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Multi-scale seafloor mapping of active seep-related structures, offshore Egypt

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Abstract :

The Nile deep sea fan system presents a rich variety of fluid escape structures, gas chimneys, pockmarks and carbonate crust mounds, brines pools, and several types of mud volcano. These seep-related structures were explored for the first time with the Nautile submersible during the 2003 Nautinil expedition and are characterized by high thermal gradients and highly gas-saturated sediments. More recently, high resolution side scan sonar data acquired during the 2004 Mimes expedition brings more detail to the geophysical imagery. The EdgeTech DTS-1 deep tow sonar coupled with a 2-8 kHz chirp subbottom penetrator was deployed around 100 m above the seafloor and operated at a frequency of 75 kHz. Several gas plumes were acoustically detected in the water column of the side scan record both in the Eastern and Central Provinces, e.g. above Isis and Amon mud volcanoes and numerous pockmarks. These observations confirm the intensity of the present-day activity offshore Egypt in terms of seepage associated with gas emissions and its continuity through time. The geophysical signature of these active sites commonly associated with high backscatter, presents, however some variability in the signal depending on the intensity and the type of seep-related structures, e.g. the presence of relatively young mud breccia or authigenic carbonate crust pavements. Acoustic mosaics of the seafloor and chirp profiles reveal subsurface sediments commonly disturbed by ascending fluids throughout the delta and usually marked by seafloor carbonate crust structures. In the Eastern Province, the wide gas chimneys, formed during successive episodes of mud extrusion associated with relatively low volume of mud breccia, are systematically associated with carbonate crust

formation. The feeder channels of these mud volcanoes, similar to the gas conduits below carbonate crust structures identified over the entire delta, are relatively narrow and, for the vast majority of them, do not exceed a few tens of metres in diameter. These seep-related structures, gas chimneys and carbonate crust structures are controlled by the local and regional tectonics in connection with a complex fault network, deeply rooted faults, and shallower ones associated with salt tectonics for instance.

Keywords: Nile Deep Sea Fan, gas chimneys, mud volcanism, authigenic carbonate crust, backscatter, free gas emission

1. Background

The eastern Mediterranean Sea is, like many other marine areas, subject to significant seepage activity. Mud volcanism, authigenic carbonate crust formation, chemosynthesic communities of macro-organisms and microbes, e.g. anaerobic bacteria and archea, characterize these areas. The first occurrence of seepage associated with mud volcanoes and brines was discovered in the early eighties along the Mediterranean Ridge, the accretionary prism of the Hellenic arc (Cita *et al.*, 1981). Since then, more and more seep-related structures have been identified on the seafloor, e.g. in the Anaximander Mountains (Woodside *et al.*, 1998, Lykousis *et al*., this issue), along the Florence Rise (Woodside *et al.*, 2002; Zitter, 2004), in the Levant Basin (Coleman and Ballard, 2001), and in the Nile Deep Sea Fan (Bellaiche *et al.*, 2001; Mascle *et al.*, 2001). Bathymetric and acoustic imagery maps of the seafloor obtained with multibeam echosounder are essential databases for identifying fluid venting areas as a basis for further investigations (Loubrieu *et al.*, 2001; MediMap Group *et al.*, 2005).

Seep-related structures were identified and mapped offshore Egypt using multibeam data and limited seismic and coring data (Fig. 1) (Loncke *et al.*, 2004; Sardou and Mascle, 2003). The Nile deep sea fan can be divided into three distinct morpho-structural Provinces. The western Province, the most currently active part of the delta, is characterized by numerous small scale mud volcanoes and a few wide calderas and gas chimneys. Seafloor in the Central Province is subject to slope instabilities and sedimentary slides, and is scattered with numerous pockmarks, and carbonate pavements and mounds. The Eastern Province, delimited on the western side by a major transpressive fault zone, is strongly controlled by salt tectonic activity. Gas chimneys are not restricted to one of these provinces, but are located in the upper slope domain along the present day continental platform boundary or close to the limit of the Messinian platform.

The rifting episodes and the Messinian salinity crisis are crucial events in the tectonic history of the Nile Delta, especially concerning the formation at depth of hydrocarbons and the occurrence at the seabed of seepage activity. Along the rifted continental Egyptian margin, sedimentary basins experienced rapid subsidence and high sedimentation rates, leading to the burial of uncompacted sediments, and eventually, to the formation of hydrocarbons. The deposition of thick evaporites above such reservoirs was essential to maturation by sealing the petroleum system. The accumulation of gas and oil combined with water and mud were later released through fault conduits, generating fluid expulsion or diffusion through the seabed. Faults associated with salt tectonics represent preferential pathways for fluids to escape. Additionally, during the Messinian, the margin was incised by large scale canyons, and infilled later on by Pliocene sediments forming important reservoir rocks (Abdel *et al.*, 2001; Dolson *et al.*, 2002). At present, the Nile Deep Sea Fan forms a sedimentary edifice more than 10 km thick (Abdel *et al.*, 2001; Mascle *et al.*, 2003).

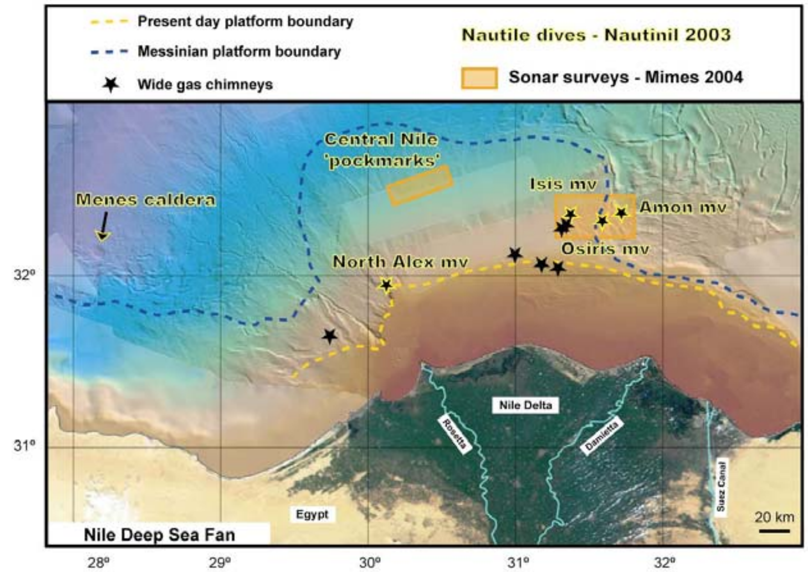

Fig. 1. Nile deep sea fan shaded morphology modified after Loncke and Mascle (2004) and Sardou and Mascle (2003).

2. New datasets and discoveries

The Mediflux Project, promoted by the European Science Foundation, is a scientific programme dedicated to an integrated study of seepage through the seabed of the Nile Deep Sea Fan. Gathering scientific teams from the Netherlands, France and Germany, this programme is strongly based on marine expeditions and acquisition of new biological, geological and geophysical datasets. During the first campaign NAUTINIL onboard the R/V L'Atalante in 2003, the French Nautile submersible was operated (Fig. 2) and, for the first time, fluid seep-related structures were observed in situ offshore Egypt, along with sampling and measurements. The second cruise MIMES, onboard the Dutch vessel Pelagia in 2004, investigated several targets in the Central and Eastern Provinces between water depths of 700 to 1800 metres with the German DTS-1 (EdgeTech) deep tow side scan sonar (75 kHz) coupled with a 2-8 kHz chirp subbottom penetrator (Fig. 2). The third and last cruise of the Mediflux programme, BIONIL, will be held in the autumn of 2006 onboard the R/V Meteor with the operation of the German ROV Quest and the French AUV Aster[x].

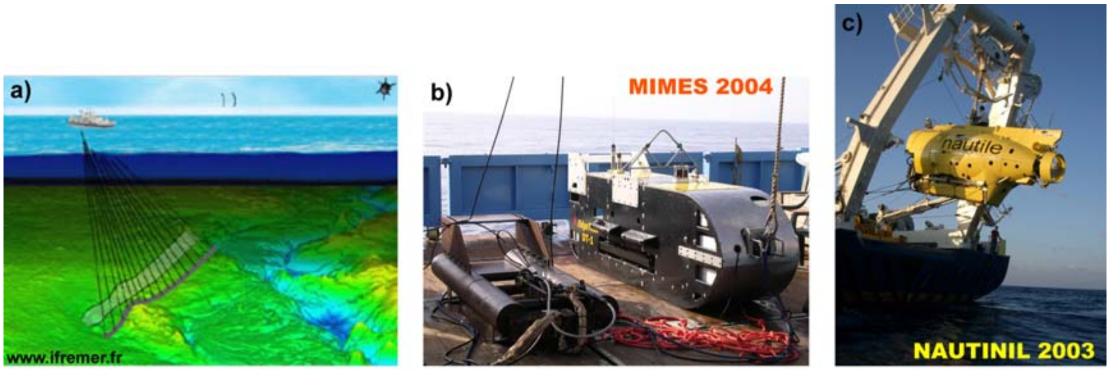

Fig. 2. Multi-scale seafloor mapping and acquisition tools a) Bathymetry and seafloor reflectivity obtained with multibeam echounder, e.g. Simrad EM12 (13 kHz) b) Backscatter imagery of the seafloor using deep tow side scan sonar, e.g. DTS-1 EdgeTech (75 kHz) c) In situ observations and measurements at the seafloor with submersible, e.g. the French Nautile (Ifremer).

Evidence of seepage activity over the entire delta was confirmed, and observed in great detail in the three explored target areas: the Menes caldera in the west (including Chefren and Cheops mud volcanoes, see Huguen *et al*., this issue), the central pockmarks (Bayon *et al*., this issue), and the four wide gas chimneys roughly located along a belt close to the continental platform boundary (North Alex, Isis, Osiris and Amon mud volcanoes) (Figs. 1 and 3). The seabed is heavily disturbed by fluid venting-related structures which cover a significant surface of the offshore delta. The spectacular intensity of these fluid emission systems was recorded by ground truth geological, sedimentological, (micro)biological, geochemical and geophysical data, revealing high gas concentration in the sediments, sulphate reduction and anaerobic methane oxidation at the subsurface (see Gontharet, this issue), high thermal gradients in the surface sediments (e.g. 40°C at 10 m depth below seafloor at the active centre of the Isis mud volcano (Foucher *et al.*, 2005, Feseker *et al*., this issue) and in the brines (e.g. 57°C at Chefren through 250 m of briny mud, Woodside *et al.*, 2005), numerous high backscatter patches on the seafloor (Fig. 4b) commonly associated with seismic gas wipe outs, acoustic plumes of free gas bubbles (Fig. 4a), and methane and higher hydrocarbons enriched water column (de Lange *et al*., this issue). The diversity of the seep-related structures at the scale of the submarine delta is remarkable. Brine pools on mud volcanoes in the caldera structure, small-scale mud volcanoes, pockmarks and carbonate crust pavements and mounds, and wide gassy mud chimneys, characterise parts of the seafloor of the Nile deep sea fan, often together (Fig. 3).

Geological mapping of seafloor morphology, seepage and related (micro)biological activity for instance, primarily based on ground truth observations along the submersible tracks, additionally provides crucial constraints for calibration of geophysical seafloor signatures, i.e. reflectivity from the multibeam echosounder and backscatter from the deep tow side scan sonar. A possible value of such a calibration is to extend geological mapping into unexplored areas and thus to be able to estimate the seepage activity and to predict the nature of the seafloor and shallow subsurface, for example, as well as the occurrences of mud volcanism or carbonate crust formation. Moreover, seafloor mosaics created from surveys using several geophysical tools operating at different frequencies (e.g. 13 and 30 kHz respectively for the Simrad EM12 and EM300 multibeam echosounder, 75 or 410 kHz for the DTS-1 EdgeTech side scan sonar) do not image geological targets in the same way due to higher penetration of low frequency emitted signals (at least 1.8 metres and less than 70 cm respectively for the

EM12 and EM300, and not more than a few tens of centimetres for the DTS-1) and different resolutions. Comparative study of these multi-spectral datasets may for instance aid identification of different successive stages in mud volcano formation.

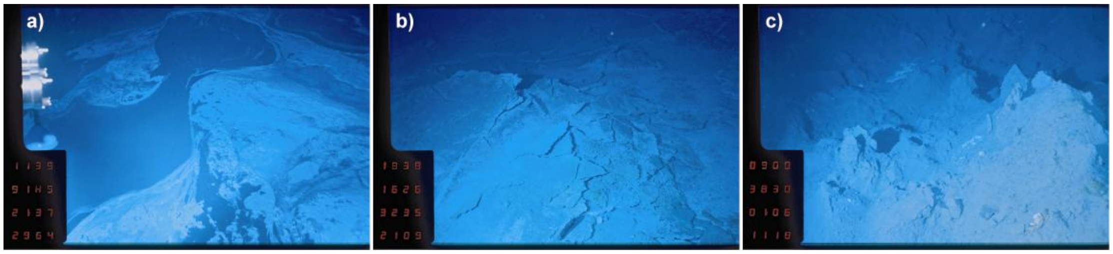

Fig.3. Nile deep sea fan seafloor pictures taken from the Nautile submersible in three active seepage sites. a) warm brine pool flows, with (sulphur/ bacterial?) white filaments on top of Chefren mud volcano, located inside the western Menes caldera b) fracturated carbonate crust turtle-back structures in the Central Nile, partly covered with a thin layer of hemipelagic sediments. c) fresh mud breccia at the active centre of the Amon gas chimney.

3. Gas chimneys and mud volcanism

Mud volcanoes investigated on the Nile Deep Sea Fan are located at the edge of either the present-day (North Alex) or Messinian continental platform boundary (Isis, Osiris and Amon) between 500 and 1100 metres water depths (Fig. 1). They correspond to large sub-circular structures of a few km in diameter with very low relief, from 50 to 100 m on average, of flat or slightly conical shape, and very gentle slope (between 1º and 4º).

The mud breccia is highly gas saturated containing essentially numerous small millimetric clasts. Gas analysis from sediment and water samples reveal a thermogenic origin of the methane and other hydrocarbons for the vast majority of the different explored sites (Mastalerz *et al.*, 2004; Prinzhofer *et al.*, 2005). Degassing, spontaneous or triggered, observed directly at the seafloor from the submersible, characterizes the central seepage zones, and additionally, several peripheral active sites. The sediments at these seeps are dark grey to black due to sulphate reduction and are commonly partly covered with white mats of inorganic precipitates and/or bacterial origin (e.g. Beggiatoa mats). The fluid venting structures observed in situ are systematically associated with a high backscatter signature on the sonar mosaic (Fig. 4b) due to the high gas concentration, the recently extruded mud breccia edifice, and carbonate crust structures. Furthermore, several gas plumes were inferred in the water column in the side scan sonar record, either at the centre of the volcano where activity was known and/or on the edges (Fig. 4a). These acoustic anomalies correspond to the presence of gas bubbles in the water column, enriched mainly in methane. CTD casts recovered above the centre of Isis for instance indicate a concentration of CH_4 of 600 ppmv at 50 m above seafloor (Mastalerz *et al.*, 2004). The subsurface sedimentary layers of these active volcanoes, imaged by chirp profiles, represent a uniform and chaotic seismic facies without any internal structure, attributed to the mud breccia; and they are associated with gas wipe outs and sometimes with narrow vertical gas conduits reaching the seafloor. Although gas saturated sediments at the seafloor are restricted to a few locations in connection with these narrow conduits, and neither coring nor heat flux revealed much activity in the periphery of the active sites, the entire structure of these volcanoes is much saturated in gas at depth.

The subsurface morphology of the different mud volcanoes exposes an alternance of relatively concentric ridges and gullies, caused by relatively slow mud extrusion which shapes the surface of the volcano and causes these irregularities (Fig. 4). Catastrophic mud eruption events are unlikely even if mud extrusion probably experiences episodic and significant events. Mud flows identified on the multibeam reflectivity maps in the close proximity of the mud volcanoes represent mass flows and not erupted mud flows, and correspond rather to gravitational collapse (Fig. 4b).

Active seepage is not restricted to a single primary location on a mud volcano. In other words, the main activity is not necessarily confined to the centre alone, but seep-related structures have been observed and/or identified on sonar mosaic and subbottom profiles on the flanks of the volcano or at the edges (Fig. 4b). Additionally, the main centre of the mud volcano activity is not necessarily the geometric centre of the structure (e.g. Osiris). The occurrence of seepage here and there at the seabed is tectonically controlled (see Huguen *et al*., this issue), as is their localization on the delta and the overall shape and morphology of fluid venting structures; and therefore they may vary from one mud volcano to another.

Mud volcanism appears to be closely associated with the formation of authigenic carbonate crust. Mud breccia in the centre of North Alex for instance exhibits small scale carbonate concretions (mm to 2 cm clasts). The western flank of Amon is partly covered with carbonate structures, chimneys, turtle-backs, pavements or massive metre-scale blocks, easily identified in reflectivity, backscatter, and chirp data. The other mud volcanoes are characterized by isolated and restricted carbonate crust structures located around the edges of the volcano and/or at the peripheries. Similarly to the narrow feeder channels connected to mud and fluid ascension, the seeps where carbonate crust forms, are underlain at depth with numerous narrow vertical gas conduits.

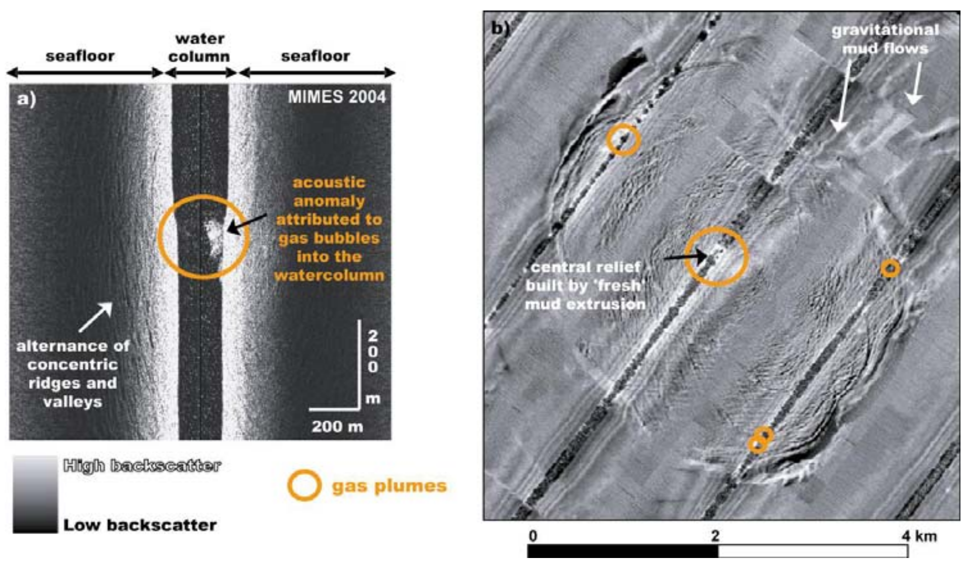

Fig. 4. a) Acoustic gas plume detected in the water column in the unprocessed side scan sonar record at the summit of Isis mud volcano. b) Backscatter mosaic over Isis with highest signal amplitudes at the active centre and close to the edges, in connection with narrow feeding conduits.

4. Seepage and authigenic carbonate crust formation

Observed in situ in the Central (Fig. 3b) and Eastern Provinces, structures associated with the formation of authigenic carbonate crust correspond to active seep environments in which are found benthic communities of (macro)organisms (e.g. vestimentiferam tubeworms, lucinidae shells). Such fluid venting structures, characterized by highly gas saturated sediments, were identified additionally and extensively on acoustic seafloor mosaic and chirp subbottom profiles. Carbonate crust structures correspond to very high backscatter from subcircular features of a few metres to a few hundreds of metres in diameter. We observe a relatively high variability in the backscatter amplitude which is related to the presence of different types of carbonate crust structures and activity, e.g. small scale pockmarks of 10-20 m diameter or thin carbonate layers partly covered with hemipelagic sediments. Several gas plumes were detected acoustically in the water column in the side scan record above pockmarks and carbonate crust mounds in the Central Delta at water depths of ~1700 m, and above the western flank of Amon mud volcano.

The formation of these structures is not restricted to the surface of the mud volcanoes, the edges, or the close vicinity. They are associated with several fault networks in the Eastern Province, along the major transpressive fault running N010 and faults related to salt tectonic activity (N020-030 and N320-330), and on the Messinian platform along ~N340 orientated faults in connection with large scale Messinian canyons, or possibly associated with slope instabilities in the Central Province.

Carbonate crust edifices occur most commonly in gentle depressions and associated with narrow gas conduits, similarly to the main fluid pathways imaged below the wide Eastern mud volcanoes. On the chirp profiles of the Central Nile, inferred gas conduits vertically cut the sedimentary reflections down to 50 m at least. They correspond mostly to narrow and localized cylindrical columns of a few meters to 10-20 m diameter, sometimes up to 100-200 m wide and with exception reaching 400 m. Seafloor depressions are commonly observed above highly disturbed sediments caused by upward gas migration.

5. Conclusions

The Nile Deep Sea Fan is an area of very active seepage with a great diversity of fluid venting structures associated with mud volcanoes, gas chimneys, brines and carbonate crust formation. These ubiquitous fluid escape structures are the sites of methane release into the water column and possibly, especially in shallower upper slope domains, into the atmosphere. Subsurface sediments are commonly disturbed by ascending fluids throughout the delta, and these are usually marked by seafloor carbonate crust structures.

The wide mud volcanoes, so-called gas chimneys, are systematically associated with carbonate crust formation, predominantly on the mud volcano summit, on the edges or close to this edifice. The feeder channels of these mud volcanoes, similarly to the gas conduits below carbonate crust structures identified over the entire delta, are relatively narrow and, for the vast majority of them, do not exceed a few tens of metres in diameter. The large mud volcanoes offshore Egypt form most likely during successive episodes of mud extrusion associated with relatively low volume of mud breccia. Catastrophic eruption events with ‘running’ mud flows are unlikely. Mud flows around the mud volcanoes correspond rather to gravitational collapse.

Seep-related structures, gas chimneys and carbonate crust structures, are not randomly localized on the Nile Delta, they are controlled by the local and regional tectonics, as is the overall shape of the mud volcanoes. Several fault networks shape the seepage distribution offshore Egypt. In the Eastern Province, concentrations of seeps are clearly connected to the major transpressive fault running N010 and (growth) faults in relation with salt tectonic activity oriented N020-030 and N320-330. On the Messinian platform, seeps are aligned along ~N340 orientation in connection with large scale canyons or associated with slope instabilities in the Central Province.

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