I - EXECUTIVE SUMMARY

1. INTRODUCTION: WORKSHOP OBJECTIVES AND OUTLINES

The workshop took place from 19 to 22 October 2005 in Bologna. Sixteen scientists from eight countries (see list at the end of the volume) attended the seminar convened at the invitation of CIESM. They were welcomed by Drs Frederic Briand, Jean Mascle and Dimitris Sakellariou, who recalled the main objectives and background of the meeting and expressed their appreciation for the top-quality logistic assistance provided by Dr Rossella Capozzi.

The workshop was dedicated to a critical review of our geological/geophysical knowledge on fluid seepages and related features (mud volcanoes, gas chimneys, gas plumes, authigenic sedimentation) and associated processes in the Mediterranean Sea, and in the Gulf of Cadiz and the Black Sea, its western and northeastern provinces. The consequences of fluid seepage on the deep biological environments, a subject of obvious importance, was deliberately left out of the discussions as it will be covered in a future CIESM workshop.

Why is the Mediterranean Sea region a unique place to study cold seeps?

In the early ’80s Italian researchers followed a few years later by scientists from the Tredmar program (Moscow State University and Unesco) described mud diapirs or volcanoes (MV) and mapped several MV fields on top of the Mediterranean Ridge in the Eastern Mediterranean. By the late ’90s systematic swath mapping (mainly, but not only, conducted by French laboratories) demonstrated the widespread occurrence of CS/MV in different geodynamic settings of the Mediterranean domain, from active to passive margins. Russian and German surveys discovered at the same time many fluid-releasing features in the Black Sea, while a consortium of European institutions initiated detailed studies of MV fields previously discovered by US scientists in the Gulf of Cadiz just at the western boundary of the Mediterranean Sea. It is by now well admitted

Fig.1. Location of the main MV provinces discussed during the workshop.

that the convergence zone, extending over almost 5,000 km long, from Azerbaijan over the Black Sea and the Mediterranean Sea to the Gulf of Cadiz and forming the contact between the progressively colliding African and Eurasian plates, constitutes one of the world's major provinces where hydrocarbon-derived fluids have been and are still massively emitted to the earth's surface both onshore (Azerbaijan, Apennines) and offshore, particularly in the deep sea (Figure 1). In the latter case features of gas-mud expulsion lead to specific deep geological/biological environments and may strongly impact the seawater chemistry and possibly climate as well.

What are cold seeps and related features?

Cold seeps are geological features generated by emissions of fluids (of non magmatic origin) such as mud, liquids and gases and are occurring on both land and at the seafloor. Depending on their settings they are characterized by distinct morphologies.

Although cold seeps also include features such as groundwater discharge, we mainly focused during this workshop on deep-rooted emissions (several kilometres) and associated surface expressions such as mud volcanoes. As the fluids are generally hydrocarbon rich, cold seeps frequently lead to the establishment of specific and 'extreme environment' ecosystems.

Morphologic features usually related to cold seeps include carbonate mounds and carbonate crusts, pockmarks, mud volcanoes, mud domes, mud diapirs, and gas chimneys. In the marine environment, gas hydrates, and their dissociation, are believed to frequently play an important role in fluid emission.

Why study cold seeps?

Although cold seep structures have been known for a long time (since ancient Greek times!) their impact on the sea floor and environment, their mechanisms of emplacement, as well as their importance in the geological records are still poorly understood.

However, marine geological/geophysical surveys from the last decade have shown that these features are abundant and common on continental margins, where they actively participate in the shaping of continental slopes. Along continental margins cold seeps may impact the stability of submarine slopes (e.g. through the dissociation of gas hydrates) and resulting geohazards (tsunamis).

Gases emitted (mainly methane) by these features are also believed to play an important role on both regional and global carbon and fluid budgets, as well as on global climate through the expulsion of greenhouse gases.

Through microbiological activities induced by cold seeps, these also support the development of chemosynthetic ecosystems and consequently provide windows to the deep bio- and geospheres.

Finally cold seeps also provide a window to deep hydrocarbon systems both on land and onshore, which is of economic interest.

2. Overview of past research

A quick review of recent and current research on cold seeps is given along a West-East transect from the Gulf of Cadiz to the Black Sea passing through the Mediterranean Sea. A few selected examples from active and past cold seep activities occurring on land were also discussed during this workshop (see Figure 1).

Gulf of Cadiz

The Gulf of Cadiz and the W. Alboran Basin form an area of extensive hydrocarbon-rich fluid seepage, located in the tectonically active westward front of the Betic-Rifian Arc, close to the Africa/Eurasia collisional plate boundary (Henriet *et al*. and Pinheiro *et al*., this volume). Since the recent discovery of the first mud volcanoes and gas hydrates in this area in 1999, a large number of fluid escape structures has been evidenced, which include numerous mud volcanoes (41 confirmed by coring), mud diapirs, pockmarks, carbonate mounds, large fields of methane-derived authigenic carbonate chimneys and crusts, and cold water coral communities (see Henriet *et al*., this volume). Many of these structures are active, with extremely interesting associated ecosystems that include both chemosynthetic macrofauna and microbial consortia; the latter have had a crucial role in the precipitation of the authigenic carbonates. The extensive carbonate chimney fields are a fossil record of extensive fluid expulsion, and its dimensions, up to now, are unique in the world (see Pinhero *et al*., this volume). The fact that the fluid escape structures in this area form a continuum from deep water (3,880 m) to the shallow continental slope/shelf and to onshore outcrops (see Hamoumi *et al*., this volume) makes it an excellent laboratory to investigate these systems. The occurrence of large mud volcanoes, relatively close to the Moroccan shore, offers promising opportunities for observation science (long term monitoring through surface and borehole instrumentation) (see Figure 2).

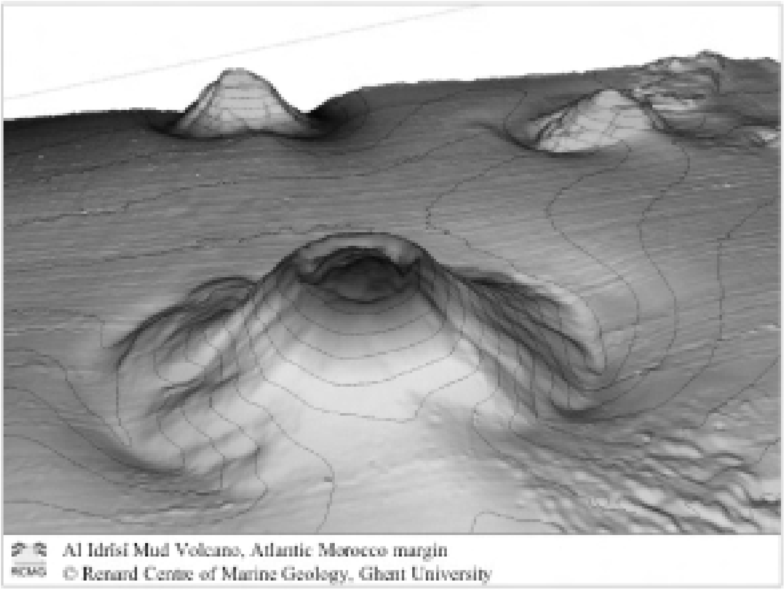

Fig.2. 3D view of Idrisi MV on the Moroccan Margin.

Calabrian Arc

The Calabrian Arc (CA) is an accretionary wedge generated by the subduction of the African plate under the European one. It is believed to be a rather young (ca. 5 Ma) and still active feature that extends (SW-NE) for about 300 km offshore the SE tip of Italy (Calabria) and connects to the Mediterranean Ridge (MR) on its NE termination.

Whereas the MR has been the focus of extensive modern geosphere and biosphere investigation during the last decades (see Huguen *et al*., this volume) - in particular concerning cold seeps and mud volcanism - the CA remains a largely unknown geo/eco system. Nevertheless, due to its similar tectonic setting, the CA is likely to contain features (and show mechanisms) related to cold seeps and mud volcanism comparable to those already described elsewhere. Sonar data (Gloria) collected in the ’60s and reinterpreted in 1981 show a few high backscatter patches indicating potential cold seeps within the backstop of the feature. In addition, high and low resolution seismic data recorded in the ‘70s showed features (also sampled by coring) interpreted as mud diapirs, this interpretation being supported by the compressive tectonics of the area. In order to investigate the occurrence of cold seeps and mud volcanism on the CA, a geophysical survey was carried out in summer 2005 by OGS (within the HERMES Integrated Project) (see Ceramicola *et al*., this volume). A new province of mud volcanoes (some of them proved to be still active) has been discovered. The starting study of these features is likely to bring new insights in the driving mechanism regulating cold seeps occurrences in active continental margins, their feeding system and their relevance to geosphere-biosphere interactions.

Mediterranean Ridge

Today the Eastern Mediterranean is undergoing a complex geodynamic evolution which results from interactions between various plates, including the northwards moving Arabic and African plates now almost in collision with the SW moving Aegean-Anatolian microplate and the European plate. Along this major converging system (extending from South-West Peloponese to southern Turkey), a main morpho-structural feature is particularly prominent: the Mediterranean Ridge (MR), a large, arc-shaped, accretionary wedge, more than 1500 km long and 200-250 km wide.

As on many other active margins, a large number of mud volcanoes have been described all along the southern Aegean active plate boundary, from its Ionian junction with the Calabrian Arc (CA) up to the vicinity of the Levantine margin. Since their initial discovery (in 1981), on the seafloor of the MR south of Crete, these sedimentary features have been investigated using a large variety of tools. The distribution, morphology, backscatter characteristics, and subsurface structures of MR mud volcanoes have been described in a number of publications and several hypotheses have been put forward concerning the source, age, and emplacement of the extruded mud, the various mechanisms leading to its extrusion, and the consequences on the surrounding deep biological and geological environments.

Over the MR, more than one hundred mud volcanoes have now been identified (see Huguen *et al.*, this volume). Usually these MVs are characterized as dome-shaped morphological structures, with diameter ranging up to 10 km, but are only a few hundreds metres high (see Figure 3). On backscatter data they are often associated with large highly reflective patches indicating recently extruded mud flows. Most of the MVs are located along, or nearby, the MR backthrust area and most of these mud constructions are clearly tectonically controlled, being emplaced on structures associated to the frontal convergence between African and Aegean plates. Compression is therefore believed to be the main driving force leading to massive expulsion of overpressured mud on the seafloor. The relationship between mud constructions and transcurrent faulting is particularly well established in the western and central MR. On the central MR, *in situ* studies have indicated various degrees of activity and stages of evolution of the Mvs. Some of them are inactive, or dormant, in term of mud or fluid expulsions and are now covered by pelagic sediments. Others are associated to important brine and gas expulsions, well-developed authigenic carbonate crusts and biologic communities. For example on Napoli MV, one of the most studied MVs lying south of Crete, carbonate crusts and concretions, mainly made of aragonite or magnesian calcite (Gontharet *et al.*, this volume), show higher $\delta^{18}O$ values,

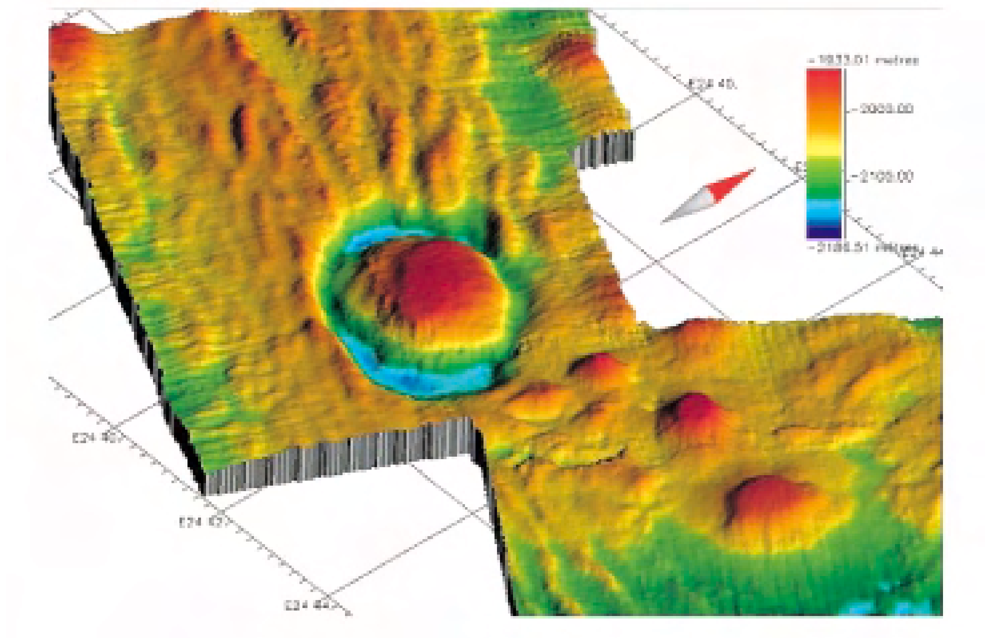

Fig.3. 3D views of Napoli and Milano MV on the Mediterranean Ridge (2,000 m water depth).

indicating a contribution of ^{18}O-rich fluids most probably originating from brines or clay dehydration (de Lange *et al.*, this volume).

Anaximander Mountains

Located on important highs (Anaximander Mountains, -AM-, south west of Turkey) just to the east of the easternmost corner of the MR, the AM mud volcanoes were discovered several years ago during a survey of the R/V '*L'Atalante*' (ANAXIPROBE project). A series of further expeditions (R/V '*Gelendzhik*' 1996, R/V '*Professor Logachev*' 1999, R/V '*Pelagia*' 2003, R/V '*Aegaeo*' 2003, 2004), combined with a few submersible dives (Medinaut in 1998) documented extensive mud expulsions, methane seeping, the presence of gas hydrates and associated deep biosphere within the AM. Among the five major mud volcanoes (see Lykoussis *et al.*, this volume) (Athina, Amsterdam, Kazan, Kula, and Thessaloniki), the latest four bear evidence of sub-surface gas hydrates (0.5-0.8 m below seabed). Amsterdam MV is so far the largest and the most active feature in terms of volume and extent of erupted mud breccias as well as in term of gas hydrate occurrence. Thessaloniki MV is the shallowest volcano bearing gas hydrates in the Mediterranean (1,260 m); it lies at the edge of the stability zone as determined from the depth and the seafloor temperature (~14ºC). The gas hydrates at Thessaloniki MV are thus sensitive to temperature changes and sea level fluctuations and therefore could be regarded as an ideal site for studies of MV activity, environmental impact and gas hydrate stability. According to litho-biostratigraphical analyses of mud and rock clasts (see Ioakim, this volume) two distinct palaeogeographic domains existed in the area prior to the initiation of mud volcanic activity. Mud volcanism in the eastern area (Kula, Kazan MVs) erupted clasts from the Anatolian Nape complex (Late Cretaceous limestones, Paleocene siliciclastic rocks, and Miocene mudstones and ophiolitic material) and related to the Cyprus Arc. The western province (Anaximander, Athina and Thessaloniki MVs) indicates a series of Late Cretaceous limestones, Eocene-Oligocene biogenic limestones, and Miocene mudstones which may belong to the easternmost Hellenic Arc.

Cyprus Arc

A smaller, also arc-shaped, feature, the Cyprus Arc (CyA), initiates south of Turkey (Anaximander Mountains), and includes the Florence Rise, the Cyprus margin, the Larnaka and West Taurus ridges; it finally stretches towards the Levantine coast off Syria. Over this subduction-collision related system only a few mud volcanoes have been identified up to now. In the Florence rise some MVs are likely active (or recently active) according to their backscatter signature, on the CyA most MVs appear as buried structures, only characterized by smooth morphologic conical shapes and devoid of any specific backscatter signature. On seismic data these structures show typical MV seismic signatures, such as a reflection free facies as well as, on both sides, inward dipping reflectors. On the eastern CyA, MVs are chiefly located on structural trends interfering with salt tectonics.

Nile Deep Sea Fan

The Mesozoic rifted continental margin along the southern corner of the Eastern Mediterranean includes the Nile Deep Sea Fan (NDSF) and the Levantine Margin; it is a thickly sedimented margin blanketed with total sedimentary thickness up to 12/13 km in the offshore Nile area. It is also an area of intense seepage activity discovered in 2000 (see Huguen *et al.* and Dupré *et al.*, this volume). On the NDSF fluid seeping distribution is controlled by a complex interplay between deep rooted regional and shallower salt-related tectonics acting as conduits on one side, and sedimentary instabilities on the other side. A wide variety of fluid venting features have been evidenced on the NDSF seafloor: mud cones, wide caldera-like depressions, gas chimneys (up to 4 km in diameter), brine pools, pockmarks and carbonate mounds, all associated with active gas escapes, authigenic carbonate crusts (see Gontharet *et al.* and Bayon *et al.*, this volume) and various chemosynthetic communities. The NDSF area has been divided into several morphostructural provinces. The western one, currently the most active domain of the deep terrigenous cone, contains tens of small-scale mud cones (a few hundred metres in diameter) and a few wide calderas (several km in diameter) all occurring at the base of the continental slope, and upper slope gas chimneys. The seafloor in the central province, submitted to numerous sedimentary instabilities and slides, is scattered by numerous pockmarks, carbonate mounds and pavements. An eastern province, bounded on its western side by a major transcurrent fault zone, is strongly controlled by salt tectonic activity. Gas chimneys, not restricted to one or the other of these provinces, delineate all along the NDSF upper continental slope a "degassing" belt.

Black Sea

Cold seeps in the Black Sea are known since ancient times as Greek authors described gas flares in the Black Sea region both on land and at sea. More recently marine exploration using multibeam bathymetry, sidescan sonar and seismic systems allowed the identification of many mud volcanoes, gas emissions and gas hydrate deposits in the entire Black Sea Basin but mostly along its margins (see Klaucke, this volume). Sedimentological and geochemical works on clasts from Black Sea MVs showed that the material and fluid composing the mud volcanoes have a common origin which is the Late Oligocene to Miocene "Maikop Formation" consisting of an up to 1,200 m thick succession of mudstones. In the absence of macrofauna in the deep anoxic basin, bacterial activity results in the formation of carbonate crusts, mainly through cementation of coccolithic carbonate oozes.

More detailed studies focusing on specific mud volcanoes determined geochemical fluxes of Li, B, CH_4 and other chemical components into the Black Sea Basin and their implication on the chemical budget of the Black Sea. Methane emissions in the Black Sea are extremely important and regional inventories of emission sites have been carried out together with budgeting the methane reservoirs at a basin-wide scale. In addition, the fate of methane in the water column has been studied in detail and the amount of methane entering the atmosphere has been quantified through both measurements and geochemical modelling.

Onshore examples

Fossil seep deposits

Studies on ancient seep/vent deposits cropping out in the Mediterranean region developed at a slower pace compared to the modern offshore seep settings (see Barbieri and Cavalazzi, this volume). Fossil seep carbonates were firstly discovered at a worldwide scale from Miocene deposits of Piedmont (Italy), and the ongoing research has been mainly concentrated on the identification of seep paleoenvironments, the geological implications, the type and amount of fluids involved, and the paleontological inventory from discrete geographic areas, such as the classical sites of the Apennines and Beauvoisin (southern France). Recent discoveries (2000) of Oligo-Miocene mud volcanoes in the Moroccan Rif belt have received geological and geochemical investigations (see Hamoumi, this volume). Whereas Mesozoic and Tertiary paleoseeps have been comparatively better investigated, Palaeozoic (even more ancient?) seeps are still at the beginning of their study. In the Mediterranean region, the best geological products of Palaeozoic cold/vent seepage occur in northern Africa (Silurian and Devonian of Morocco and possibly Algeria), and the Middle Atlas region (Morocco) hosts the oldest known (Silurian) paleoseep ecosystem. Past research on the Devonian conical mound deposits of Morocco (Hamar Laghdad and Maider basins) has focused in the stratigraphic context, some paleontological inventory and geochemical investigation (see Barbieri and Cavalazzi, this volume).

Modern onshore seepages

Surface seeps of gas, oil, and saline waters presently occur along the Adriatic side of the Apennine chain (see Capozzi and Picotti, this volume) (Figure 4). They have been considered to be indicators of deep-seated hydrocarbon accumulation and have been used, for more than 60 years, as a guide to hydrocarbon survey. A wide spectrum of seepages belongs to different geologic settings, within the uplifting chain, along the deformed foredeep on land as well as in the Adriatic Sea. The origin of these spontaneous fluid emissions has been mainly discussed on the base of the isotopic composition of gases, for exploration purpose. Recently, additional data for the reconstruction of different migration pathways of fluids have been provided by geological studies coupled with geochemical and isotopic characterization of gas, condensates and on the chemical composition of the saline waters. These studies allow understanding the first-order control played by the local geological features, which generates a very rapid spatial variation of fluids vents and variation of the geochemical characters of the seepages.

Fig.4. MV near Modena. Northern Apennines.

3. Multi reconnaissance and functioning -scale

After two days during which regional and more thematically focused presentations were made, a general discussion was organized to identify scientific questions which arise from the presence of widespread cold seep/MV phenomena (almost unknown 10 years ago) within the Mediterranean Sea and adjacent areas. The participants discussed and agreed on seven key questions and possible strategies to tentatively answer some of them.

3.1. Geological context

The control of cold seep distribution, and of their variability, by the geodynamic/geologic setting appears as the first order parameter. This parameter is the only one that is relatively well established.

Within the Mediterranean domain as a whole, cold seeps and their most spectacular morphologic expression -*Mud volcanoes*- are preferentially located on active margins and especially within the different accretionary prisms. Tectonically accreted wedges constitute obviously domains where both sedimentary loading and compressive stresses are particularly important, and where natural pathways to the seafloor are generated by ongoing tectonic activity (Gulf of Cadiz, Apennines, Calabrian Arc, Mediterranean Ridge, Anaximander Mountains, Cyprus Arc, Black Sea pro-parte). Huge sedimentary accumulations and resulting sedimentary loading represent a second typical setting for occurrence of mud volcanoes (Nile Deep Sea Fan and pro-parte Black Sea) in the Mediterranean area (Figure 4).

Many morphologic similarities exist between MV features from different geological settings (size, shape, presence of mud flow, authigenic carbonate crusts, microbial activity, etc.). Differences in the geodynamic/geological setting as well as in source rocks, in nature, volume, pressure of fluids, may however induce significant differences in the surface signatures of fluid emissions and consequently in their morphologic expressions. For example the presence of brines, gas hydrates, carbonate chimneys is not ubiquitous among the various features discussed during the workshop. More specifically, massive and thick Messinian formations in the Mediterranean Sea act as geological seals, generate specific tectonics, and have obviously played a major role in fluid seepage functioning and distribution. One of the important recommendations raised by the participants is to favor and increase comparative studies between different MV settings to better evaluate their common geological parameters. It appears also important to take advantage from onshore existing data where observations are far easier to handle, even if other environmental parameters are interfering in this specific setting.

3.2. Why cold seeps are being formed?

In order to be formed cold seeps need at first an underlying organic-matter rich source rock where thermal or microbially-induced degradation may occur. Fluids issued from this degradation will circulate into the sediments and will be stored at shallower sedimentary levels, if a necessary seal prevents them to progressively diffuse on the seabed. Such seals could be either geological seals such as for example the Messinian evaporites in the Mediterranean Sea, or secondary "physical" seals such as hydrates where important quantities of gas can be trapped. Fluids are then progressively concentrated and later discharged to the surface, if there is enough overpressure (in the case of geological seals) or adequate pressure/temperature variations (in the case of gas hydrate dissociation). This holds true if the necessary pathways such as fractures and faults exist. Among the questions to be addressed are: what are the driving mechanisms of fluid uprising? How do the feeding systems function? What are the impacts of fluid discharges on deep and shallow geo-biosphere environments?

It is fundamental to recognize and characterize the initial/deep signal (= original composition) of fluid/gas and their effect on the diagenesis.

Others crucial questions to be addressed concern the relationships between gas hydrates (formation, stability, microbiology) and gas emanation into the water column.

3.3. How are cold seeps functioning?

By analogy to lava-volcanoes, MVs are characterized by strong spatial and temporal variability. They may be explosive, eruptive, intrusive and appear to have different periodicities of (major) activity (like Stromboli compared to Vesuvius, and Napoli MV compared to Milano MV in the Eastern Mediterranean). Clearly there is no direct observation of any major MV event, but evidence is overwhelming that such events have occurred in the past and will happen again. The periodicity of activity phases clearly will have an impact not only on the amount of fluid flow but also on gas fluxes into the water column (and subsequent microbiology) and on the potential stability of gas hydrates.

We still know almost next to nothing on the duration and cyclicity of cold seeps, even though a few attempts have been made recently to sample by shallow drilling different mud flows around some MV in the Eastern Mediterranean Sea. Are fluid emissions submitted to cyclic activity? If yes, at which time scale? Do MV show intense activity phases and then are dormant before being refueled? Are small fluid emission centers such as pockmarks functioning similarly to bigger features (MV)?

The participants agree that the only way to tentatively answer some of these questions will be to develop long term basic monitoring (temperature, salinity, methane flux, etc.) in order to record direct activity signals, to assess MV variability (of moderately active MV), and to record the signal in the surrounding environment. Finally, the relationship between cold seep activity and seismicity should also be determined and eventually estimated.

3.4. Fluxes

Most of the time fluids from cold seeps are referred to as methane, carbon dioxide and hydrogen sulfide. Gases heavier than methane (ethane, propane), indicating underlying hydrocarbon systems, have been discovered locally, but the amount and variability of the different gases and other chemical compounds coming out of such features is still not known. Gas sampling is restricted to the seafloor or to shallow subsurface depths. As a consequence their composition may not be fully representative of the original composition of the gases when they formed in the source rocks.

Similarly, cold seeps are not necessary cold! Temperatures in excess of 60°C have been measured on some of the MV from the Nile margin indicating high temperature at depth. Heat flow measurements are still very scarce. Such measurements are, however, absolutely necessary to tentatively model the physical functioning of MV.

3.5. Cold seeps and gas hydrates

Some cold seeps/MVs are located in gas hydrates provinces, and gas hydrates have effectively been sampled on several of them (Gulf of Cadiz, Anaximander Mountains). In the Mediterranean Sea, the majority of MVs lies in areas where no evidence of gas hydrates has yet been found. Is the occurrence of gas hydrates only controlled by the combined effects of pressure/temperature? Why are there mud volcanoes with gas hydrates and mud volcanoes without gas hydrates?

In some areas free gas bubbles can be observed while being within the gas hydrate stability zone? Why? Is this due to gas saturation?

Is the MV activity variability related at some stage to decomposition/formation of gas hydrates?

3.6. Seeps and life

Cold seeps have a direct impact on deep sea biological environments. The degradation of gases and other chemical compounds by consortia of bacteria and archaea lead to progressive colonization by Metazoan (Figure 5). The highly contrasted Mediterranean Sea fluid seepage record may allow to answer the following open questions:

- what is the response of life (bacteria, metazoan) on fluid seepage in the full range of oceanic environments, from fully anoxic (Black Sea end term) to fully oxic (Atlantic end term) conditions?

- how does life in such environments control mineral precipitation (carbonate crusts, chimney fields) and transformation (early diagenesis in pelagic sediments and carbonate mounds)?

- what is the importance of cold seeps during the course of the Phanerozoic?

- can present day cold seeps be considered as analogues to similar associated geo/bio-processes in the past?

- is it possible to match fossil cold seep occurrences with geodynamic events?

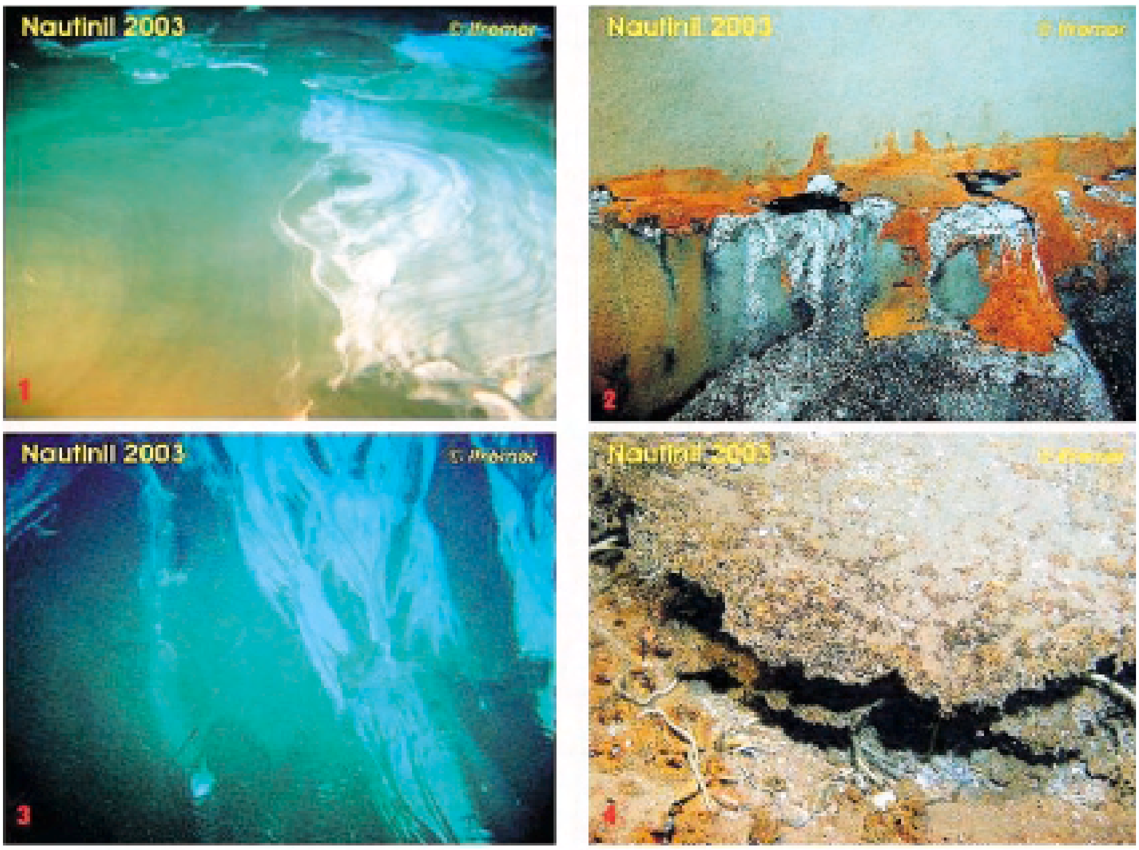

Fig. 5. Nautinil views of fluid seepages on the Nile Deep Sea Fan.
(**1**) Brine lake by 3,000 m water depth; (**2)** Bacterial aggregates on fluid seepages (3,000 m. water depth); (**3**) Bacerial filaments and flowing brines (3,000 m. water depth); (**4**) Authigenic carbonates, worm tubes and shells (2,000 m. water depth).

3.7. Cold seeps and their mineral/sedimentary environments

Understanding the processes of anoxic diagenesis in relation to different kinds of carbonate formation and their composition (including carbonate chimneys, crusts) is an important issue. Once understood the carbonate composition can be diagnostic for the processes involved.

The mineral record

Are recent seep-related mineralizations and their biological controls a key to understanding palaeoseeps, and vice-versa? (see above)

Do mineral precipitations and transformations provide us with a long-term record of fluid seepage?

The sedimentary record

Beyond the spatial extent of mud lobes and the local direct fluid-related mineralizations, can we read within the proximal pelagic sedimentary sequence a comprehensive and undisturbed record of the activity and periodicity of a fluid seepage / mud volcanic system (e.g. fall-out from explosive events and plumes)? What are the diagnostic features, the proxies that we may use to infer such processes?

4. Strategy and tools

Two types of studies are considered: (a) exploratory studies remain important issues considering for example that 10 years ago MVs were identified only onshore and partly in the Black and the Mediterranean Seas and (b) process-oriented studies are needed to understand the functioning and environmental impacts of cold seeps.

Exploratory studies

Onshore: onshore exploratory studies need to include among others remote sensing, mapping, morphostructural and stratigraphic analyses, and sedimentological studies. Particularly, the knowledge on the geotectonic/geological setting of active onshore cold seeps and MV may and should be used as guide to the search for fossil structures in similar settings of the past.

Offshore: recent experience shows that further swath bathymetry and back scattering research in standard scale in combination with other geophysical measurements is necessary before the list of the existing cold seeps occurrences in the Mediterranean and the Black Seas and the Gulf of Cadiz is completed. Deep penetration reflection-refraction seismic together with high resolution and 3D reflection seismic studies are needed to shed light to on deep seated source rocks, the possible conduits and feeding channels, as well as the detailed structure of the cold seeps and MV. High resolution micro-bathymetry, back scatter data and deep-tow vehicles are needed for a detailed image of the seep-structures and as a basis for more detailed bio-geochemical studies.

Process oriented studies

The participants of the workshop highlighted on the need for process oriented studies aiming at a better understanding of all kinds of mechanisms responsible for the formation of cold seeps phenomena. The following list of key studies may be considered as indicative and is by no means exhaustive:

- direct seafloor observations by ROVs and other specific tools may provide valuable data on the physics of active seeping and the relation between gas and brine flows;

- together with targeted short and/or long coring and subsequent laboratory analyses, they may provide insights into the largely unknown geochemical, biogeochemical and geo-microbiological processes related to the formation of, or triggered by, the cold seeps;

- novel geochemical techniques to be developed are needed to give answers;

- measurements of geotechnical properties of the mud flows are needed to better establish slope stability issues and possibly differentiate between successive flow episodes;

- the use of autoclave samplers, which will lead to the retrieval of samples under *in situ* pressure conditions, will enable the performance of innovative analyses in the laboratories;

- *in situ* measurements of temperature, salinity, and pore-pressure may shed light on the functioning of cold seeps, particularly fluxes like heat flow and fluid flow;

- the deep biosphere associated with cold seeps, the episodicity/periodicity of their activity as well as the flow stratigraphy of the MV and within the surrounding sediments need to be accessed by targeted drilling or transects of drill-holes on MVs– off MVs;

- deep fluid circulation and flow through the possible conduits may be well studied by the proper borehole instrumentation (CORK);

- last but not least, dating through improved isotopic techniques, was raised during the workshop as an absolute necessity in order to better understand the fourth dimension of cold seeps processes and the formation of structures.

Monitoring – benthic observatories

Significant variations of MV activity with time have been proven by direct observations obtained during successive cruises devoted particularly to MVs of the Mediterranean Ridge. Thus, monitoring of mud volcanoes and related processes constitutes a major task as cold seeps research evolves.

Two types of monitoring were addressed during the workshop and should be considered as a valuable technique to be included in future research initiatives: short term monitoring and long term monitoring.

In both cases among the parameters to be monitored should be micro-seismicity and its relationship with pore pressure, geochemical variations of fluids, ecosystems variability and temperature variations.

Future research efforts should focus on the deployment of benthic observatories equipped with the proper sensors which will allow the research community to monitor for the first time processes in real- or near-real time.

Modeling

Laboratory modeling may answer questions such as geological controls, episodicity, etc. Numerical modeling is however absolutely necessary to understand the physical functionning of cold seep features and particularly MVs. The temperature and geochemical properties of fluids and sediments expelled at MVs commonly differ significantly from the regional background values and therefore create anomalies of the heat flow and geochemical pore water composition. Quantifying these anomalies in time and space yields information on the nature and strength of MV activity. Numerical modeling provides a link between the different fields of observations, helps to identify the key processes that control the activity of the MV, and yields important information for planning further research. As the transfer of heat and the transport of chemical compounds in pore water are associated with different time scales, coupled geothermal and geochemical models are particularly promising for reconstructing the evolution of MVs. In addition, viscous flow models help to understand the relationship between the rheological properties of the mud and the various different topologies of MVs observed on land and on the seafloor.

5. RECOMMENDATIONS/STRATEGY

As the Mediterranean Sea cold-seeps system, from the Gulf of Cadiz over the Mediterranean Sea to the Black Sea, is by no mean exhaustively surveyed and even less understood, the need for further research towards all previously mentioned directions was stressed by all workshop participants.

Exploratory studies

Enhanced efforts should be undertaken aiming at comparing offshore cold seeps with similar structures, both active and fossil, occurring on land. Further on it is highly suggested that the present day knowledge on the geotectonic setting and the occurrence of mud volcanoes and cold seeps preferentially on the accretionary prisms of the Gulf of Cadiz, the Calabrian Arc and the Eastern Mediterranean Ridge should be applied and guide future research in order to locate similar phenomena in comparable geotectonic environments, such as the flysch deposits, of the Alpine orogenic belt around the Mediterranean Sea.

Further exploratory efforts, based on swath bathymetry, backscatter imaging and various seismic techniques at different levels of resolution, are needed in order to possibly achieve the most complete pattern of cold seeps outcrops on the seafloor of the Mediterranean Sea, including the Gulf of Cadiz and the Black Sea.

Exploratory studies should also include comparative studies of cold seeps on different geotectonic settings and try to decipher the way geodynamic processes and the presence/absence of Messinian salt control their formation, functioning and variability in activity.

Process oriented studies and monitoring

Process oriented studies should focus on specific cold seeps sites where a large data set already exists.

Active processes of fluid flow in and around mud volcanoes, including both microbial and metazoan associated ecosystems, form a straightforward target for long term observation (see also Henriet *et al*., this volume). On- and off-MV drilling transect may shed light on the temporal activity at various time-scales and may also provide evidence within the sedimentary record round them.

Process oriented studies should target among others the delineation of the initial composition of fluids and gas. As highlighted during the workshop (see also de Lange *et al*., this volume), chimneys offer a window to fluid and gas of rather initial composition compared to that at the sediment surface. Thus, actual sampling of fluid and gas at depths of a few hundreds meters below active chimneys is a real challenge, both technically and analytically.

Further on and in analogy to the Maikop Formation, which constitutes the common source rock of fluids seeping out from the Black Sea floor, efforts should be taken to identify potential source rocks in the various settings of Mediterranean Sea and Gulf of Cadiz cold seeps fields.

A fundamental target of future research should be to establish the control of different flow patterns on the morphological structure of the cold seeps. Once a cold seep is being formed, what parameters, and in which way, are responsible for the development of the one or the other cold seep structure?

The necessity of long term monitoring and the deployment of benthic observatories on key structures were already pointed out earlier. The participants agreed that beyond and in excess of any exploratory and process oriented studies, a major effort should be made to be able to monitor major parameters associated with the activity of known cold seeps.

In conclusion the workshop participants wish to stress the following principles:

- ***cold seeps need to be studied in an interdisciplinary framework;***

- ***they will provide a fertile ground for a welcome, enhanced trans-Mediterranean cooperation.***