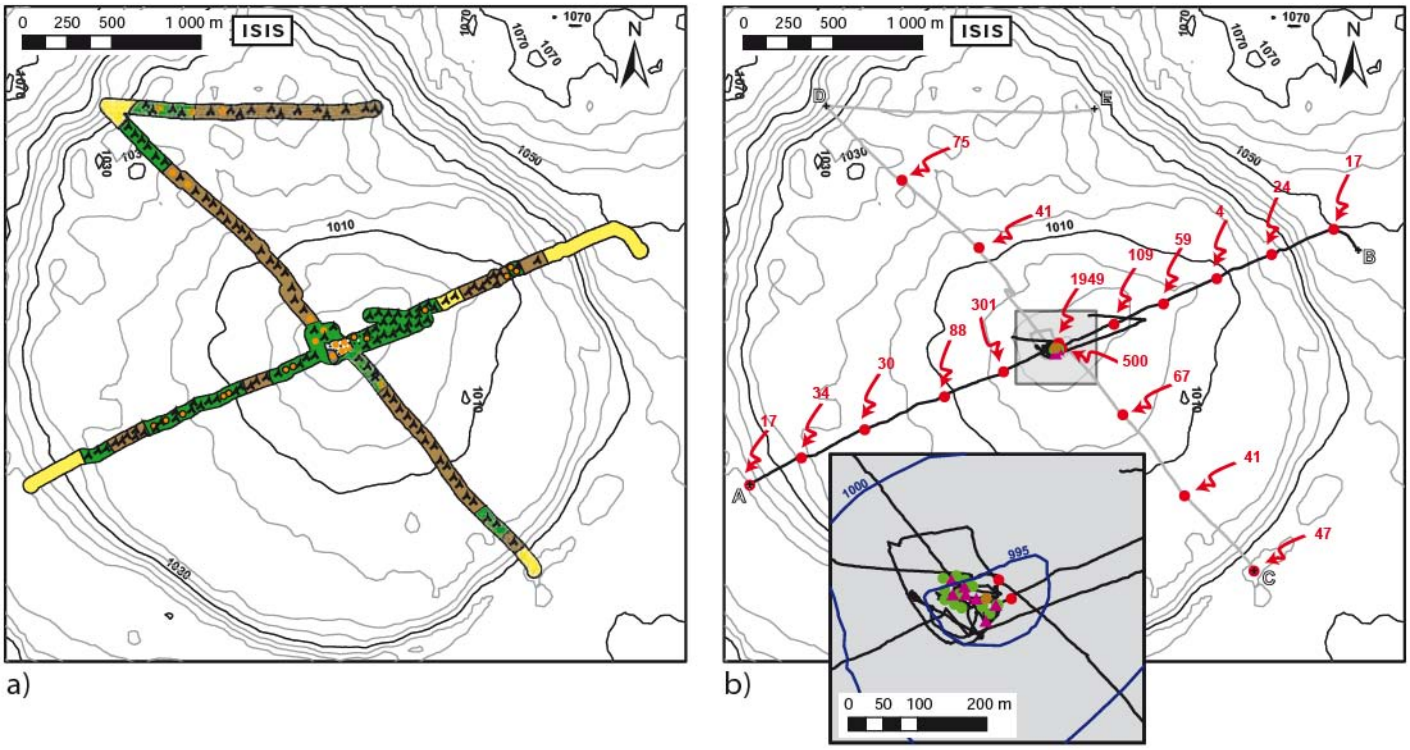
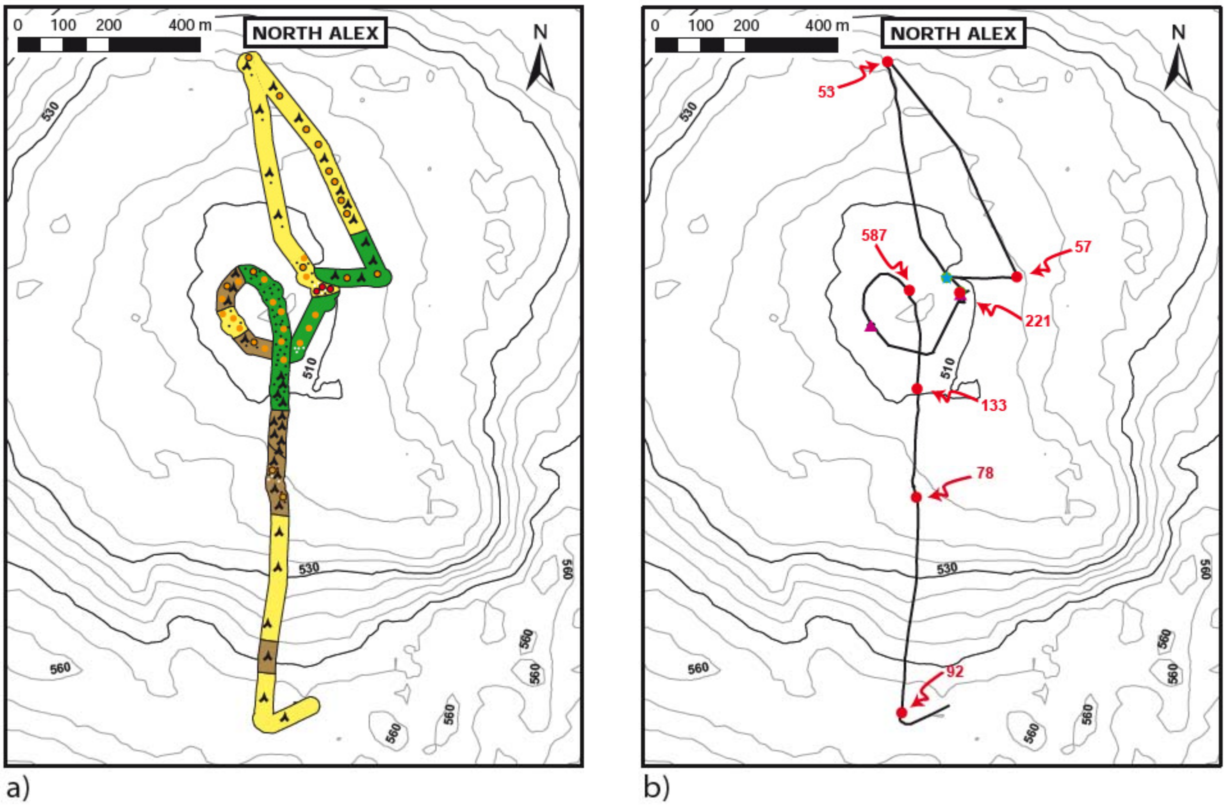

0 250 500 1 000 m
ISIS
N
1070
1050
1030
1010
a)
D
E
75
41
1010
17
24
4
59
109
1949
301
88
500
30
34
17
67
41
47
A
B
C
1000
995
0 50 100 200 m
b)

Figure 6



0 100 200 400 m
NORTH ALEX
N
530
510
530
560
560
560
560
560
a)
0 100 200 400 m
NORTH ALEX
N
53
587
57
221
133
78
92
530
510
530
560
560
560
560
560
560
b)

Figure 7

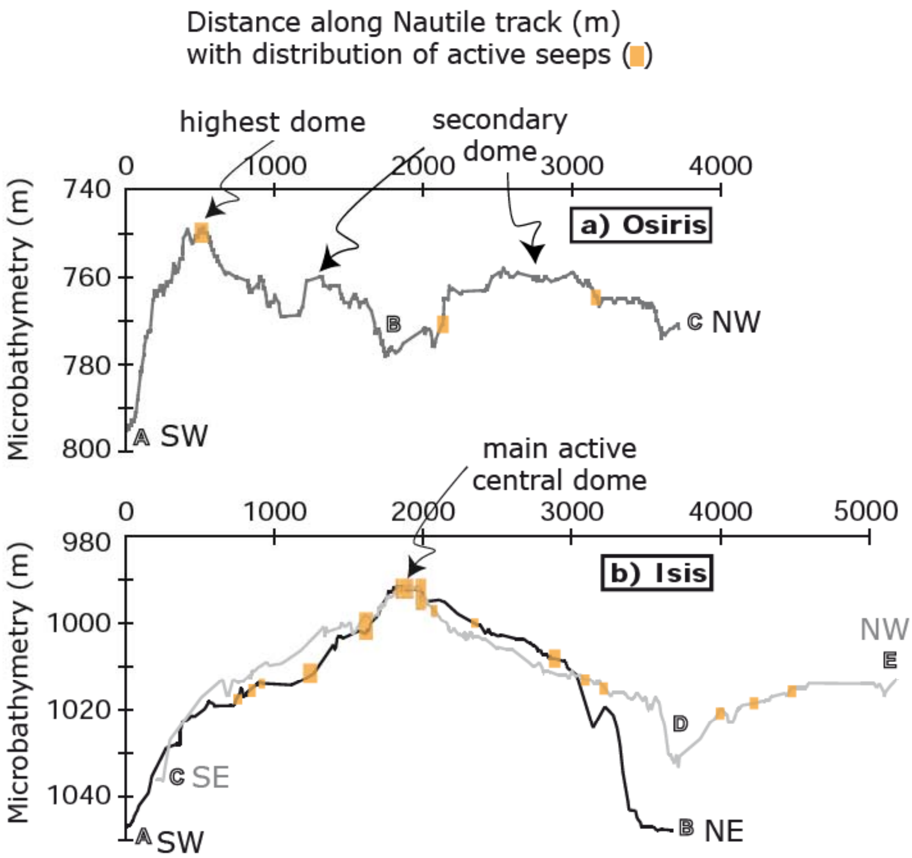

Distance along Nautile track (m)
with distribution of active seeps ( )
highest dome
secondary
dome
0
1000
2000
3000
4000
740
760
780
800
Microbathymetry (m)
a) Osiris
A SW
B
C NW
main active
central dome
0
1000
2000
3000
4000
5000
980
1000
1020
1040
Microbathymetry (m)
b) Isis
A SW
C SE
B NE
D
NW
E

Figure 8

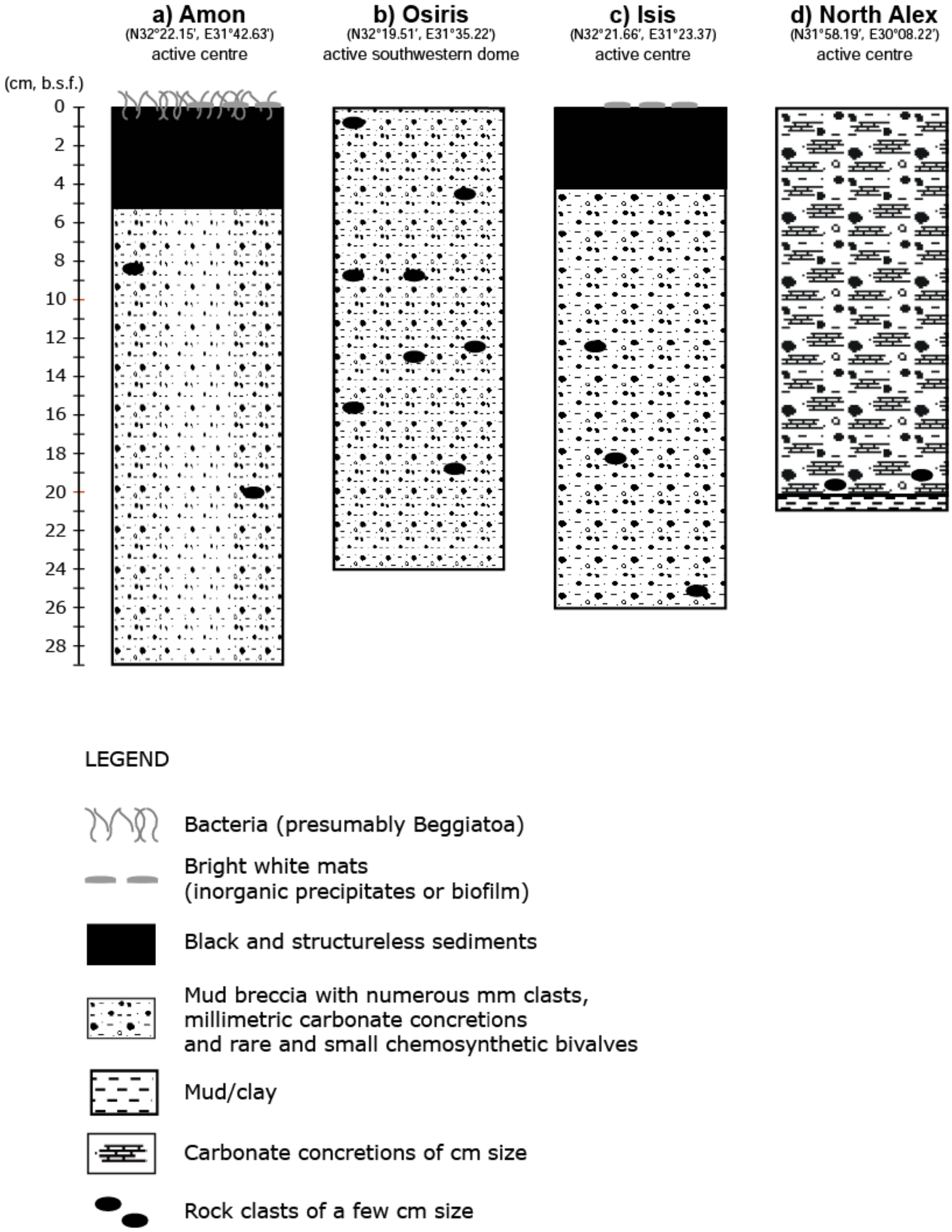

a) Amon
(N32°22.15', E31°42.63')
active centre
b) Osiris
(N32°19.51', E31°35.22')
active southwestern dome
c) Isis
(N32°21.66', E31°23.37)
active centre
d) North Alex
(N31°58.19', E30°08.22')
active centre
(cm, b.s.f.)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
LEGEND
Bacteria (presumably Beggiatoa)
Bright white mats
(inorganic precipitates or biofilm)
Black and structureless sediments
Mud breccia with numerous mm clasts,
millimetric carbonate concretions
and rare and small chemosynthetic bivalves
Mud/clay
Carbonate concretions of cm size
Rock clasts of a few cm size

Figure 9

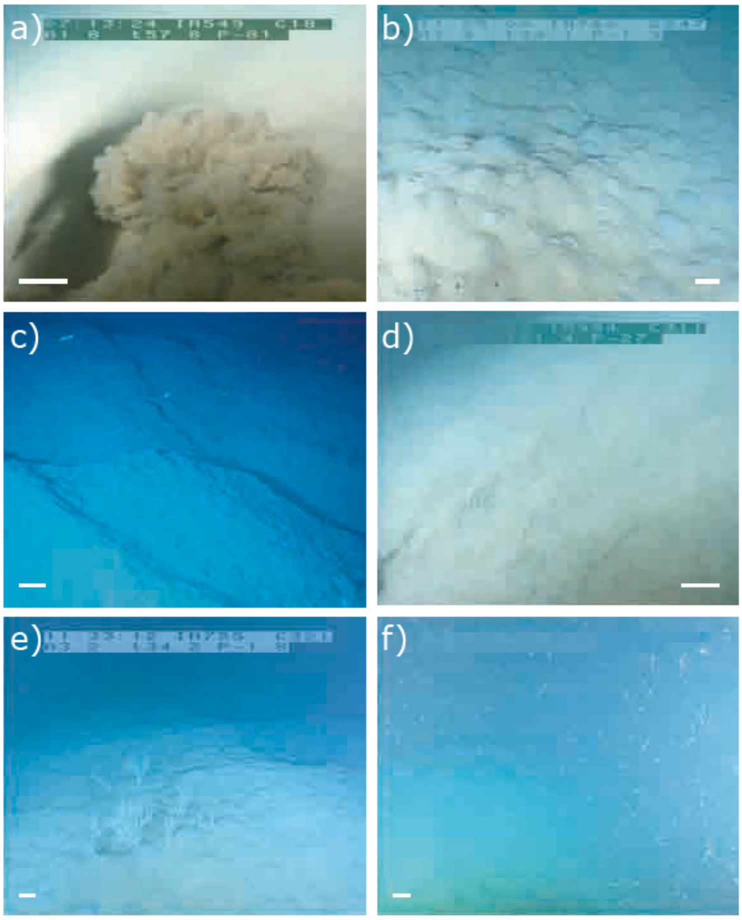


Figure 10

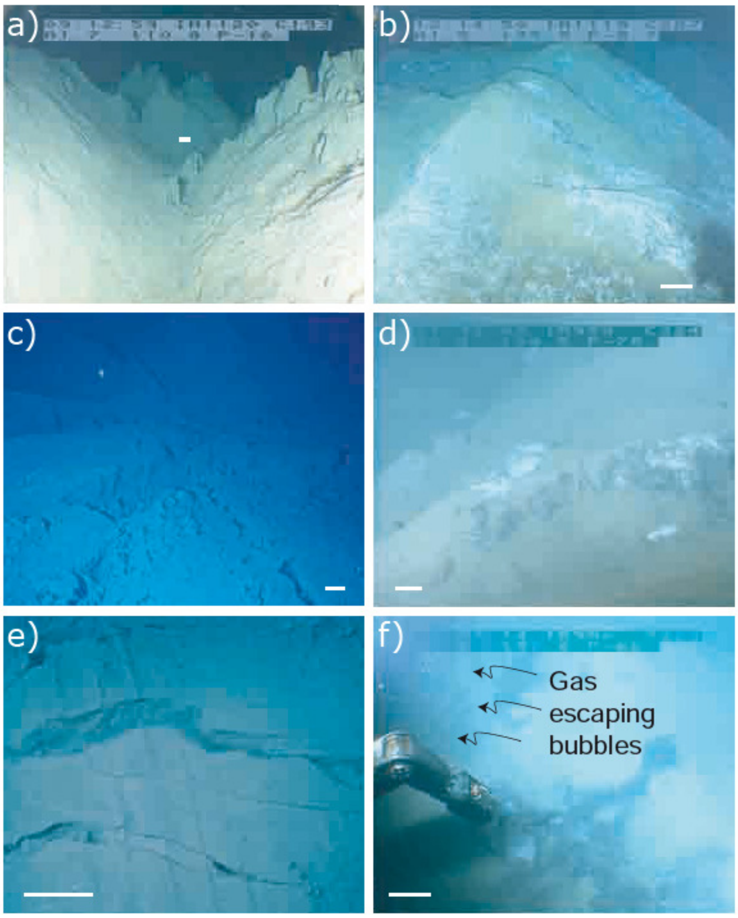


Figure 11

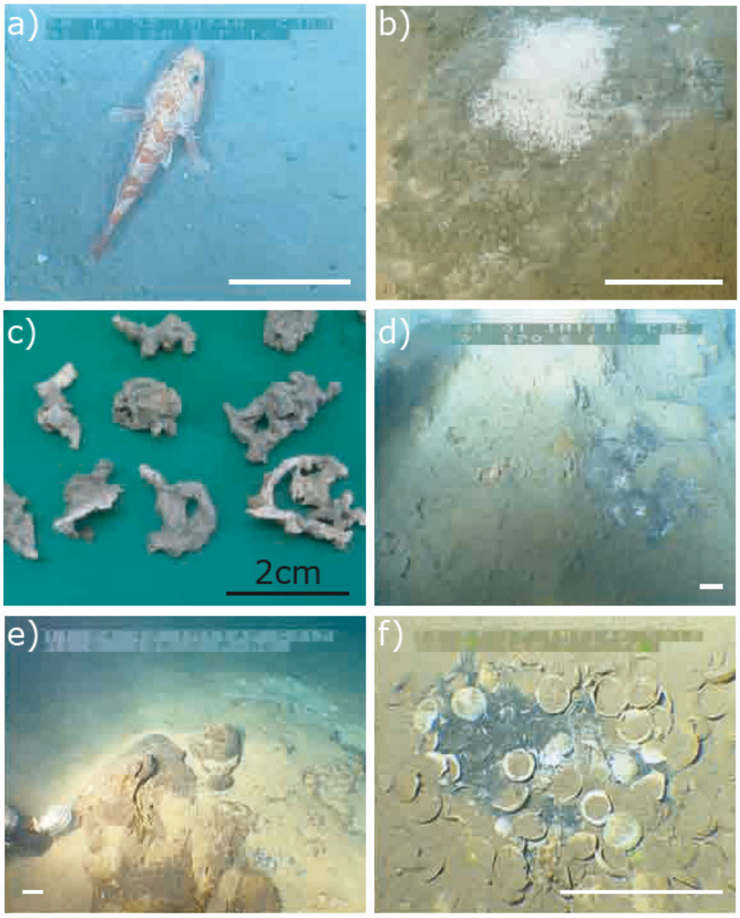


Figure 12