1. INTRODUCTION

The workshop was convened in Bucharest, Romania, from 5 to 9 June 2002. The meeting benefited from the kind hospitality and the perfect organization of the GEOECOMAR Institute. During these four days, 20 scientists from ten countries (see list at end of volume), plus a few guest researchers from GEOECOMAR and the Geological Department of Bucharest University, attended this seminar on the invitation of CIESM.

After welcoming remarks by Nicolae Panin, Director of GEOECOMAR and Corneliu Dinu from Bucharest University, the meeting was opened by Frédéric Briand, Director General of CIESM, followed by Jean Mascle, Chair of CIESM Marine Geosciences Committee and coordinator of this workshop, who briefly presented the context, background and objectives of this event.

1.1. Background and objectives

Turbidite systems and deep sea fans are particularly developed all along the continental margins of the Mediterranean and Black seas. Both of these marine basins are surrounded by major mountain ranges and, as a consequence, prone to very high rates of clastic sedimentation. Moreover, within the recent geological past, both seas have been evolving in rapidly changing climatic environments, which have exerted strong impacts on the sedimentary supply and the relative sea level fluctuations. Finally, both land-locked seas are still surrounded by emergent areas with strongly contrasting environmental conditions.

The explicit aim of the workshop, at the onset, was not only to produce a general overview of our current stage of knowledge of the main turbidite systems and deep sea fans from these two seas, but also to compare processes active in clastic sediment in different structural, climatic, orogenic and orographic settings. During the first two days of the meeting, a total of 20 oral presentations addressed most of the major turbidite systems and fans studied in the western Mediterranean sea (including the Adriatic Sea and the Po River system), the Eastern Mediterranean and the Black seas.

After these first two days of presentations, two parallel sessions were organized to facilitate extensive discussions and explore future paths for research on more focused topics. The first working group, led by John Damuth and Neil Kenyon, concentrated mainly on the architecture, depositional processes and controls in fans and related systems. The second group, led by Christian Hübscher and Jean Mascle, focused on the importance of different structural controls, and the implications of fluid systems on deep-sea fan development. These open discussion sessions have allowed us to: (a) evaluate the best approaches, methods and models needed to refine our understanding of turbidite sedimentary processes and related deep sea fan construction and evolution; and (b) tentatively identify promising trends and targets for further research at regional and/or thematic scales. The final session included a general discussion where both groups presented their findings. The main conclusions are reported herein.

2. ARCHITECTURE, DEPOSITIONAL PROCESSES AND CONTROLS ON FANS AND RELATED SYSTEMS

The first working group outlined the problems that need to be addressed in the future concerning the architecture and depositional processes of deepwater and put forward some general guidelines for the methodology and tools to carry out such future studies. Three general components were identified and addressed: (1) architecture; (2) depositional processes; and (3) controls.

2.1. Architecture of fans and related systems

The working group agreed that a major task is understanding the variability of the overall architecture (size and geometry) of fans, deep-sea fans and related depositional systems, as well as understanding the variability of architectural elements (e.g. channel-levee systems, lobes, etc.) within these systems. If possible, this should be tackled at different spatial scales including, internal architecture of individual deepwater elements and detailed facies analysis.

Models for deep-sea fans and related systems are still too simple and incomplete, and need to be greatly improved (e.g. Damuth, this volume). This will require detailed comparative studies of the shapes (both lateral and vertical) and sizes of a wide variety of fans and other depositional systems. To date, “high-input” fans – those fed by rivers with very large drainage basins – such as the Nile (e.g. Bellaiche *et al.*, this volume), Danube (e.g. Popescu *et al.*; Panin *et al.*, this volume), Rhône (e.g. Droz *et al.*, this volume), Ebro (e.g. Alonso and Ercilla, this volume) and Po (Cattaneo *et al.*, this volume) have been the best studied systems. In contrast “low-input” fans, which are usually fed by small drainage basins and that form the majority of hinterland areas in the Mediterranean and the Black Seas, have not been investigated in any detail except around Corsica (e.g. oral presentation by Kenyon and Akhmetzhanov; see also Kenyon, CIESM Workshop Series, volume 13, pp. 91-94), on the Spanish margin (e.g. Alonso and Ercilla, this volume), and in a few other places. Poorly known areas off North Africa, the Caucasus Mountains and off the margins of Turkey, are particularly recommended for study. Individual elements of deep-sea fans also require further investigation. In particular, we need a better understanding of the transition zone from channel to lobe, and of the internal architecture of lobes themselves. A better understanding of the types and distribution of mass-transport deposits is also a high priority. Such studies will ultimately be needed to understand the growth patterns of fans and related systems.

The working group made several recommendations concerning the tools and methodology required in future studies.

• In all studies of fans and related systems, the highest quality swath-bathymetric mapping should be undertaken. Large portions of the Mediterranean and Black seas (perhaps as much as one half) have already been swath mapped, and the group strongly recommends that swath mapping of all unmapped areas be completed as soon as possible.

• Studies with deep-towed side-scan sonar and high-resolution reflection systems should be undertaken as well. These studies should use a “nested” approach, starting out at the regional to sub-regional level and systematically focusing on smaller and smaller fan elements and features. High-resolution refraction studies are also recommended.

• Where available, 3D seismic data should be acquired (from oil companies?) and utilized. Seafloor renderings of 3D data are as good as, and in many cases superior to, bathymetric swath data; and sub-seafloor 3D data can be used to map buried channel-levee systems, lobes, mass-transport deposits, fluid seeps and mud volcanoes and other fan elements in much greater detail than could be accomplished with 2D seismic data.

• Another promising approach to fan studies, which has been inadequate to date, is actual sediment sampling to “ground truth” the seismic and bathymetric data. A wide range of sampling tools is available. Short (< 20 m) gravity and piston cores are relatively cheap to acquire and can be used to define the surficial distribution of sediments for fan elements. Long piston-coring facilities, such as employed by the R.V. *Marion Dufresne*, can recover cores 20 to 50 m in length. Companies that do hazard studies for oil industry prior to drilling and platform emplacement could obtain “soil borings”, which are actually continuous cores that recover up to several hundred meters of sediment below the seafloor. With the initiation of the International Ocean Drilling Program in ca. 2005, the capability will exist to continuously core to depths of 1-2 km or even deeper on deep-sea fans. A major problem with coring on fans is recovery of sand intervals. Tools such as hydrostatically powered vibracorers, for example the corer operated by the British Geological Survey (limited to 2000m) or the Selcorer, (limited to 3500m), should be used to assess the best methods of sand recovery.

2.2. Depositional processes of fans and related systems

To better understand the growth patterns and evolution of deep-sea fans and related depositional systems, the processes that allow transport and deposition of sediments basinward must be fully understood. This will require much additional research. For example, understanding the distribution and the processes of sand deposits throughout a fan is not only important for unraveling fan growth and evolution, but also for predicting reservoir geometry to the petroleum industry. It is important to differentiate true turbidity-current deposits, which are the product of fluidal or turbulent flows, from other gravity-driven mass-flow deposits (such as debris flows), which are the product of plastic or streamline flows. The whole range of mass-transport processes, including slumps, slides and debris flows, must be better understood in terms of their contribution to the sedimentary budgets of deep-sea fans and related system. In addition to gravity-driven processes, other types of bottom currents, including contour currents, must be studied to understand their importance in continental margins and their interaction with downslope deposition. Lesser known currents need to be studied to determine their importance to depositional systems. For example, there are locations where strong density currents, called “cascading flows,” flow downslope from the shelf edge and may have profound effects on sediment redistribution and sorting. Also, the effects of internal tides in some limited areas might be important for moving sediments downslope. Study of hemipelagic and pelagic sedimentation is also necessary because these sediments accumulate more slowly and continuously and thus, provide good stratigraphic records for determining ages and sedimentation rates on deep-sea fans and related systems. In particular, relatively slow, but continuous deposition of terrigenous sediment by some type of gravity-driven flows (sometimes referred to as hemi-turbidite) can often provide stratigraphic zonation for deep-sea fans and related continental margin deposits. All these types of depositional processes must also be evaluated in terms of their frequency, cyclicity (if any) and the triggering mechanisms (e.g. hyperpycnal flows for turbidity currents; earthquakes or gas hydrate decomposition for mass-transport processes). More study is necessary to determine the differences between confined and unconfined flows, as little attention has been devoted to the latter, although they may be very important in this setting.

Another problem is determining the lateral and vertical distribution of sediment facies throughout various submarine fans and related systems. There has been little drilling to date on modern fans. As a result, turbidite facies associations and facies distributions are poorly known and there is at present no way to compare modern fans, which are known mainly from geophysical studies, with ancient deep-sea fans, which are known mainly from facies distributions in outcrops. Without thick vertical facies successions through the various architectural elements of modern fans, we cannot test fan models such as those of Mutti (e.g. thickening and thinning upward successions), which are based on thick outcrops. We also cannot accurately define the distribution of sand vs. shale in fans. Therefore a high priority should be placed on systematically drilling and continuously coring as many submarine fans and other systems as possible in the future.

In addition to the lateral and vertical facies distributions, we need more detailed studies of the growth patterns and depositional processes of various fan architectural elements. For example, does a channel-levee system bifurcate only by avulsion, or does branching also occur? Do braided distributary channel systems exist, and if so, under what conditions? Does bypassing occur and if so, under what conditions? We need also to study the formation, facies and detailed characteristics of lower fan lobes because, to date, we have a very poor understanding of these features.

Even if, to some extent, facies represent the result of deep water processes (there will always be an interpretative jump between observations and processes), the main type of data needed to study depositional processes, and to address the problems are long, continuous sediment cores which contain thick successions of facies from various elements of modern fans. Most likely these cores will have to be acquired by drilling. Suites of wire-line logs will also be quite helpful for facies determination, especially in determining sediment types for non-recovered intervals. The recent systematic drilling of submarine fan elements of Amazon Deep-Sea Fan during ODP Leg 155 in 1994 provides a model and, to date, the only example, of this type of coring program that is needed to study thick facies distributions and depositional processes on other modern fans (see references to ODP 155 results in Damuth, this volume). Once thick facies successions are recovered from modern fans, they can be compared to ancient fans known from outcrops to develop newer, more realistic models. Both core and geomorphic (geophysical) data from modern fans can then be utilized in modelling and flume studies to calibrate and develop better models of deep-sea fans and the depositional processes that create them.

2.3. Controls on fans and related systems

The participants recognized that there are several major factors that control fans and deep-sea fans deposition. It is important to weigh these in order to fully understand fan deposition and growth pattern.

• One major control is the sediment input from the continents. The amount, types and quality of the sediments entering the sea are important in determining the type and size of the fan or of other depositional feature that forms. These factors are determined by the size and relief of the drainage basin(s) (e.g, Alonso and Ercilla, this volume), as well as the rock types, tectonics and rainfall within the basin(s) (e.g., Bellaiche *et al.*; Panin *et al.*, this volume).

• Tectonics (structural heritage, thin-skin tectonics, etc..) also constitutes an obvious first order control factor (e.g. Gaullier *et al.*; Loncke *et al.*; Hübscher *et al.*, this volume) and is discussed in detail in Section 3 below.

• Sea-level fluctuations are another major control of deep-sea fan sedimentation. Glacial-interglacial cycles cause sea-level to fluctuate more than 100 m over 10 to 100 ky periods. This, in turn, may control the amount of sediment input to a deep-sea fan and cause large inputs during phases of lowered sea-level (glacial), and little or no input during high sea-level (interglacial cycles). During phases of sea-level lowstand, the Black Sea is cut-off from the Mediterranean and isolated (e.g Wong *et al.*; Lericolais *et al.*, this volume). During such periods of isolation, the Black Sea receives only fresh water, and effectively becomes a fresh-water ocean. In addition to glacio-eustatic sea-level changes, tectonic activity around the Mediterranean and Black Sea basins can cause relative sea-level changes.

• Climate is another important factor that affects deep-sea depositional systems. Regional and local climates throughout the Mediterranean and Black seas basins show much variability between glacial and interglacial fluctuations, in particular in terms of rainfall pattern; these changes affect the erosion of sediments and their transport to the sea. In addition, glacial melting probably introduced large amounts of fresh water into the Black Sea for brief intervals.

• A lesser, but important factor is anthropogenic activity. Damming of rivers (for example, the River Nile) has caused important changes in the sediment transport and discharge into the Mediterranean. This, in turn, can have significant effects on coastal dynamics, distribution and accumulation of contaminants and on fisheries. Although such man-made changes in the environment are extremely recent in relation to the time required to form the Nile Fan and other depositional systems, and thus have had little effect to date, they nevertheless must be understood and factored into predictions of future sediment input into the Mediterranean and Black seas. For example, on an afternoon in October 1979, in relation to a construction project, a sediment failure and consequent turbidity current occurred in the Var system; the associated tsunami fortunately had limited effect as the neighboring shore was somewhat deserted at the time.

The major type of data needed to study all these controlling factors are sediment cores of various lengths. Good stratigraphy is essential for identifying the timing and effects of glacial-interglacial and other climatic cycles and activity. Determining reliable and detailed stratigraphy, especially in the Black Sea, will require integration of several down-core measurements including bio-stratigraphy, chemical stratigraphy (e.g. isotope stratigraphy; salt vs. fresh water fluctuations in Black Sea), magnetic stratigraphy (susceptibility), tephrochronology, and physical properties. In any case, integration of different methodologies, such as coring and very high resolution seismic data, remains fundamental for this type of research.

3. Structural controls and fluid systems on fans and related systems

Several criteria might be used to subdivide deep-sea fans into different classes: e.g., recent *vs.* ancient fans, active *vs.* passive margin fans, or point *vs.* multiple feeder systems. However, several of the workshop presentations have pointed out that structural controls at various scales of deformation can profoundly affect fan construction both directly and indirectly. For example, gravity tectonics causing salt or clay deformation has direct impacts at the scale of an entire margin, whereas mud volcanoes, fluid seeps, small scale sediment failures, caused by overpressured shales or by sedimentary load, are frequent phenomena in fans, which locally, but significantly, interfere with deep sea fan construction.

Based on observations that deep pre-existing structures represent an additional and fundamental controlling parameter, the group first discussed the impact of these pre-fan structures and then discussed fluid systems and their influence on deep-sea fan evolution and dynamics. The group introduced a classification dependent on the presence or absence of an interbedded mobile layer deformed by gravity tectonics, which can be salt (e.g. the Nile and Rhone fans), but can also consist of shale as observed beneath the Niger Fan in the Atlantic. We believe that the presence or absence of such mobile layers constitute a fundamental controlling factor for deep sea fan evolution. For this reason, we identify two distinct models which we respectively name:

(1) Mobile Layer Model (MLM) (e.g., Nile, Rhone, Valencia, Var Ridge Fan),

(2) Non Mobile Layer Model or Stable Layer Model (SLM) (e.g., Almeria, Danube-Dniepr Fan).

We first discussed major structures and processes, which have to be studied at several depth intervals. We outline the various controls that must be taken into account for fan construction and evolution, and that depend of the presence, or absence, of a mobile layer. We suggest several fans on which to focus future research.

3.1. Control by pre-existing deep crustal or basement structures (valid for MLM and SLM)

Understanding of the crystalline basement, and of its variations in space and time, is crucial to further elaborate both the MLM and SLM models. In particular it appears important to investigate:

- basement (thickness, geometry, flexures, faults, oceanic *vs.* continental origin),
- geodynamic setting (regional stress field, active and/or reactivated faults, earthquake activity),
- heat flow.

Any modeling attempt of the long-term response of the basement to sediment loading would require these parameters. A good understanding of the geodynamic setting is necessary to distinguish between basement tectonics and gravity tectonics within overlying salt or clay. To determine the causative process for sediment remobilization, other triggering processes must also be taken into account (e.g. sediment overload or gas hydrate destabilization).

3.2 Control by pre-fan sedimentary deposits (valid for MLM and SLM)

In most settings, deep-sea fans are deposited on pre-existing older sediment packages. These older units may consist of fans as well. The term “pre-fan sediments” includes here all previously deposited sedimentary units. Pre-fan sediments, and their interaction with the overburden of any kind, control both MLM and SLM deep-sea fans. The overburden of the pre-fan sediments appears influenced by different parameters such as:

- geometry,
- tectonic activity,
- lithology / compaction,
- fluid content (gas, water...),
- sediment tectonics.

Some pre-fan sediments may undergo more greater brittle deformation than the crystalline basement beneath. We can distinguish between pre-, syn-, and post-tectonic fan sedimentation, only if the upper boundary of the pre-fan sediments and their tectonic activity are well known. This is particularly important to understand any fan geometry.

3.3. Control by the presence of a mobile layer subjected to gravity tectonics (MLM only)

A mobile layer beneath a deep-sea fan causes drastic changes of the fan’s basement in space and time. Generally mobile layers can consist also of shale or mud. In Mediterranean fan systems a mobile layer consists of Messinian evaporites / salt. The following characteristics have to be taken into account for reconstruction of any 3D-evolution of a fan:

- geometry (thickness, lateral extension),
- lateral variability (litho-facies: salt / detritus),
- physical properties (viscosity, density, thermal conductivity),
- fluid permeability (faults),
- salt tectonic styles: upslope extension, mid-slope translation, downslope compression.

3.4. Fan architecture (valid for MLM and SLM)

3.4.1. General characteristics of MLM and SLM fans

Regarding the evolution of both types of fans, the following characteristics have to be considered:

- 3D-structure,
- lithological parameters,
- physical properties,
- geomechanical properties,
- chronostratigraphy,
- sedimentation rate,
- oceanography (e.g., bottom currents),
- sediment input,
- fluid (generation, migration, accumulation, escape).

Some of these characteristics have to be discussed in a specific way and on different scales. For instance, fluid traps can be dependent of large scale features like salt ridges. Mud volcanoes, mud “cakes” or pockmarks are mesoscale features, whereas chemoherms or bioherms are generally small scale structures. The identification and age determination of key seismic reflectors (chronostratigraphy) would significantly contribute to deep sea fans’ global analysis.

3.4.2. Specifics for the MLM model

Understanding the interaction between the mobile layer and the overburden represents a major scientific challenge, especially control of the mobile layer on:

- sediment transport (e.g., possible channelization of turbidity currents by salt structures),
- sediment remobilization (e.g., mass wasting processes triggered by salt tectonics),
- pressure field (affects compaction, faulting and therewith fluid flow),
- permeability anisotropy (affects fluid flow),
- fluid trapping (stratigraphic traps).

3.4.3. Specifics for SLM fans in the Black Sea

Isolation from the open sea during glacio-eustatic lowstands implies that the sea-level curve for the Black Sea may be significantly different than the world-wide eustatic sea-level curve. Therefore it is critical that a specific sea-level curve for the Black Sea be constructed.

3.5. Fluid systems (valid for MLM and SLM)

Most of the deep-sea fans represent high sediment accumulation areas with under compacted sediments caused by pore water overpressure in the upper sedimentary units. High-resolution seismic and bathymetry data provide evidence for hydraulic fractures, isotropic compaction, or tectonically controlled fluid escape structures (e.g. Nile and Danube; see Mascle *et al.*; Ion *et al.*, this volume). The impact of salt tectonics in MLM fans on the pressure field and, consequently on fluid migration, has been little studied.

Because of the high biogenic material in the sediment discharge of feeder rivers, deep-sea fans are considered to be important carbon sinks. Biogenic methane can be produced in the upper few hundred meters. In the easternmost Nile Fan, thermogenic gas is present in the Pre-Messinian and in gassy sediment above the Messinian evaporites (Hübscher *et al.*, this volume). Depending on depth (pressure) and temperature, gas hydrate may be formed. In the Danube Fan a peculiar succession of up to four BSRs (Bottom Simulating Reflectors) has been observed (Ion *et al.*, this volume) and must be investigated in more detail. The role of fluids in terms of slope stability and sediment remobilization must be investigated. Large scale mass-wasting deposits on the continental slope or small scale slumping e.g., on levees, are common.

3.6. Target areas

A possible target area for SLM fans in the Mediterranean is the Almeria turbidite system. The fans in the western Mediterranean or Alboran Sea are important targets where the interplay between transform faulting and fan evolution can be studied (Alonso and Ercilla, this volume). The isolation of the Black Sea during sea-level lowstands makes the Danube and Dniepr Fans, which both interfinger with each other in their distal portions (Popescu *et al.*, this volume; Wong *et al.* this volume) important target areas for future research. It will be necessary to distinguish within the upper-, middle-, and lower fans the effects of fluids on fan architecture, sediment remobilization, fluid migration and fluid escape structures (see Ion *et al.*, this volume).

MLM fans can best be studied using two end members of this model, the Rhone Fan and the Nile Fan (Droz *et al.*, Loncke *et al.,* Gaullier *et al.*, this volume). Many geophysical and drill hole data are already available from the Rhone Fan. Only a slight impact of fluids has been reported. The Plio-Quaternary sediment cover is very thick compared with the Nile Fan. Salt tectonic features are mainly covered by the overburden (Droz al., this volume). The other MLM end member, the Nile Fan, has complex dynamics and obvious important fluid related processes (Mascle *et al.*, this volume). Salt tectonics are more mature and better developed and expressed than at the Rhone Fan (Gaullier *et al.*, this volume).

3.7. Missing data and recommended acquisition methods

The desired knowledge about the deep structures, including the crystalline basement and the pre-fan sediment overburden, can likely be achieved by standard geophysical methods including seismic refraction, multi-channel seismic reflection, gravity and magnetics. Beside their extraordinary scientific importance, the target areas in the Mediterranean have the advantage that industrial seismic data are often available. Industrial drilling has been carried out in the Rhone Fan, the Nile Fan, and at the eastern Nile lobe off the southern Levantine margin (Hübscher *et al.*, this volume). Parts of the drilling results may be made available from the companies. The compilation of available industrial data should play in important role in future research.

For future science-motivated seismic research, we strongly recommend optimization of the trade-off between signal penetration depth and seismic resolution. The usage of ocean-bottom seismic techniques, where receivers (3k-ocean-bottom-seismometers or ocean-bottom-cables) and/or sources rest on or near the seafloor, will help in making an important step towards an increased characterization of fluid reservoirs. The entire set of seismic methods should include modern high-resolution sources, which cover the frequency range from some Hz up to 2 kHz (G.Gun clusters, GI-Gun arrays, waterguns, hydroacoustic sources). Because of their enhanced lateral resolution, deep-tow systems are recommended to investigate fluid-related structures like BSRs, migration paths, mud volcanoes and other escape structures. Generally there is a need for more high-resolution seismic grids to image the responding features in three dimensions. The use of monitoring systems to measure *in situ* pore pressure, coupled with coring devices able to preserve the fluid content of core for analysis, would also greatly improve knowledge of fluids (including shallow gas) within sedimentary successions.

Multi-channel seismic and gravity remain the best appropriate tools to analyze the entire mobile layer. On the Nile Fan, where salt tectonic features are very well developed and are expressed on the seafloor, swath bathymetry remains a very important and fast tool to map salt-tectonics features in wide areas. The evolution of the mobile layer can also be analyzed by digital or analog modeling.

The importance of heat flow measurements for fluid research and fluid potential maturation is generally underestimated. Because fluid flux is commonly accompanied by energy transport, the thermal field has a significant impact on BSR evolution.

Architecture of modern turbidite systems in different geologic settings on the Spanish margins (NW and SW Mediterranean Sea)

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INTRODUCTION

We present here a selection of some research activities of two modern turbidite systems in the NW Mediterranean Sea (Ebro and Valencia) and five modern turbidite systems in the SW Mediterranean Sea (Almeria, Calahonda, Sacratif, Fuengirola, and Guadiaro). These turbidite systems occur in different geologic settings: (a) passive margin (Ebro and Valencia) and (b) relatively active tectonic margin (Almeria, Calahonda, Sacratif, Fuengirola, and Guadiaro). The latter systems developed in an active tectonically region of the northern Alboran Sea that is characterised by a complex morpho-structural framework with several basins separated by structural highs.

The study of these turbidite systems has been focused to the architectural analysis with different degrees of resolution, from high and ultra-high resolution seismic, and sedimentological characteristics (Alonso *et al.*, 1985; Maldonado *et al.*, 1985; Alonso *et al.*, 1990; Alonso and Maldonado, 1992; Palanques *et al.*, 1994; Estrada *et al.*, 1997; Alonso *et al.*, 1999; Lebreiro and Alonso, 2000; Galimont *et al.*, 2000; Pérez-Belzuz *et al.*, 2000; Alonso, 2000). In all cases we have used the terminology proposed by Mutti and Normark (1991) about the architectural elements identified in the turbidite systems. This work shows two major themes:

• characterisation of critical factors of turbidite systems for understanding their geological evolution;

• stratigraphic architecture and sedimentary processes for establishing sedimentary models.

For the characterisation of critical factors we analysed four groups of variables/parameters:

1) source area features (area, river length, maximum height, morphology, types of source, valley axial gradient, and flood plain axial gradient);

2) morphology setting of continental margin (depth, width, and gradient of the shelf, slope, and base of slope);

3) deep marine basin (area, length, width, maximum depth, morphology, and type of tectonic activity;

4) turbidite system (area, depth, length, width, environment, and features of architectural elements).

Characteristics of the turbidite systems on the Spanish margins

The Ebro TS has an alongslope elongate shape (50 km long x 111 km wide) that develops at the Ebro continental slope and base of slope. It is fed by the Ebro River, shelf prograding wedges and multiple submarine canyons represented by short slope canyons (<10 km). The development of this system is truncated by the presence of a mid-ocean channel, known as the Valencia Valley. The initiation occurred at the end of the Pliocene and the major growth was during the Quaternary. The architecture model is composed of canyon-fill deposits, channel-levee complexes, which mostly have migrated southwards, and apron deposits.

The Valencia TS has an elongate lobe-shape (164 km long x 88 wide) that develops at the distal part of the Valencia Trough extending down to the Balearic Basin Plain. It is fed mainly by two point sources: one longitudinal, represented by the Valencia Valley (over 400 km); the other lateral, represented by the Blanes Canyon. The initiation of this TS occurred at the end of the Pliocene and the major growth was during the Quaternary. The architecture model is composed at least by canyon-fill deposits, channel-levee complexes, and channel-lobe transition deposits. The spatial and temporal distributions of the turbidite deposits involve significant upslope/ downslope migrations.

The Almeria TS has an elongate lobe-shape (99 km long x 30 km wide) that develops on the Almeria slope, base of slope and Alboran Trough. It is fed by the Andarax River, a relatively long submarine canyon (55 km) and several gullies that erode the slope deposits. The canyon mouth locates on the base of slope, at 1,200 m water depth, and the depositional area extends down 1,800 m along the Alboran Trough. The initiation occurred during the Upper Pliocene, and their deposits (canyon-fill, channel-fill, overbank, and lobe) have relocated since that time showing lateral and longitudinal migrations.

The Calahonda TS has a fan shape (15 km long x 14 km wide) that develops from Motril slope to base of slope (850 m water depth). It is fed by ephemeral rivers, shelf-deltas, several gullies that are eroding the front of shelf-deltas, and four small slope canyons. This system developed during the Quaternary. The architectural elements are: mass-transport deposits, canyon-fill, channel-levee complexes, lobe deposits, and drape deposits.

The Sacratif TS is a fan shape (25 km long x 16 km wide) that develops from Motril slope to Motril Basin (890 m water depth). It is fed by the Guadalfeo River and two important slope canyons. The initiation occurred during the Upper Pliocene until present. The architecture model is composed of mass-flow deposits, canyon-fill deposits, channel-levee complexes, and lobe deposits. Its development has involved lateral relocation (towards eastern) of the channelised high-energy gravitative flows.

The Fuengirola TS has a fan shape (65 km long x 52 km wide) that develops from Fuengirola slope to Western Alboran Basin. It is fed by the Fuengirola Canyon (26 km long) and by shelf prograding wedges. This turbidite system has its maximum development during the Upper Pliocene, thereafter its sedimentary activity decreased until it ceased at the beginning of the Upper Quaternary. The architecture model is composed of canyon-fill deposits, channel-levee complexes, and lobe deposits.

The Guadiaro TS has an elongate lobe-shape (25 km long x 10 km wide) that develops from the Marbella slope to base of slope (800 m). It is fed by the Guadiaro River and by a short slope canyon (7 km). The initiation occurred during the Quaternary. The architecture model is composed of canyon-fill deposits, channel-levee complexes, and lobe deposits. Its depositional architecture indicates the absence of shifting of turbidite deposits.

Models and overview

On the basis of submarine feeder system the seven turbidite systems are grouped into two types (Fig. 1): (1) point-source turbidite system, and (2) multiple-source ramps turbidite system.

With regard to the point-source we differentiate those fed by a mid-ocean channel (Valencia TS), a canyon (Almeria TS, Guadiaro TS, and Fuengirola TS), and two canyons (Sacratif TS). In relation to the second type, we use the term “ramp” in the sense of Reading and Richard (1994):

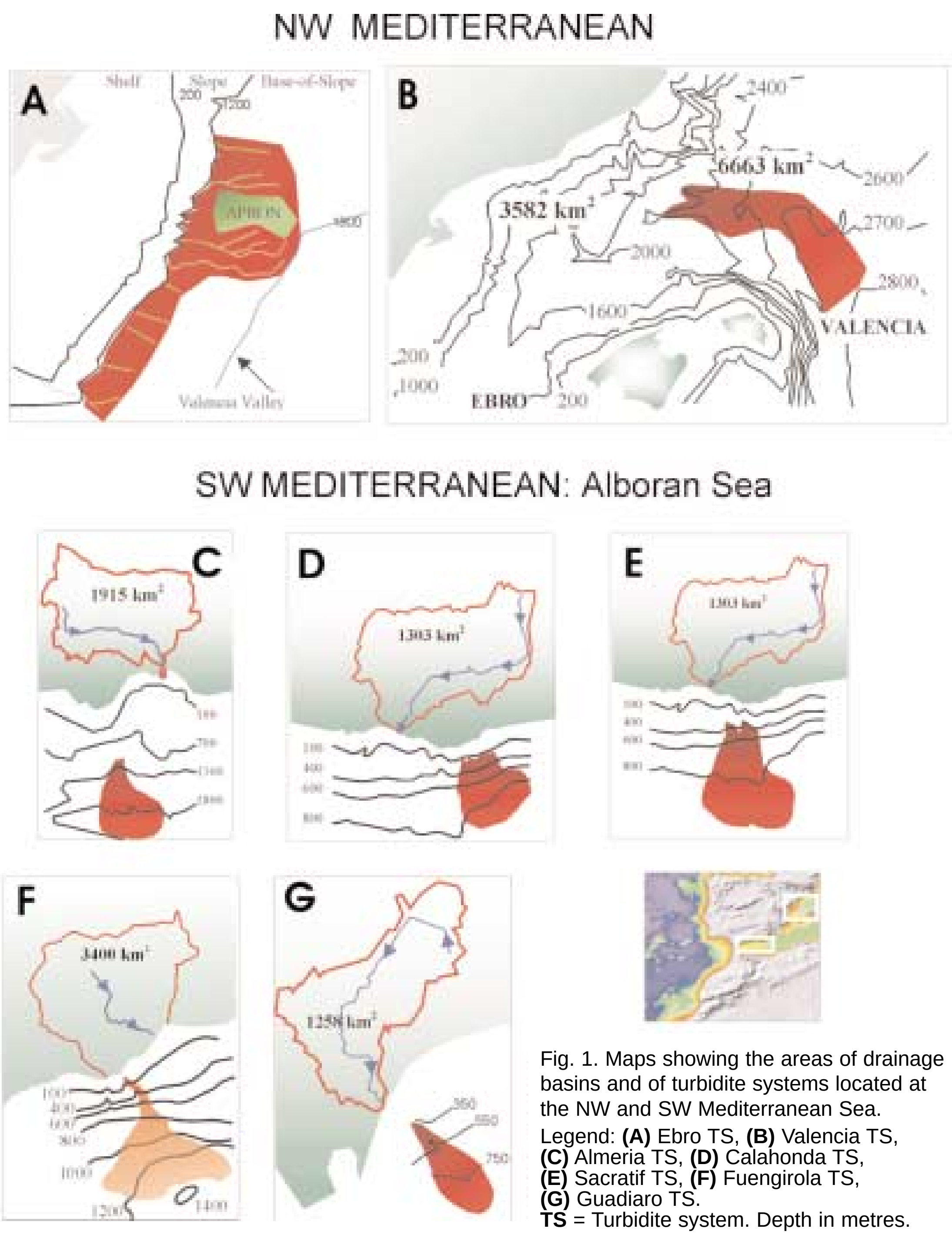

Fig. 1. Maps showing the areas of drainage basins and of turbidite systems located at the NW and SW Mediterranean Sea.
Legend: **(A)** Ebro TS, **(B)** Valencia TS, **(C)** Almeria TS, **(D)** Calahonda TS, **(E)** Sacratif TS, **(F)** Fuengirola TS, **(G)** Guadiaro TS.
TS = Turbidite system. Depth in metres.

a broad constructional area of the slope and base of slope that have multiple source in the upslope region. In this study the multiple source type is represented by multiple slope canyons that are often simultaneously active and by shelf margin deltas; this type of source occurs in the Ebro TS and Calahonda TS.

Finally, we conclude that the high and ultra-high resolution information about modern turbidite systems developed in the NW and SW Mediterranean provide sufficient data for a plan-view classification. This scheme is inspired by a similar classification proposed by Kenyon (2001). This classification into a spectrum of types is distinguished by their tributary and distributary systems, in which the main control seems to be the size of the drainage area and/or long-term rate of sediment supply. In the present study we observe that the size of the drainage area is proportional to the size of the turbidite system when developing in non-confined morphologically areas, and then to the volume and rate of sediment supply. This because the Spanish margins demonstrate a range of setting of turbidite systems influenced strongly by climate history and sea-level dynamics, which influence the rate of sediment supply. In spite of the different geological frameworks on which the turbidite systems develop, the canyons and channels seem to be similar; the canyons are steep and straight and the distributary channels are mainly sinuous with well developed levees along their margins. Downslope the main distributary channels, channelized lobe deposits develop, except for the Ebro turbidite system. On the other hand, the depositional model of the distributary systems are controlled mainly by the type and dynamics of the submarine sources. Likewise, the relocation of the turbidite deposits is governed by the lateral displacements of the canyons and avulsion processes of the distributary channels.

Turbidite systems of the Gulf of Lions (Western Mediterranean): architecture and sedimentary evolution

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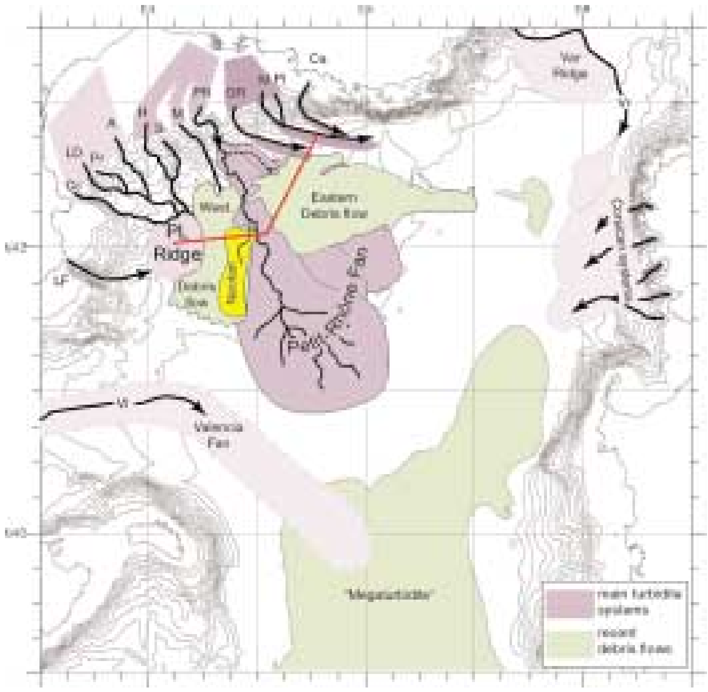
The Gulf of Lions' slope and rise have been the site of thick sedimentary accumulations deposited by gravity processes since the Pliocene (Fig. 1). The outer shelf and slope are dissected by numerous canyons that provided pathways to the deep Balearic basin for the Rhodanian and Pyrénéo-Languedocian detritic sediments, where they accumulated as turbidite systems with contrasting architectures. Several huge allochtonous unconformable transparent bodies also attest to the importance of cyclic instability periods during the Quaternary.



Canyons/valleys nomenclature :
Ca: Cassidaigne Canyon, **Pl:** Planier Canyon, **M**: Marseille Canyon, **GR**: Grand-Rhône Canyon, **PR**: Petit-Rhône Canyon, **M**: Marti Canyon, **S**: Sète Canyon, **H**: Hérault Canyon, **A:** Aude Canyon, **Pr:** Pruvost Canyon, **LD**: Lacaze-Duthiers Canyon, **Cc**: Cap Creus Canyon, **LF**: La Fonera Canyon, **Vl**: Valencia Valley, **Vr**: Var Valley.

Fig. 1. Main turbidite systems and recent mass-movement deposits in the Gulf of Lions and the Balearic Abyssal Plain. Valencia, Var and Corsican turbidite systems are also figured. The thick straight line is the location of the schematic cross section presented in Figure 2.

QUATERNARY TURBIDITE SYSTEMS

Two thick turbidite systems and several smaller ones are facing the main rivers outlets of southern France:

- the Pyrénéo-Languedocian Ridge to the west is about 900 m thick. Detritic sediments were supplied to the sea partly by the Pyrénéo-Languedocian rivers at the southwestern corner of the Gulf of Lions and partly from the Rhône River (Berné *et al.*, 1999);
- the 1500 m-thick Petit-Rhône Fan in the central part of the Gulf was fed mainly by alpine inputs of the Rhône River (Droz et Bellaiche, 1985);
- at the eastern corner of the Gulf of Lions, turbidites accumulated in the thinner and smaller Grand-Rhône and Marseille/Planier Ridges, that were fed by the Rhône River (Droz, 1991).

The Quaternary Petit-Rhône Fan is an overall symmetric feature. It is composed of stacked channel/levee systems grouped in three main complexes (lower, middle and upper complexes from the oldest to the youngest) overlapping each other while migrating westwards, and shows a basinward divergent architecture from a common landward point source, the Petit-Rhône Canyon. The main building process of the fan ended at 21 ky BP. After an episode of remobilisation during which debris flows accumulated (see below), a period of renewed aggrading activity occurred that deposited a small lobate channel/levee system (the Neofan) resulting from a recent avulsion. Definitive abandonment of the Neofan (and Rhône fan) was dated at 15 ky BP (Bonnel, 2001).

The Pyrénéo-Languedocian Ridge is an asymmetric feature located on the right-hand side of the Sète Valley. The Pyrénéo-Languedocian canyons and the Marti Canyon all converge to merge into the Sète Canyon that constitutes the main feeding path for detrital sediments to the ridge and base of slope. The ridge is made of stratified undulating seismic facies that aggraded vertically all along the Quaternary, the valley undergoing only a faint progressive lateral migration towards the east. Although we lack dating information, building of the ridge was probably synchronous with that of the Petit-Rhône Fan (excluding the Neofan).

MASS-MOVEMENT DEPOSITS

In addition to the turbidite systems, gravity deposits are also present as broad and thick, unconformable transparent mass-movement deposits at several places around the Western Mediterranean: in the Gulf of Lions, the western and eastern debris flows, representing an estimated total volume of 370 km^3 truncate both levees of the Petit-Rhône Fan (Bellaiche *et al.*, 1986); on the Ebro Margin, Canals *et al.* (2000) identified the “Big95” debris flow; in the Balearic Abyssal Plain, Rothwell *et al.* (2000) described the “Megaturbidite” that seems to originate from the north.

Altogether, these allochtonous bodies, that are surficial mass-movement deposits of the same age, represent a minimum volume of 900 km^3, attesting of a major episode of instability at the end of the Quaternary.

Similar, but smaller deposits are also known to be interstratified at a specific stratigraphic level between the Rhône Fan middle and upper complexes (Fig. 2), suggesting that instabilities are recurrent phenomena. In the present state of our knowledge, the origin and recurrence of these mass-movement processes cannot be specified.

PLIO-QUATERNARY SEDIMENTARY EVOLUTION

The absence of chronostratigraphic data in the Gulf of Lions prevents the full understanding of its sedimentary evolution. Industrial borehole GLP1 (e.g. in dos Reis, 2001) provided the Pliocene/Pleistocene boundary that was correlated on industrial HR multitrace seismic profiles. This allows to propose the following evolution (Fig. 2):

Plio-Pleistocene

Main turbidite sedimentation occurred during the Pleistocene and led to the building of huge turbidite systems linked to the main canyons or convergent systems of canyons of the margin, as described above. However, turbidite deposition began in the basin as early as the Pliocene. The initiation of turbidite deposition during the Pliocene is identified as small distal channel/levee systems, more or less synchronous and connected to the Messinian canyons, under the Petit-

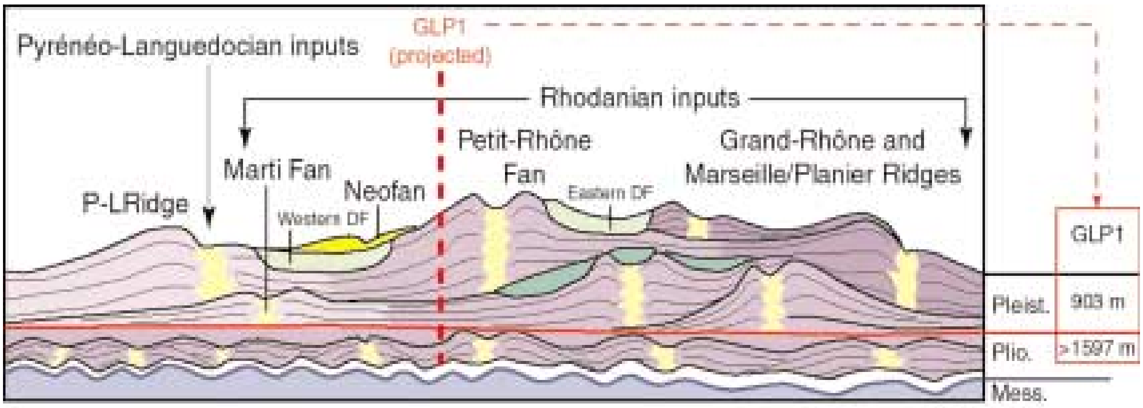


Fig. 2. Schematic cross section at the base of slope of the Gulf of Lions, showing the sedimentary architecture of the margin. Approximate location of this cross section is shown on Figure 1. Not to scale.

Key to colours: violet and pale yellow: resp. levees and channels of turbidite systems; light yellow: Rhône Neofan; green: mass-movement deposits; blue: Messinian series (salt and evaporites).

Rhône Fan (Droz, 1991) and all along the margin (dos Reis, 2001). The distal characters of the Pliocene turbidites at the base of slope indicate a strong progradation of further Quaternary turbidite deposits that are recovered much more basinwards.

During the Pleistocene, sedimentation was interrupted at least twice by instability processes of great volume, suggesting a recurrence in the occurrence of broad mass-movement processes. The absence of absolute dating prevents, however, to propose any origin and frequency for this recurrence.

- 15 ky B.P. to present

While deposition was dominated by gravity processes during most of the Plio-Quaternary, (turbidity currents and mass-movement processes), at the end of the Quaternary, the sedimentation conditions on the rise changed to a mainly erosional regime. These erosional conditions were highlighted in the area between the Petit-Rhône Fan and The Pyrénéo-Languedocian Ridge (Droz *et al.*, 2001), with evidence for strong erosion inside the Sète Valley and redeposition of eroded sediments as very thin unchannelized lobes at the outlet of Sète Valley and La Fonera Canyon.

FORTHCOMING ACTIONS AND EXPECTED PROGRESSES

In order to collect key information to fully understand the sedimentary evolution of the Gulf of Lions, two main actions will be conducted in a near future:

• Scientific drillings (50-300 mbsf) on the outer shelf and upper slope in the western part of the Gulf of Lions (European program PROMESS 1, 2002-2005, co-ordinator: S. Berné, IFREMER). This will provide, among other key results, a stratigraphic framework over the last 500 ky for mass-wasting and canyon incisions affecting the shelf edge. These results will be complemented by longer drillings (up to 1300 mbsf) in deeper water targets on the Rhône Fan (PROMESS 3, IODP framework).

• The Gulf of Lions has also been selected as one of the targets of the European-American program EUROSTRATAFORM (2002-2004, co-ordinator: P. Weaver, SOC, for the European side; C. Nittrouer, UW, for the American side) that aims to study margins' sedimentary evolution in an integrated manner, from source to sink. A bathymetric and seismic survey should be conducted next year to investigate the relations between turbidite sedimentation and mass-movement process, and the regional extension of the Late Quaternary erosional regime.

Recognition of turbidite elements in the late-Quaternary Adriatic basin: where are they and what do they tell us?

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Introduction

Deep-sea submarine fans are one of the depositional products of repeated turbidite flows on continental margins. Although they have been recognised in very different domains (active or passive margins, high- or low-latitude areas, coarse-grained or fine-grained sources) submarine fan systems are only one of the possible products of currents. As an example, the topography of the receiving basin may significantly affect the architecture of deepwater sediment systems and result in turbidity-current deposits that do not form a morphologically-detectable turbidite fan. In confined slope basins, the spatial distribution of depositional elements reflects progressive phases of basin infill and spill over, as observed in some of the interconnected slope basins of the Gulf of Mexico (e.g., Bouma, 1979) and of the Mediterranean (Trincardi *et al.*, 1995). Semi-enclosed epicontinental basins are similar in morphologic turbidity confinement and present further complications related to their vicinity to deltaic sediment sources, affected by short-term supply fluctuations of large magnitude. Additional complication comes from the role exerted by oceanographic processes and their complex interplay with basin morphology (presence and orientation of sills, morphologic barriers and other local elements acting to restrict flow paths).

Developments in seismic stratigraphic tools and interpretation techniques over the last 30 years led to the definition of criteria for identifying key turbidite elements composing submarine fan systems (Mutti and Normark, 1987; Normark *et al.*, 1993). These criteria were successfully applied to Quaternary continental margins and, to some extent, to discriminate geometries that are instead indicative of prevailing contour-current reworking. In this study we review available evidence for turbidity-current deposits in the Adriatic basin, an example of modern mid-latitude epicontinental margin dominated by the impact of Quaternary glacio-eustatic changes. In the Adriatic, the Quaternary sedimentary architecture was strongly influenced also by basin morphology and water-mass circulation. During the last sea-level cycle spanning ca 120 ky, the Po system, in spite of its conspicuous sediment supply, did not form a submarine fan; rather, it contributed to the south-eastward shelf progradation resulting in the partial infill of the Adriatic foreland basin. Despite the lack of a morphologically detectable submarine fan, evidence of repetitive turbidity-current deposition can be found in more subtle reflector geometries imaged by ultra-high-resolution Chirp sonar profiles. The review of such evidence is the main goal of this paper.

Setting of the Adriatic basin

The Adriatic basin is a complex geodynamic and depositional siliciclastic domain that occupies the foreland of the Apennine and Dinaric fold-and-thrust belts, originated by the collision of the African and the European plates. The modern Adriatic basin encompasses a substantial portion of the Apennine foredeep in the North, a transitional area affected by recent tectonic deformation in the center and a remnant Oligo-Miocene extensional basin in the South (Ricci Lucchi, 1986; Royden *et al.*, 1987). During the late Quaternary, the Adriatic basin has been filled mainly from the north-west in an axial direction, by a composite SE-ward progradational wedge (Ori *et al.*, 1986; Ciabatti *et al.*, 1987). Axial progradation produced also distal, fine-grained, turbidity flows during lowstands and prolonged phases of relative sea-level fall.

During the late Pleistocene and Holocene eustatic rise (between ca 16 and 5.5 ky BP; Fairbanks, 1989), a wide portion of the glacial-time alluvial plain in the northern and central Adriatic was progressively drowned resulting in an eight-fold widening of the shelf areas (Trincardi *et al.*, 1994; Correggiari *et al.*, 1996a, b; Cattaneo and Trincardi, 1999). Today, the modern Adriatic sea is a narrow epicontinental basin (ca 200 x 800 km; Fig. 1).

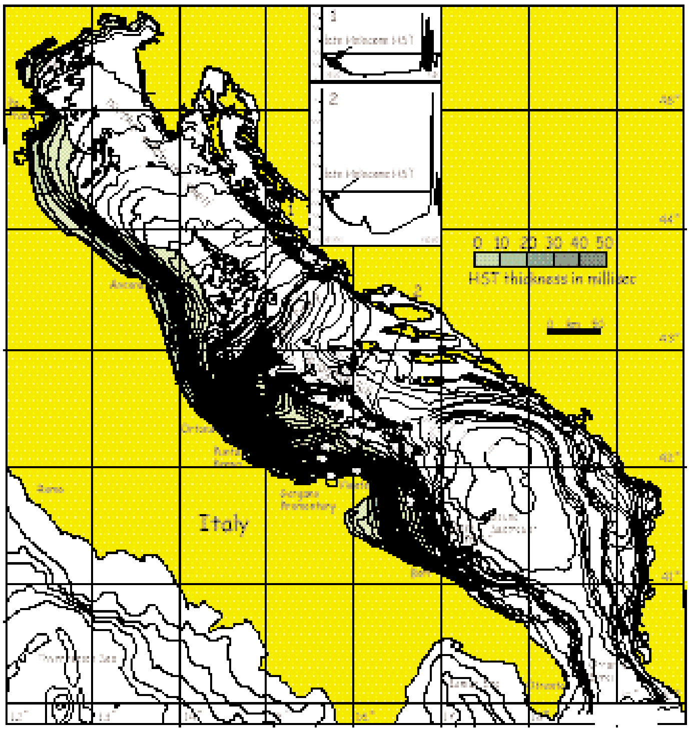

Fig. 1. Bathymetry of the Adriatic Sea and isopach map of the late-Holocenehighstand systems tract (HST).

During the present peak highstand conditions the Adriatic is composed of three distinct physiographic domains (Fig. 1). The northern domain is a shallow and low-gradient shelf, with a mean longitudinal dip of ca 0.02°. The central Adriatic is characterized by a narrower shelf and the presence of localised structural heights on the shelf and slope, and reaches a maximum depth of 260 m in two remnant slope basins aligned in a SW-NE direction (Mid Adriatic Deep; Fig. 2). Progradational geometries on the shelf surrounding this slope basin indicate a centripetal fill from the SE, W and NW sides during the late Quaternary. The Pelagosa sill (shallower than 170 today) was a narrow and shallow conduit between the Mid Adriatic Deep and the Southern Adriatic deep basin during glacial sea-level lowstands. The southern Adriatic reaches a depth of ca 1200 m and is flanked by a steep slope and narrow shelf. Several incisions cut the slope, locally breaching the shelf edge, formed during glacial lowstands (Fabbri and Gallignani, 1972; Colantoni and Gallignani, 1978). The major sediment conduit in the area is the Bari canyon deeply incising progradational sequences deposited during the last few Quaternary eustatic oscillations (Ridente and Trincardi, 2002). Bari canyon is a large and deep conduit that was actively cut (or re-incised) during the last glacial lowstand (Fig. 3). Modern shore-parallel shelf transport is likely intercepted by Bari canyon. Although structurally distinct, the three main Adriatic domains are, and have been, connected and affected by a common oceanographic regime that strongly influenced sediment transport and deposition.

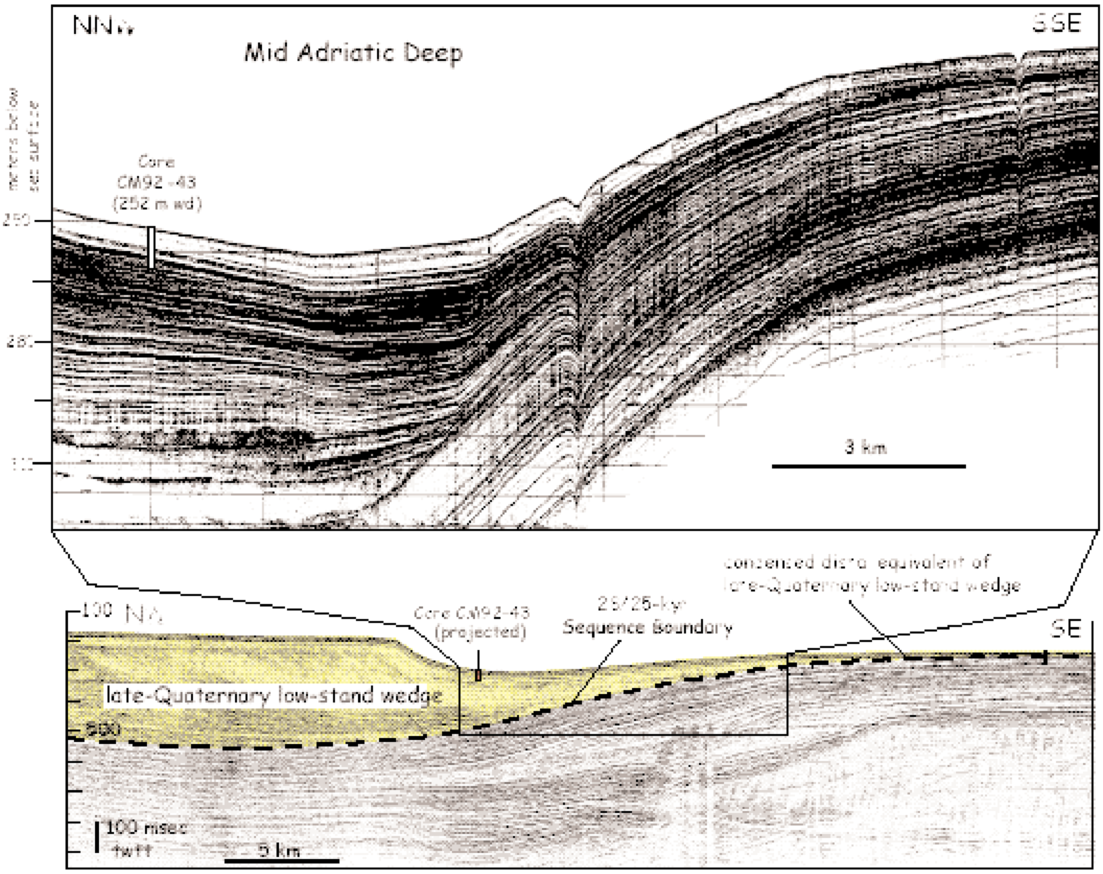

Fig. 2. Multichannel seismic line (below) and CHIRP-sonar profile (above) across the Mid-Adriatic Deep.

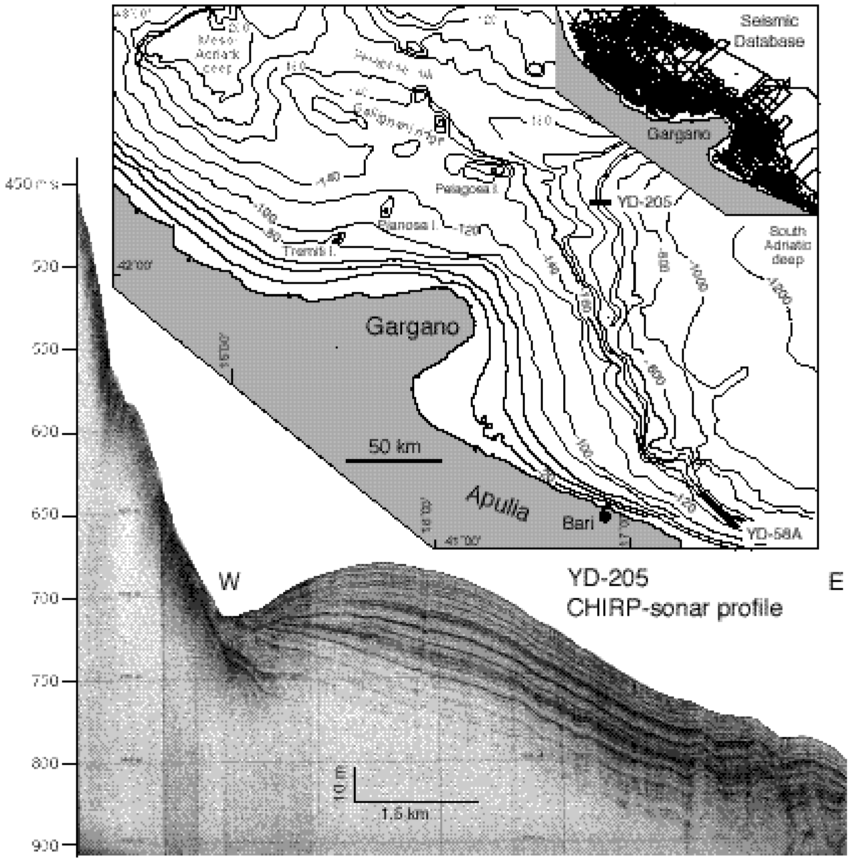

Fig. 3. Possible sediment drift seaward of the Pelagosa sill.

Systems tract subdivisions, asymmetries and controlling factors

A large database of Chirp-sonar profiles, sediment cores and chronological data allow the recognition of depositional sequences reflecting 100-ky cyclicity during the late Pleistocene (Regione Emilia-Romagna and ENI AGIP s.p.a., 1998; Trincardi and Correggiari, 2000; Ridente and Trincardi, 2002). This presentation addresses only the deposits that accumulated during the recent-most sea-level cycle, for which direct core control is available (Asioli *et al.*, 1999; Trincardi and Correggiari, 2000). The late-Quaternary sequence in the Adriatic basin may be subdivided into four systems tracts, each displaying remarkable lateral variability in thickness and facies assemblages: the highstand (HST), transgressive (TST), lowstand (LST) and falling stage (FSST) systems tracts (Trincardi *et al.* 1996; Trincardi and Correggiari, 2000). Direct stratigraphic, geochronological and paleoenvironmental data come from continuous cores reaching the transition between Marine Oxygen Isotope Stage 5 and 4 (Asioli, 1996; Trincardi and Correggiari, 2000).

Modern HST

The major component of the late-Holocene High-stand Systems Tract (HST) is a mud wedge deposited along the western side of the Adriatic shelf, up to 35 m in thickness and 180 km^3 in volume, composed of forestepping sigmoids with gently dipping foresets resting above a regional downlap surface (the maximum flooding surface, mfs). The mfs marks the time of maximum landward shift of the shoreline attained around 5.5 cal. ky BP (Trincardi *et al.*, 1996; Correggiari *et al.*, 2001). This HST mud wedge encompasses three genetically-related and physically-continuous depositional elements: (a) the Po delta system, including the major subaerial deltaic system and its related delta plain and prodelta, draining the Alps and northern Apennines ($15x10^6$ t yr^{-1} of sediment supplied from a single entry point); b) the central Apennine mud wedge fed by numerous coalescing rivers characterised by high sediment yield along the eastern coast of Italy ($32.2x10^6$ t yr^{-1}, Frignani *et al.*, 1992; Milliman and Syvitski, 1992); and c) the Gargano subaqueous delta located east and south-east of the Gargano promontory, away from any direct river source.

The HST mud wedge is shore-parallel, reflecting the almost exclusive location of sediment entry points on the western side of the basin and the time-averaged effect of the cyclonic circulation on sediment dispersal. Phases of rapid progradation alternated with times of relative basin starvation. These fluctuations may reflect short-term climate change and human impact: indeed, the most recent shelf-wide progradational phase developed during the outbuilding of the Po delta (from AD 1500) encompasses the Little Ice Age (Oldfield et al, in press). In the south, the Bari canyon likely acts as the ultimate sink for any sediment flowing along the western side of the shelf (Figs. 1 and 4).

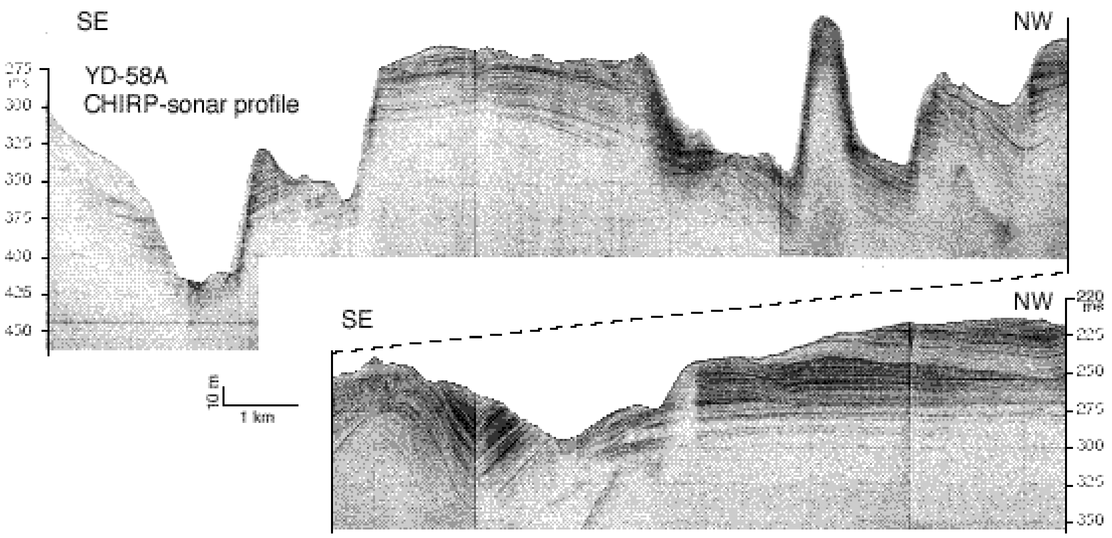

Fig. 4. Bari canyon

LATE PLEISTOCENE - EARLY HOLOCENE TST

During the late-Quaternary sea-level rise, between ca 16,000 and 5,500 years BP, several factors influenced the deposition of the TST in the Adriatic basin. Short-term climatic instability caused repeated changes in sediment flux, while the transgressive drowning and widening of this semi-enclosed basin permanently changed the oceanographic regime, thereby changing the prevailing mechanisms of shelf sediment dispersal.

In the central Adriatic shelf, the late-Quaternary TST consists of three distinctive units recognized through high-resolution seismic profiles, sediment cores, and multiproxy stratigraphic data, separated by drowning surfaces, likely formed during short intervals of maximum rates of relative sea level rise. The middle unit, in particular, records a short interval of extremely enhanced sediment supply and includes proximal progradational and distal mounded deposits on the outer shelf. The middle unit also marks the onset of a shore-parallel dispersal similar to the modern one on the shelf. The upper unit includes time-equivalent sand patches (reflecting transgressive drowning and reworking of barrier-lagoon systems) in the North and “onlapping” mud units in the southern shelf (Cattaneo and Trincardi, 1999). This evidence reflects the alongshore facies partitioning between a northern area with barrier-lagoon deposits and a starved shelf and a southern area with thick and complex mud-dominated shelf units.

LAST GLACIAL MAXIMUM LST

A large volume of sediment, including most of the marine sands of the last sea-level cycle in the Po system, deposited during lowstand. In an initial phase, extensive mass-failure deposits accumulated in the Mid Adriatic Deep slope basin generating acoustically-transparent lenticular seismic units. Later, a very thick prograding wedge was fed from the Po plain along the axis of the Apennines foredeep, causing progradation of the shelf margin for as much as 250 km (based on correlation to direct stratigraphic information in areas of reduced deposition; Trincardi *et al.*, 1994; Trincardi and Correggiari, 2000). This progradation is organised in clinoform packages that might record very-short-term supply fluctuations. In the distal part of the Mid Adriatic Deep, these deposits show alternating onlap and drape geometries. During the glacial lowstand, the Pelagosa sill was the only connection between the Mid Adriatic Deep and the rest of the Mediterranean. The area shows the occurrence of sediment mounds and erosional moats disposed along the flanks of the sill. Likely, the presence of this shallow-water and narrow passage, accompanied by the flow of dense waters produced by cooling in the North or turbidity currents generated from the low-stand Po system, generated favorable conditions for the deposition of “sediment drifts” in the area.

In the undersupplied southern Adriatic surrounding the Gargano Promontory, shelf-margin sand wedges represent the only sedimentation, with active downcutting by the multiple heads of Bari canyon (Ridente and Trincardi, 2002). The downslope configuration of this important system, including the possible occurrence of levee wedges and channel-lobe deposits, is at present unknown.

FALLING-STAGE SYSTEMS TRACT

A composite stack of shingled regressive depositional sequences separated by shelf-wide erosional uncomformities accumulated on the Adriatic shelf and upper slope. The erosional uncomformities formed during subaerial exposure and ensuing transgression, while most of the progradational sequences record prolonged intervals of sea level fall (Trincardi and Correggiari, 2000). These regressive sequences record high-frequency glacio-eustatic cycles, characterised by 100-120 ky duration between 400-450 and 30-20 ky ago (Trincardi and Correggiari, 2000). Core information accompanied by the great penetration of acoustic signal in Chirp-sonar profiles indicate that these progradational wedges are dominantly composed of mud to fine sand deposited in a low-energy environment.

TURBIDITE “ELEMENTS” IN THE ADRIATIC DOMAIN

Within each systems tract we try to recognise evidence for turbidity current deposition through the recognition of turbidite elements in seismic profiles and for turbidity-current deposits in our limited core data.

Modern highstand: the thickness distribution of the late-Holocene mud wedge indicates that during highstand conditions most sediment is trapped on the shelf. Observation of modern river floods indicates that the system is dominated by hypopycnal flows shedding sediment plumes that are variably redirected by the dominant thermohaline circulation. Minor turbidites (if any) can therefore result from local instability events on the deep slope south of Gargano or within the Bari canyon that may also represent the potential gateway for sediment coming from the North.

Post-glacial sea-level rise: the short-lived middle-TST phase of coarser grained and rapid deposition likely reflects the dominance of hyperpycnal regime of the Apennine "dirty rivers" possibly accompanied by a temporary stop or substantial decrease of the rate of sea level rise. Core data show sharp-base sand-mud couplets at the scale of few cm during this interval. Where identified, however, these deposits do not seem to extend beyond the shelf edge.

Last Glacial Maximum: within this interval two seismic geometries indicate the activity of turbidity currents: a) the seismically transparent deposits that fill the slope basin indicate provenance from the NW and pounding against its western and southern flanks, with a total volume of about 300 (Western basin) and 600 km^3 (Eastern basin). Several of these acoustically-transparent deposits are stacked on top of each other showing a progressive decrease in thickness and lateral extent. Adopting a sequence-stratigraphic template, these deposits may represent a "basin floor fan", but their origin and depositional mechanisms need to be further studied; b) the overlying lowstand prograding wedge shows evidence of alternating onlap/drape terminations to the south and west, suggesting that fine grained turbidites were the distal equivalent of the prograding wedge. Evidence of thickening of turbidite onlapping beds towards the West is consistent with flows coming from the north under the effect of the Coriolis deflection to the right. It is worth to note that no channel-levee complex developed following the deposition of the acoustically transparent mass-transport deposits. In the same time interval, similar deposits were growing in several sectors of the Mediterranean margins (e.g., Alonso and Ercilla, this volume; Bellaiche *et al.*, this volume; Droz *et al.*, 2001; Kenyon and Akhmetzhanov, this volume; Popescu *et al.*, this volume). Likely, morphologic confinement and reduced slope relief prevented the formation of channelised flows despite the substantial volume of sediment delivered at lowstand from the NW. In the slope south of Gargano the evidence of large-scale drifts is dominant (Fig. 3), but geometries consistent with deposition from turbidity current and mass-transport processes were also observed (Biasini *et al.*, 1990).

Overall Pleistocene sea-level fall: closely-spaced erosion at the shelf edge indicates a possible phase of gully formation close to the end of the sea-level fall (as no further progradational unit deposited after the phase of gully erosion). However, the distal product of this possible phase of erosion (likely through increased discharge) remains unknown based on the available data.

Continental slopes are commonly affected by canyon downcutting, followed by conduit stabilisation and growth of levee wedges. Channel avulsion and abandonment is part of such evolution (Flood *et al.*, 1991; Kenyon *et al.*, 1995; Droz *et al.*, 2001). In the Mediterranean Sea also bottom-current activity played an important role in sediment transport (Marani *et al.*, 1993; Kenyon and Akhmetzhanov, 2002.). The Adriatic basin has always been a slope basin in the majority of its extent and has been dominated by shelf sediment redistribution by thermohaline circulation. Compared to other deepwater systems in the Mediterranean region, the Adriatic basin shows therefore peculiar conditions due to its epicontinental nature and the presence of morphological barriers of tectonic origin that enhanced the role of currents in governing sediment routes to the deeper part of the system. Limited data coverage suggest that sediment drifts likely formed in response to the interaction of deep-water formation and morphological forcing on the slope and along the Pelagosa Channel, the narrow conduit connecting the Central Adriatic basin to the rest of the Mediterranean during lowstand. These data also show that turbidite elements can be recognized even in the absence of a "typical" deep sea fan.

Growth of mud reliefs within the Adriatic late-Holocene prodelta deposits through sediment load and fluid escape processes

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A growing bulk of seismic-stratigraphic evidence indicates that fluid flow is a significant process on continental margins. However, the mechanisms controlling the subsurface flow and emission of fluids at the seabed are not yet well understood. At the scale of whole continental margins, many studies focused on active margins and accretionary wedges, emphasising the presence of mud volcanoes and deformation features related to the presence of overpressured fluids within the sediment (e.g., Milkov, 2000). The role of fluids on passive margins is being increasingly recognised, as for example in the area of the Nile deep-sea cone (Mascle *et al.*, this volume). The properties of fluids and their relation to the hosting sediment are relevant in relation to: (1) the occurrence of potential deep reservoirs (as in the case of methane), and (2) their role as potential factors conducive to sediment instability through over-pressurisation beneath impermeable layers.

Little is known on the mechanisms responsible for the formation of a variety of features detected on high-resolution seismic profiles, swath bathymetry and side-scan-sonar mosaics, whose origin may be associated with the presence of fluids within the sediments. These features range from large-scale mud diapirs, typically of large dimensions (up to several kilometers in diameter), mud volcanoes, pockmarks and smaller scale vertical disturbances possibly related to conduits of escaping fluids (Embley, 1980). The occurrence of this broad range of features requires high sedimentation rates and/or lateral tectonic compression on continental margins (Milkov, 2000). Recently, on larger scales, many studies investigated the formation of polygonal faults triggered by early compaction of fine-grained sediments accompanied by dewatering (Cartwright and Dewhurst, 1998). Soft-sediment deformation may result from over-pressurisation due to internal processes (such as mineral dehydration and seepage forces associated with fluid flow) or to a rapidly applied external load (Maltman, 2001). The effects of fluid mobility at shallow stratigraphic levels and the role of permeability barriers was documented also in the Adriatic sea (e.g., Hovland and Curzi, 1989). Furthermore, the Adriatic is characterised by the occurrence of high-magnitude earthquakes and tsunamis (Tinti *et al.*, 1995) that may have acted as triggering mechanisms for sediment mobilisation (Correggiari *et al.*, 2001).

We describe the anatomy of a variety of small-scale mud reliefs (either buried or exposed at sea floor) that affect the late-Holocene mud prism accumulated since the attainment of the present sea-level highstand (about 5.5 cal. ky BP), on the western side of the Adriatic sea (Trincardi *et al.*, 2000; Correggiari *et al.*, 2001). This area is characterised by high sediment accumulation rates during the late Quaternary with high organic matter content (Correggiari *et al.*, 2001) and presence of gas and seepage-related features (Hovland and Curzi, 1989). The mud reliefs discovered in the Adriatic are elongated features having an acoustically transparent core on seismic profiles and a non-random spatial distribution. These reliefs occur in water depths greater than 70 m in two main stratigraphic settings: a) seaward of main depocentres (35 m) of the late-Holocene mud prism, in areas characterised by shore-parallel seafloor crenulations and on a basal surface sloping seaward typically less than 0.2° (offshore Ortona); or b) seaward of areas of thinner late-Holocene sections but relatively steeper gradient (> 0.5°) on the basal surface; the increase in basal gradient is caused by the occurrence of buried basement highs (offshore Vieste) or large-scale depositional mounds within late-Quaternary transgressive deposits (offshore Bari and Monopoli; Fig. 1).

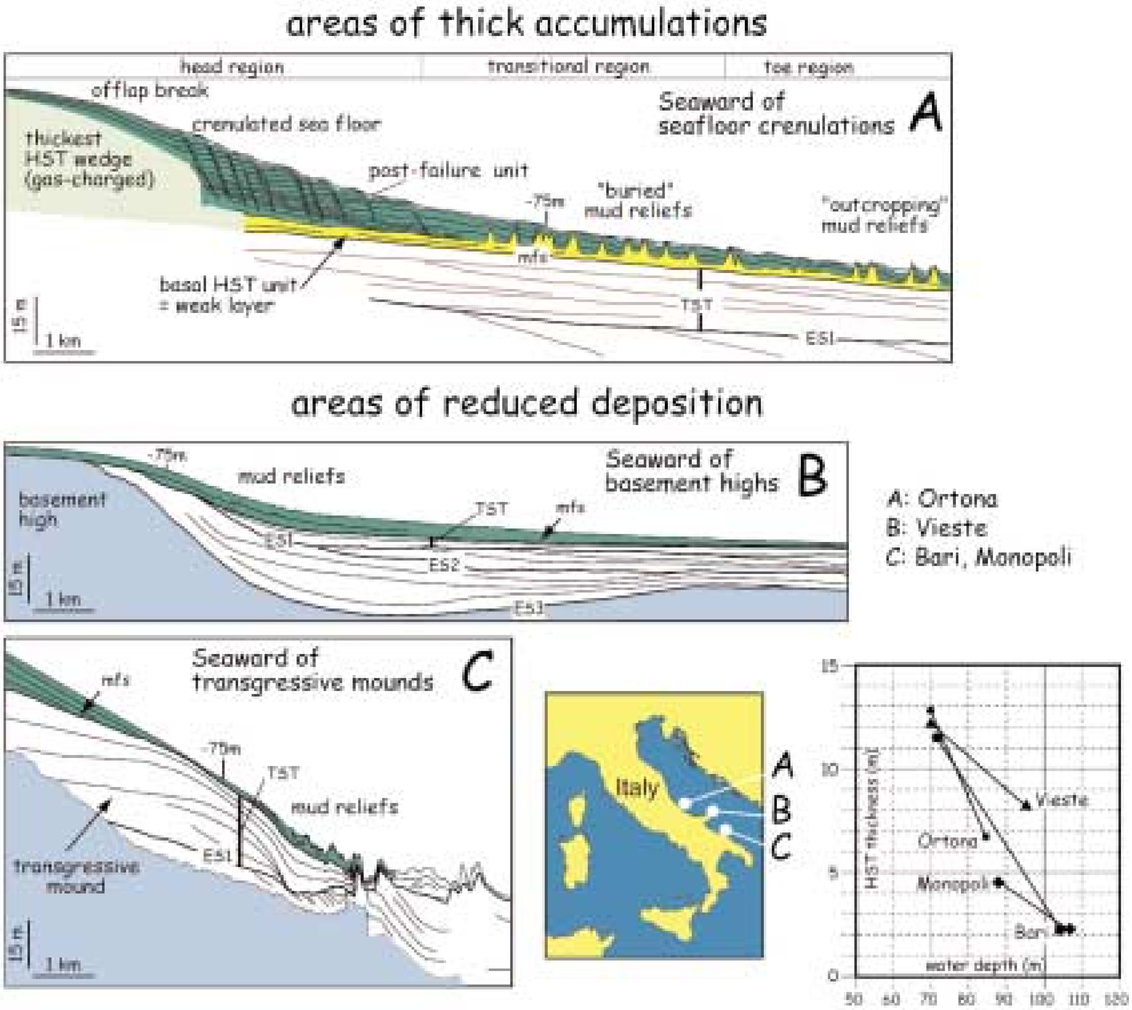

Fig. 1. Occurrence of mud reliefs in late-Holocene muddy deposits (HST wedge) of the Central Adriatic Sea.

In sections perpendicular to the coast, the late-Holocene mud prism shows an overall progradational geometry and a basinward downlap termination above a thin basal unit recording condensed deposition between 5.5 and 3.7 cal. ky BP, in turn floored by a regional downlap surface (the maximum flooding surface, mfs; Correggiari *et al.*, 2001). The sediment affected by deformations is entirely muddy and variations of amplitude in the seismic reflectors and/or seismic wipe-outs evidence the presence of shallow gas (likely methane), often trapped in very shallow levels or at the top of the thin basal unit. Both high-resolution CHIRP-sonar profiles and seafloor images (multibeam and side scan sonar surveys) show the orientation of mud reliefs (Fig. 2).

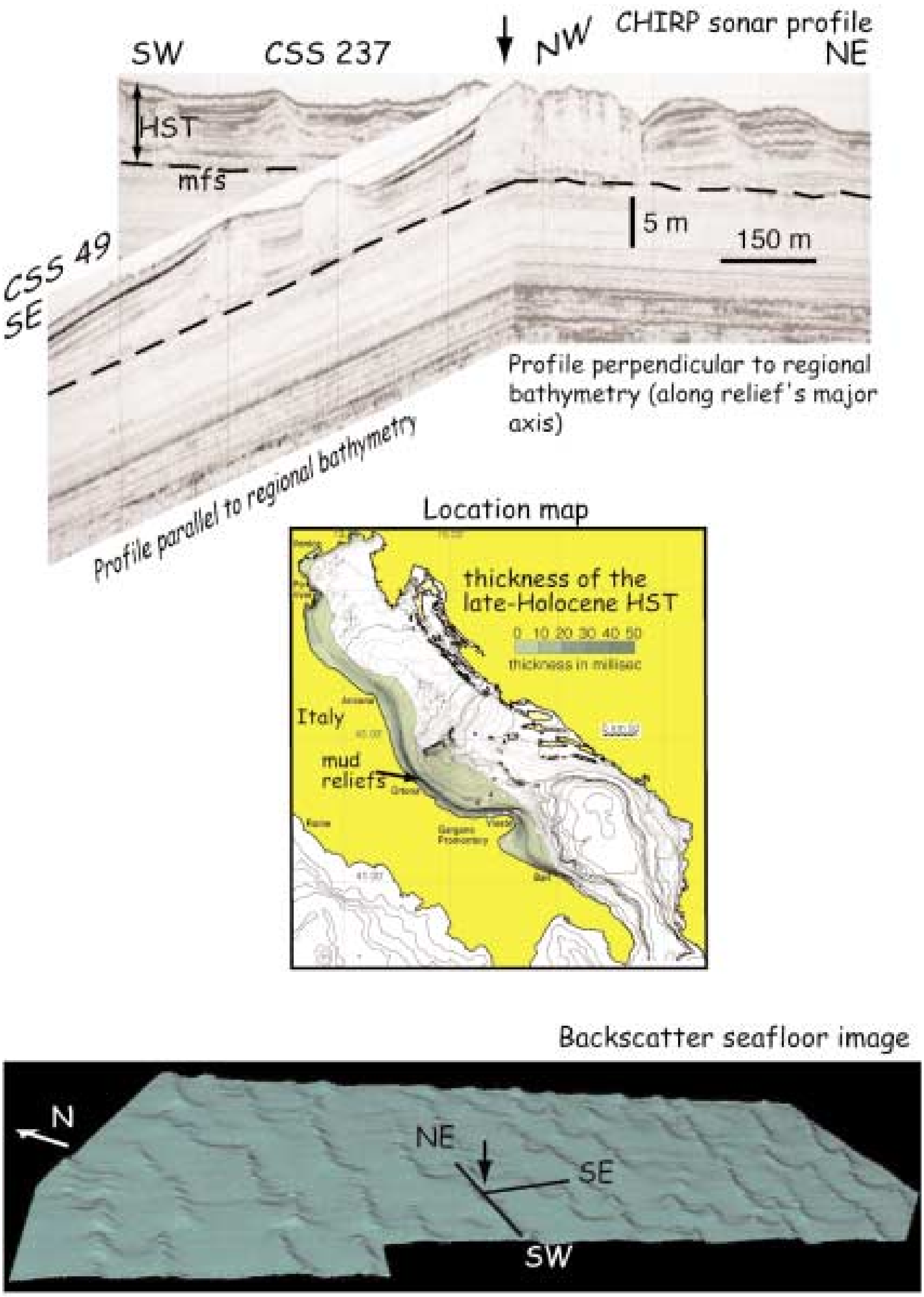

Fig. 2. Geometry of seafloor mud reliefs within the late-Holocene HST (Central Adriatic Sea)

Offshore Ortona mud reliefs occur in swarms that are preferentially oriented SW-NE or SSW-NNE, therefore roughly normal to regional bathymetry (Fig.2, backscatter image from side scan sonar survey). Individual swarms are typically ca 1 km long and few hundreds of metres wide and are spaced ca 500-1000 m from each other. Individual reliefs within each swarm vary slightly in elevation above the seafloor (typically ca 2-4 m), are sub-circular in plain view with a diameter of ca 50-200 m and show relief crests elongated in a NW-SE direction (corresponding to the direction of the regional shelf current flowing south-eastwards). The flanks of the reliefs are markedly asymmetric and show two different gradients: the flanks facing SE are steeper than NW-dipping ones, because sediment swept by bottom currents accumulate against the latter resulting in a more gentle slope. This asymmetry is therefore the expression of sediment accumulation by shelf currents on the up-current sides of the reliefs, as indicated clearly by onlap terminations of seismic reflector against the acoustically transparent core of the reliefs (Fig. 2).

Mud reliefs in the areas offshore Vieste, Bari and Monopoli affect areas of thin late-Holocene deposition above a common basal surface (mfs), as observed in the Ortona example; however, these features are more elliptical and tend to have greater continuity parallel to the regional contour (based on side-scan sonar mosaics). In quite different stratigraphic and morphologic contexts, the occurrence of mud reliefs is limited to water depths deeper than 70 m. In these areas, an inverse relation exists between the thickness of the HST wedge and the depth of occurrence of the reliefs (Fig. 1).

Preliminary core information shows that magnetic-susceptibility logs from the acoustically transparent reliefs correlate quite precisely to those from the adjacent non-deformed flank areas where sediment is acoustically stratified (Trincardi *et al.*, 2000). This evidence indicates that the reliefs unlikely represent mud diapirs or mud volcanoes, because a more thorough remoulding of the sediment column would be expected. We ascribe the origin of these reliefs to giant fluid-escape features accompanied by bed upwarping around fissured areas of fluid venting. The location of these deformations is likely controlled by sediment overload from the HST mud wedge on the mfs, while the mobilisation occurs in response to upward expulsion of fluids. Core data also show changes in water content and in geotechnical parameters in the thin basal unit above the mfs. This unit may have acted as a weak layer due to over-pressurisation by shallow gas impregnation. The non-random distribution of the mud reliefs remains to be explained. However, the occurrence of orientations sub-perpendicular to the regional bathymetric slope in the Ortona area is consistent with the occurrence of hydraulic fracturing in the section above the basal weak layer (Fig. 2). The bathymetric expression of the elongated swarms composed by mud reliefs is partially buried by subsequent asymmetric deposition by bottom-hugging shelf currents coming from the NW and piling up sediment on the upflow side of the reliefs.

The kind of mud reliefs described in the Adriatic shelf are not commonly observed on continental margins for two possible reasons: 1) the reliefs develop as a transitional deformation which is removed anywhere seafloor slope facilitates a more thorough downslope translation; 2) if occurring in deeper waters, these features are hardly resolved, because of limited spatial resolution on conventional seismic surveys, and would appear as a set of overlapping hyperbolae on acoustically-transparent units.

Salt tectonics in the Nile and Rhône deep-sea fans : comparison on the basis of seismic data and physical modeling

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The present-day setting of the Mediterranean includes the combined influences of thick-skinned, crustal-scale tectonics and thin-skinned, gravity-driven spreading and/or gliding of the Messinian evaporites, acting as a décollement and their brittle Plio-Pleistocene overburden. Furthermore the continental slopes and rises in the Mediterranean are shaped by numerous channel-levee complexes having map geometries and sizes varying from large cones, such as the Rhône and Nile deep-sea fans, to smaller curved asymmetric sedimentary systems, such as the Pyreneo-Languedocian, Var or Cassidaigne Ridges in the northwesternmost area. In such settings, rapid sediment aggradation and progradation typically enhance thin-skinned deformation of the evaporitic Messinian series and their overburden. Gravity spreading and gliding cause (1) upslope extension, characterized by listric normal growth faults detaching on the Messinian décollement associated with salt rollers in the footwalls and synsedimentary rollovers in the hanging walls; (2) midslope translation characterized by low-amplitude highs and lows; and (3) downslope contraction causing diapirs, salt walls and buckle folds (Vendeville, under review).

The above structures have been observed in both the Rhône (Fig. 1a, Gaullier and Bellaiche, 1996) and Nile (Fig. 1b, Sage and Letouzey, 1990) deep-sea fans, but also in other places in the world such as along the Gulf of Mexico margins (Worral and Snelson, 1989). These structures have been reproduced experimentally in analogue models of linear sand wedges (i.e. parallel to the coastline) prograding above a viscous silicone layer (Fig. 1c).

Although the along-dip changes in structural style of the Nile and Rhône deep-sea fans are fundamentally similar, the two deep-sea fans exhibit drastic differences in terms of 3-D structural characteristics. In the next sections, we compare the geophysical data from each deep-sea fan with results of two sets of physical experiments.

RHÔNE DEEP-SEA FAN

Diapirs are largely displayed in the downslope domain of the Rhone deep-sea fan, where they correspond to circular salt stocks or elongate salt walls (Fig. 2a). They typically result from gravity gliding of the Messinian salt décollement and the Plio-Pleistocene turbidites, above the pre-Messinian subsalt basement dipping basinwards (Gaullier and Bellaiche, 1996; Dos Reis, 2001).

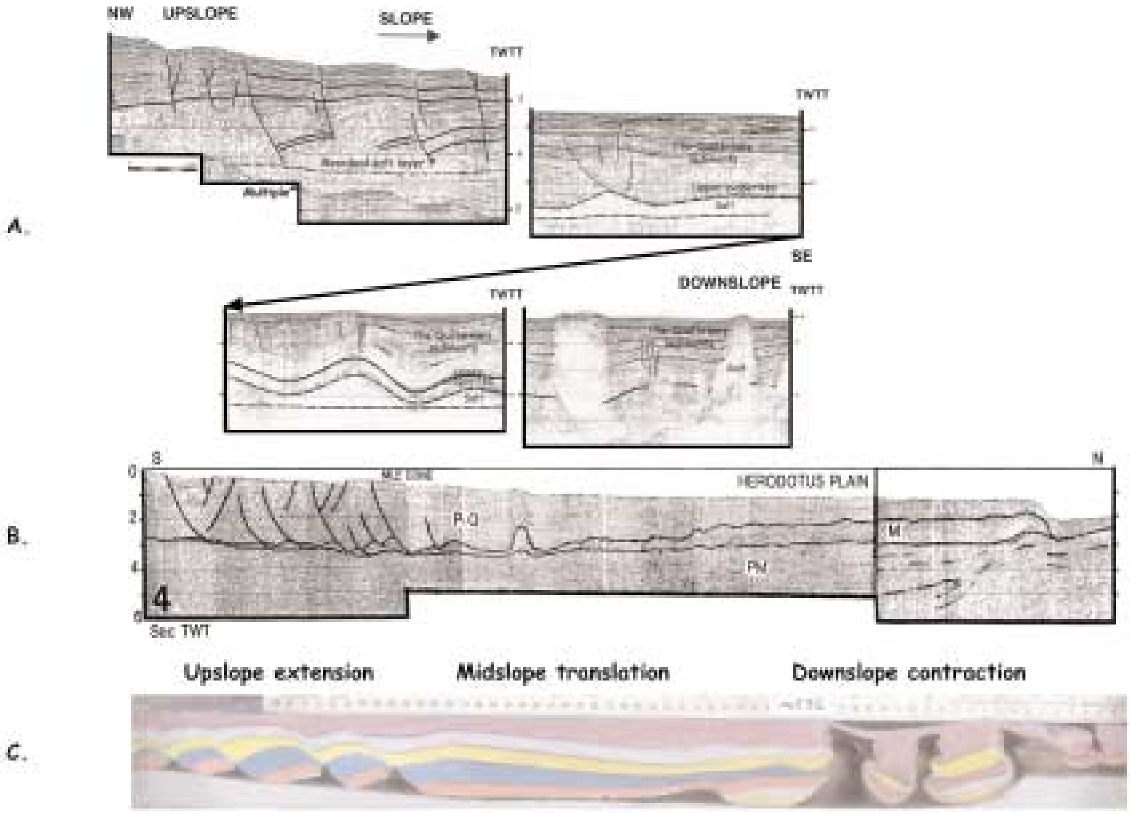

Fig. 1: Along-dip variations in structural style associated with gravity-driven thin-skinned tectonics, including upslope extension (Listric normal growth faults, associated sedimentary rollovers and salt rollers), midslope translation, and downslope contraction (Salt anticlines, keystone faults, diapirs and distal buckle folds). **A.** Seismic-reflection profile intersecting salt-related structures along the Rhône deep-sea fan (Location in Fig. 2a). **B.** Seismic-reflection profile intersecting salt-related structures along the Nile deep-sea fan (Location in Fig. 3a). **C.** Along-dip cross-section in an experimental model simulating the gravity gliding of a sedimentary overburden above a salt layer.

Regional mapping reveals that: 1. diapirs present two main orientations: N-S and NW-SE, 2. the upper boundary of the diapir province, regionally perpendicular to the slope direction (trending NE-SW in the Liguro-Provençal Basin and N-S in the Balearic domain), comprises three local NW-SE-trending reentrants located above deep transfer zones formed during the Oligo-Miocene basin opening (Fig. 2a, Gaullier *et al.*, 2000a). We hypothesize that the correlation of both location and orientation between the basement features and the younger salt structures can be explained by (a) differential compaction of the post-basement, presalt strata, which transmits the basement relief upward, thus deforming the base salt, and (b) the coeval gravity gliding of the overlying salt and overburden. A recent series of experiments have therefore been carried out to test the effects of differential compaction of a sediment layer above a stepped-basement, with or without a regional basal slope in order to simulate a thin-skinned gravity-driven tectonics (Fig.2b).

NILE DEEP-SEA FAN

The western and northern provinces of the Nile deep-sea fan show salt-related structures typical of those found on other salt-bearing passive margins, and especially in the Rhône Cone (Fig. 3a, Gaullier *et al.*, 2000b). In contrast, the structural pattern of the eastern part of the fan drastically differs. It comprises a long (>200 km) NW-SE deformation corridor trending obliquely with respect to the direction of the slope (Fig. 3a, Mascle *et al.*, 2001). Along dip, the corridor exhibits a structural progression typical of salt-bearing passive margins, including small distal buckle folds; midslope minibasins surrounded by salt ridges, and proximal normal growth faults. The corridor is bounded by narrow, NW-SE fault zones underlain by narrow salt ridges (Loncke *et al.*, 2002a) which is less typical. We used physical models to test whether such pattern was

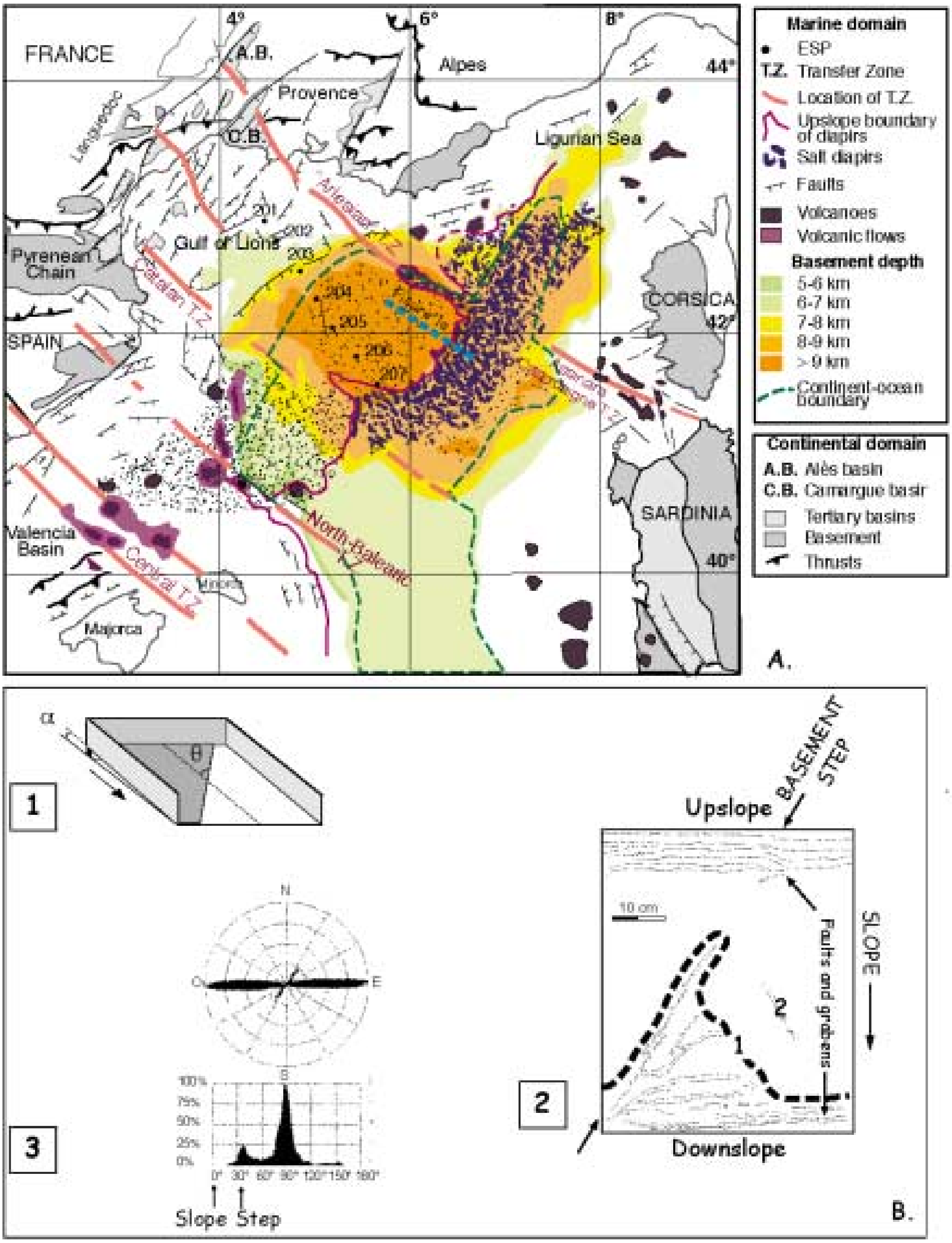

Fig. 2. **A.** Structural map of the northwestern Mediterranean Basin illustrating the depth of the basement top, the upslope limit of Messinian salt diapirs, and the transfer zones. Regionally, the upslope limit of the diapir province trends NE-SW, perpendicular to the slope direction, but also includes three NW-SE-trending reentrants located above the basement transfer zones. See text for explanations. **B.** Results of analogue models of gravity gliding above a residual topography (modified from Gaullier *et al.*, 1993). 1. Experimental set up, a: regional slope; q: angle between the slope-line and the basement step direction. 2. Line drawing of the surface deformation (with a: 2,8° and q: 30°, 1: upslope limit of downslope fault province, 2: edge effets). 3. Corresponding statistical analysis of fault directions.

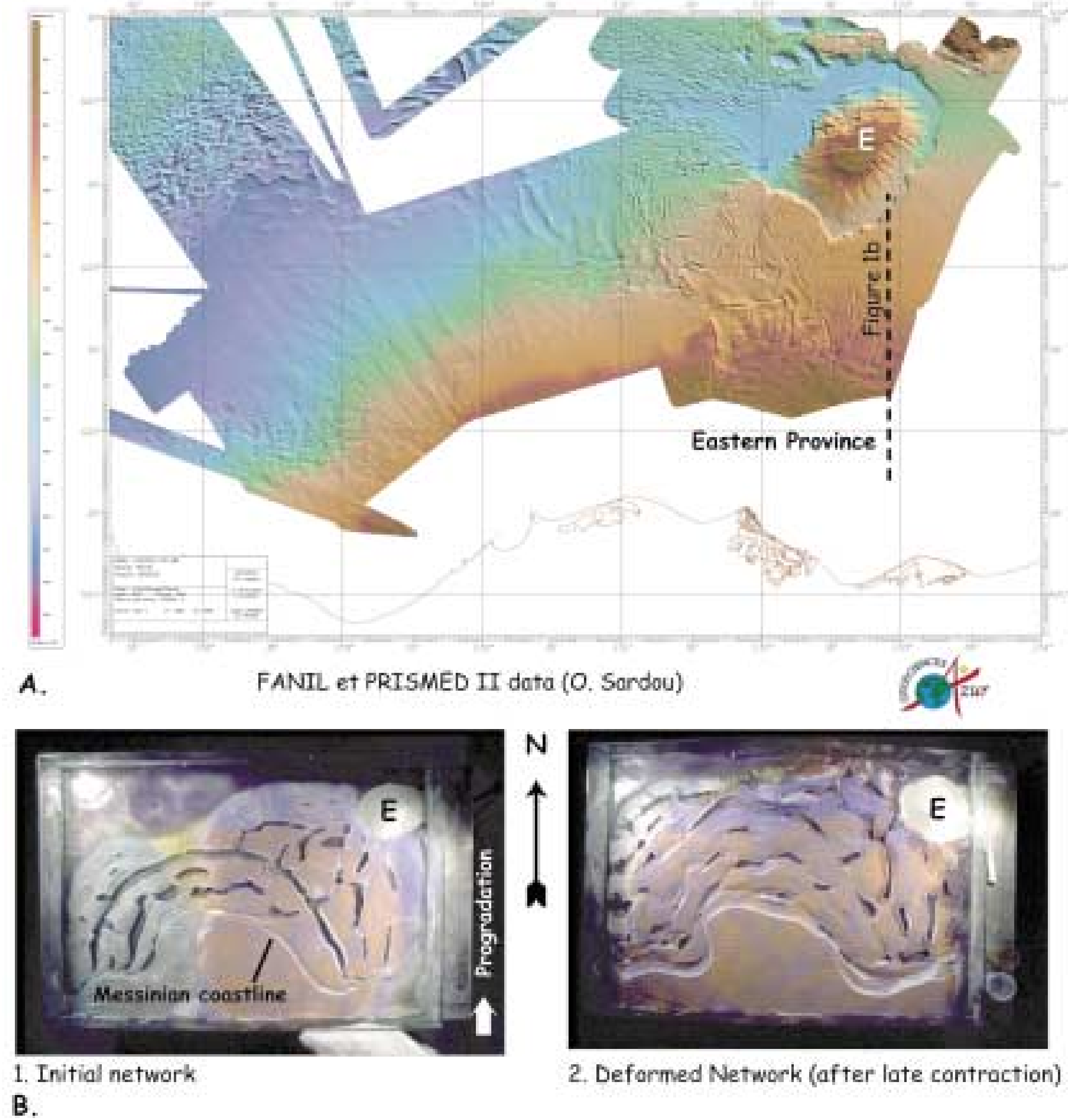

Fig. 3**. A.** Bathymetric map of the Nile Deep-sea fan acquired during the Prismed II and Fanil cruises. **B.** Overhead photographs of a physical model of gravity spreading during progradation. 1. Early stage showing radial and concentric fault-bounded salt ridges. 2. Late stage showing the reactivation in strike-slip of NW-SE structures, owing to the buttressing effect of the Eratosthenes (E) Seamount.

caused by the presence of NW-SE dormant or active subsalt relief or of a bathymetric high (the Eratosthenes seamount) acting as a buttress during spreading. Model results clearly indicate that the presence of a passive subsalt relief and/or of a buttress, rather than that of an active subsalt relief, has caused this peculiar structural pattern (Fig. 3b). Early gravity spreading caused radial thin-skinned extension (Fig. 3b1, Gaullier and Vendeville, under review) and the formation of minibasins and NW-SE and ENE-WSW salt ridges, a pattern also enhanced if basement steps are present. Later, buttressing by the seamount opposed further northeastward extension (Fig. 3b2). The salt and overburden spread northwestward, reactivating the NW-SE salt ridges as strike-slip zones bounding the corridor.

Shallow structure of the Nile deep-sea fan: interactions between structural heritage and salt tectonics; consequences on sedimentary dispersal

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INTRODUCTION

The Nile deep-sea fan is the largest sedimentary clastic accumulation within the entire Mediterranean (about 100 000 km^2). This deep-sea fan has been surveyed during two marine geophysical campaigns (PRISMED II and FANIL in 1998 and 2000, respectively) using concurrently multibeam swath bathymetry, acoustic imagery (EM12 and EM300 echo-sounders), continuous 6 channels and a few 24 channels HR seismic reflection. As a consequence, and for the first time, the Nile deep-sea fan (NDSF) was nearly entirely mapped (Fig. 1). The cone which is bounded

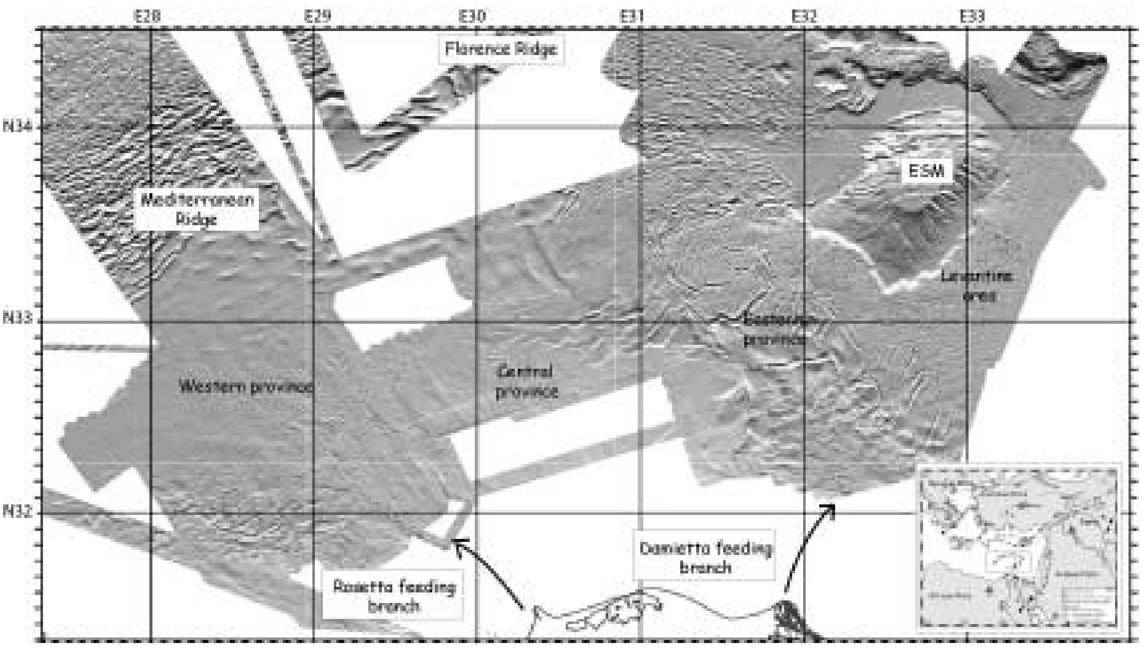


Fig. 1

northwestward, by the Mediterranean and Florence Ridges features formed in response to the subduction of the African plate beneath southern Europe, is limited to the northeast by an almost flat-topped sub-circular seamount (Eratosthenes seamount, ESM) believed to have rifted away from the Levant margin (Mart and Robertson, 1998; Guiraud and Bosworth, 1999).

The aim of this study using swath bathymetry, seismic data and physical modelling, is to propose a comprehensive synthesis of the Nile deep-sea fan shallow structure and evolution. Special attention is given to the impact of the structural pattern on post Miocene sedimentary dispersal mechanisms.

Geological background

Believed to have initiated in the Oligocene times, the Nile cone lies on a mesozoic passive margin segment. In Oligocene the surrounding continental area has partly been reactivated as a consequence of the Red Sea rift southern opening which, later on, propagated to the north following two distinct branches: the NW-SE oriented Suez Rift branch, and the NE-SW oriented Dead-Sea shear. The Suez rift is believed to have extended as far as the present offshore Nile delta; its activity slowed down, or ceased, around 15 My, when the main motion between African and Arabian plates was transferred to the East. In Messinian times a strong sea level drop affected the entire Mediterranean and has led to deposition of thick evaporites. During the same time span, ESM was emerging, eroded and strongly karstified. In early Pliocene, the Mediterranean Sea was refilled and throughout Pliocene, until present day, Messinian evaporites and subaerial deposits were progressively covered by a wide deep-sea fan. Simultaneously subsidence and block-tilting affected both the onshore and offshore Nile delta areas, as well as the southeastern Levant margin. In the meantime, ESM started to collide with Cyprus while the Mediterranean Ridge (MR) thrusted considerably in front of the Aegean subduction. While compression was operating on the Mediterranean Ridge and initiated on the ESM, the Egyptian and Arabian continental margins remained in a “passive margin” stage.

Post-Messinian package structure

The main morphostructural provinces of the cone have already been defined on the basis of bathymetric and backscatter data. They comprised a western, a central, an eastern and a Levantine province (Fig. 1). The western province is mainly characterized by a well-developed channel-levee system. The central province shows only very few channel-systems and a series of E-W trending growth faults forming a 200 km long belt. The eastern province is bisected by a more than 200 km long NW-SE trending tectonic corridor, and finally, east and south-East of ESM, the Levantine province shows few sedimentary channels and a gently folded surface.

The morphology of the three western provinces is controlled by similar processes: along dip, these domains exhibit a morphostructural progression which can be interpreted as typical of salt-bearing passive margins undergoing gravity spreading (Vendeville and Jackson, 1992 a,b). These include:

- in the western province: distal buckle folds (progressively incorporated into the nearby Mediterranean ridge), mid-slope diapirs, proximal regional and counter-regional growth faults;
- in the central province: distal buckle folds, mid-slope diapirs, proximal growth faults;
- in the eastern province proximal regional and counter-regional growth faults, mid-slope small polygonal basins surrounded by salt-ridges, distal buckle folds and, toward ESM, an important scarp (quite similar to the well-known Sigsbee scarp).

Along an upslope-downslope transect, the shallow structure of the cone thus appears strongly controlled by thin-skinned extension driven by the gravity spreading of the sedimentary overburden on salt (see concepts of thin-skinned extension in Vendeville and Jackson, 1992a and b). In a 3D model attempt (upslope to downslope but also from west to east), important contrasts (particularly within the eastern province compared to the other ones) and differences of maturity of salt-related structures, suggest however interferences of deeper inherited structures. A sediment package, deposited above salt, tends to spread parallel to the bathymetric slope, implying that the spreading direction and structural pattern of a lobate sediment load should be expected to vary in 3D with a certain amount of symmetry. Typically, the NDSF's structures cannot be understood using only cylindrical gravity spreading and gliding concepts.

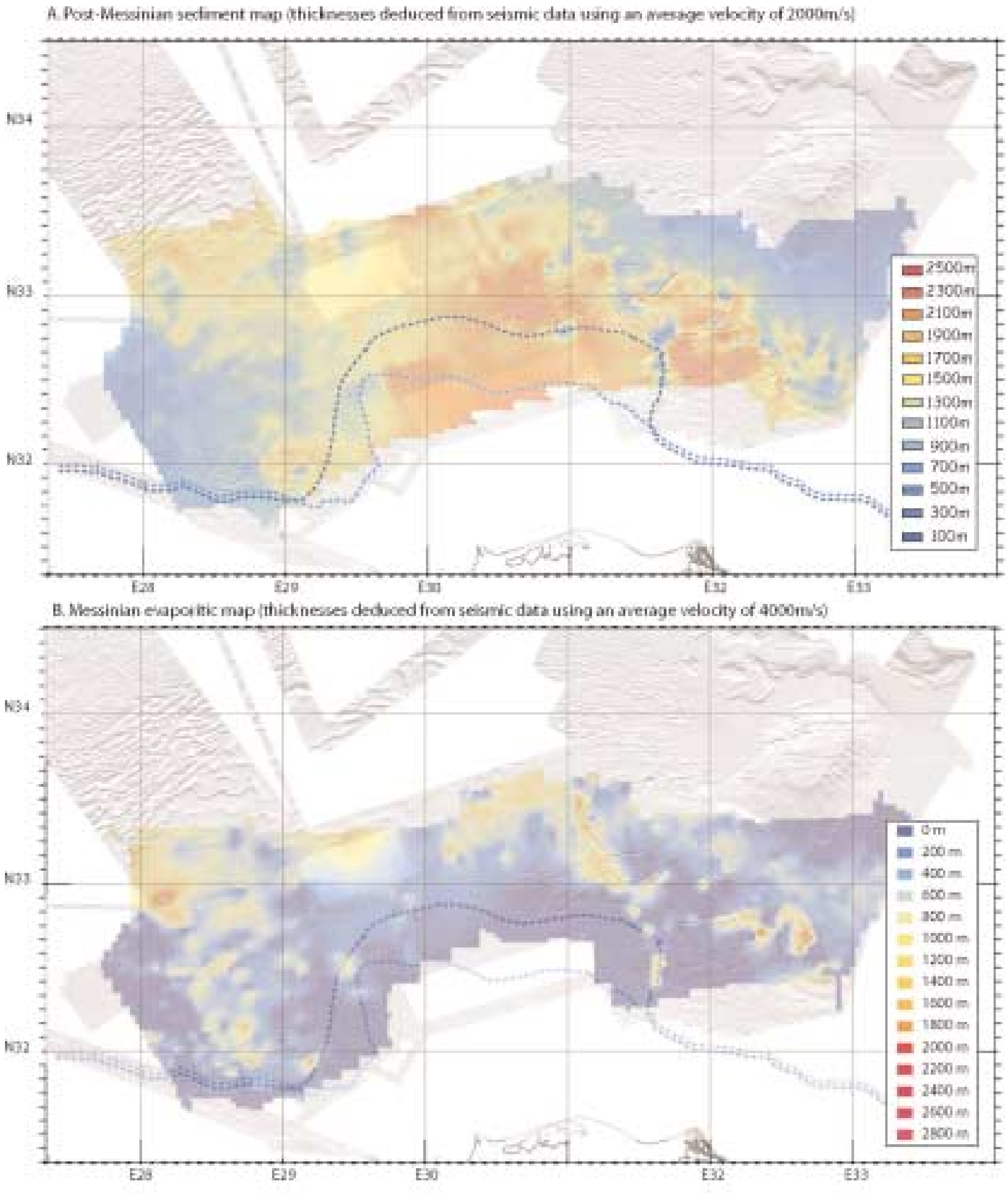
Different hypotheses have been proposed to explain the observed dissymmetry:

(1) Given the structural characteristics of the NW-SE tectonic corridor near ESM, we may infer that the seamount may act as a kind of passive butress preventing lateral spreading of the sedimentary cover and introducing, as a consequence, significant dissymmetries in the structural pattern.

(2) Alternatively, taking into account the orientation, the size and the location of the tectonic belt, we cannot exclude the possibility that this corridor may partly reflect an offshore extension of the Suez rift system (Mascle *et al.*, 2000; Guiraud and Bosworth, 1999).

PLIO-QUATERNARY AND MESSINIAN EVAPORITIC DISTRIBUTIONS

To assess the importance on the sedimentary distribution of potential deep-seated sub-salt reliefs, we have constructed two sediment distribution maps; one of the post-Messinian cover and one of the evaporitic deposits (see Figs. 2, 3). These two maps show an overall radial distribution, characterized, however, by two main depocenters: one depocenter approximately centered



Figs. 2 and 3

on the central province, a second within the southern area of the eastern province. The thickness of the sedimentary pile decreases progressively downslope while salt thickness (mobile layer) progressively increases; this tends to indicate that the proximal sedimentary overload has induced salt migration. Post-evaporitic sedimentary thicknesses can reach nearly 4 km, while salt thicknesses reach 2.8 km at the base of the cone near the Mediterranean ridge, and about 1km toward the ESM.

Our study also allowed to better define the boundaries of the salt layers which correspond in most cases to a Messinian slope/shelf break (Figs. 2 and 3). Towards the coast, this boundary shows a specific shape which suggests the presence of an underlying Messinian paleorelief centered around E30°30'. Above this promontory (which was likely a platform area in Messinian times), plio-pleistocene sediments are nearly horizontal and almost undeformed since there is no underlying mobile Messinian evaporites. Downslope, and until the abyssal plain, the Plio-Pleistocene package is by contrast often strongly deformed as a result of thin-skinned extension triggered by underlying gliding salt.

The Western province

In the upslope domain of this province, the plio-quaternary blanket is thickened by growth fault activity. The presence of growth faults, and associated residual salt rollers, indicate the previous presence of Messinian salt, which has progressively glided downslope. Downslope, both the salt layers and the plio-quaternary isopach maps show the presence of sub-circular depocenters, sometimes bounded by salt ridges. Near the Mediterranean Ridge, the salt layer becomes thicker (up to 2.8 km) as a consequence of its northward withdrawal and progressive gliding. Despite this rather standard salt-triggered pattern, an anomaly can be observed in the westernmost border of this province; this poorly sedimented and almost undeformed area, with a plio-pleistocene thickness on the order of only 700 meters, appears correlatable to a Messinian high (about 30 km wide and 50 km long) devoid of salt.

The Central province

Within this region, and according to industrial data (Abdel-Aal *et al.*, 2000), the salt southern limit fits with a Messinian paleo-shelf break extending until N32°40'. North of this feature, the post evaporites cover reaches 2,5 km, while the evaporites are very reduced or absent. The transition between salt occurrences and this paleo-slope is underlined by a long belt of anastomosed growth faults. Within this area, nearly all the evaporites seem to have been expelled downslope, except for a few salt rollers associated with growth fault's planes. Along the midslope, polygonal depocenters, well imaged on bathymetry, are characterized by drastic sediments thickness variations. Positive elongated and sub-circular topographies indicate salt pillows, while depressions represent thick syncline-shaped depocenters.

The Eastern province

In this province, the southwestern boundary of the salt follows a N-S oriented trend. Downslope the sedimentary distribution is more or less radially organized. N-S, E-W and NW-SE trending faults, and associated salt ridges, delineate numerous small polygonal depocenters. The structural corridor, well shown on bathymetry, does not show any significant thickness contrast with respect to the central province. Within this corridor we observe the following zonation:

- on the upper slope a strongly fractured area, interpreted as a region where previous depocenters have collapsed; there, the brittle, post-Messinian, cover is particularly thick, and no evidence of salt can be observed on seismic data with the exception of some residual salt rollers associated to growth faults;
- crestal grabens (well evidenced on bathymetry) associated to local salt thickening, characterize the middle slope, where the thicknesses of the sedimentary cover remain almost constant while the salt thickness progressively increases;
- downslope, the overburden's thickness decreases while the salt layers, which may reach thickness up to 1000 meters, are affected by a series of gentle arcuate folds well marked on the seabed.

The Levantine province

Finally, east of the NW-SE corridor, in an area which corresponds to the easternmost edge of the prograding deep-sea fan, the thickness of the overburden decreases progressively, from 1700 meters on the upper slope to about 100 meters just east of ESM. Facing ESM exists a plateau-like domain, where up to 1000 meters of salt are detected at depth, bounded by an about 400 meters high scarp delineating the northward extension of the salt layers. NE of Eratosthenes seamount, a drastic thinning of the salt layer is associated with an acoustic basement high which corresponds to an eastwards, hidden, extension of ESM (Figs. 2 and 3). Above this feature, the plio-pleistocene cover is thin (about 200 meters) and strongly folded; this indicates an active northward translation of the sedimentary cover, although its salty sole appears quite thin.

SYNTHESIS

1. For the entire Nile cone, the structural zonation as observed across the slope can be regarded as typical of gravity spreading of a brittle overburden on a mobile layer. The differences between the provinces can mainly be attributed to differential maturity of salt tectonics which relate in turn to initial salt thickness and distribution (i.e. Messinian paleotopography) or/and local plio-pleistocene sedimentary input variations.

2. The absence of significant plioquaternary thickness variations between the central and eastern province suggests that the tectonized corridor is not the simple prolongation of an active NW-SE graben related to the Suez rift system, but rather a consequence of interactions between the ESM butress effect and pre-Messinian structural heritage.

3. This hypothesis is supported by a kinematic sketch deduced from the integration of bathymetric and seismic data and isopachs analysis (Fig. 4). This sketch shows that most of the deformation can be accommodated along observed NW-SE lineaments bounding piano-key like blocks. These blocks are thus moving independently one from the other. In terms of tectonic regimes we observe, from SE to NW, a gradation from an extensional to a transpressional regime.

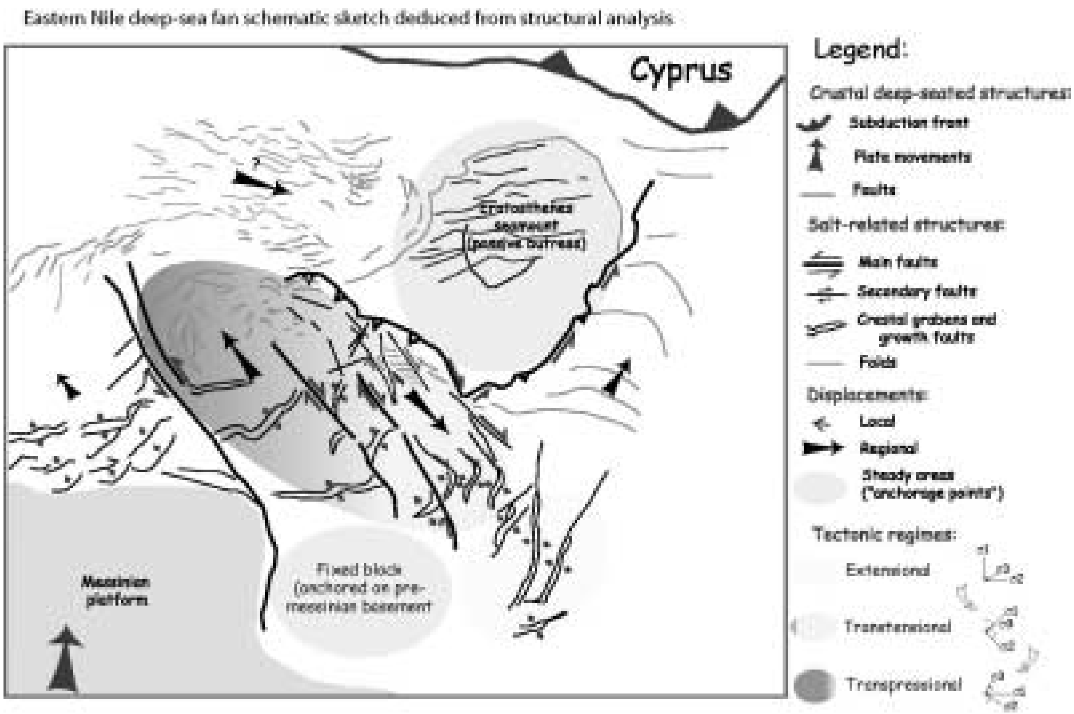


Fig. 4.

In summary, both the structural analysis and the sediment isopach maps, suggest that chiefly Messinian topographies, potentially inherited from previous structures in the eastern and western provinces, and a wide Messinian platform acting as a promontory around E30°30', have exerted direct bearing on subsequent gravity spreading.

IMPLICATIONS FOR SEDIMENTARY DISTRIBUTIONS

The somewhat particular structural pattern of the NDSF, which results from complex interplays between pre-Messinian/Messinian inherited features, and gravity spreading, has direct impacts on the present day sedimentary dispersion processes. As a matter of fact, turbiditic channel systems are drastically different between each major province. In the eastern province, the depositional system appears strongly segmented while channels-levees are highly ramified in the central and western cone domains where they spread on large areas (see Bellaiche *et al.*, this volume). Such a differentiated sedimentary pattern seems to have been prevailing during most of plio-pleistocene times (Loncke *et al.*, 2002b and Abdel-Aal *et al.*, 2000), even if channel-levees are, at present, chiefly observed in the western province, and seem to have been only relatively recently covered by debris-flows in the central one (Loncke *et al.*, 2002b). In the distal part of the central province, a few channels, recently disrupted by salt-related tectonics, are still seen on bathymetry. In the eastern province, active tectonics impacts differently on sediment distribution mechanisms. In some areas, fault trends are directly channelizing turbiditic, while elsewhere, particularly within the middle slope polygonal depocenters area, fault activity is strongly disrupting the channel systems. Similarly faulting seems to have triggered numerous destabilizations now interbedded as lenses within turbiditic deposits (Loncke *et al.*, 2002b). The numerous small pounded basins, characteristic of this province, are thus filled by confined turbiditic sequences and interbedded lens-shaped debris flows. Such rather specific geometric and sedimentological characters may be promising for petroleum exploration.

CONCLUSIONS

A combination of structural analysis with physical experiments highlights the importance of the heritage on the shallow structure and evolution of thick clasctic piles deposited on mobile layers. It appears thus fundamental to take into account this parameter to better understand modern fans' architecture and evolution even if these features are decoupled from their passive margins "basement" by mobile layers such as salt deposits or shales. Several major deep-sea fans are concerned by these results, particularly within the Mediterranean sea where the Messinian salt layers are widespread (Gulf of Lions, Ebro), or along the Atlantic margin where mobile shale or salt layers are incorporated into margin sedimentary covers (North sea, Nigeria, Angola, Gulf of Mexico, etc.).

Finally, the specific structure of the Nile cone offers a particular pattern which controls not only the sedimentary dispersal and depositional processes, but also the distribution of fluid releases on the seabed (see Mascle *et al.*, this volume).

The Nile deep-sea fan and its channel-levees system : results from the PRISMED II and FANIL cruises

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INTRODUCTION

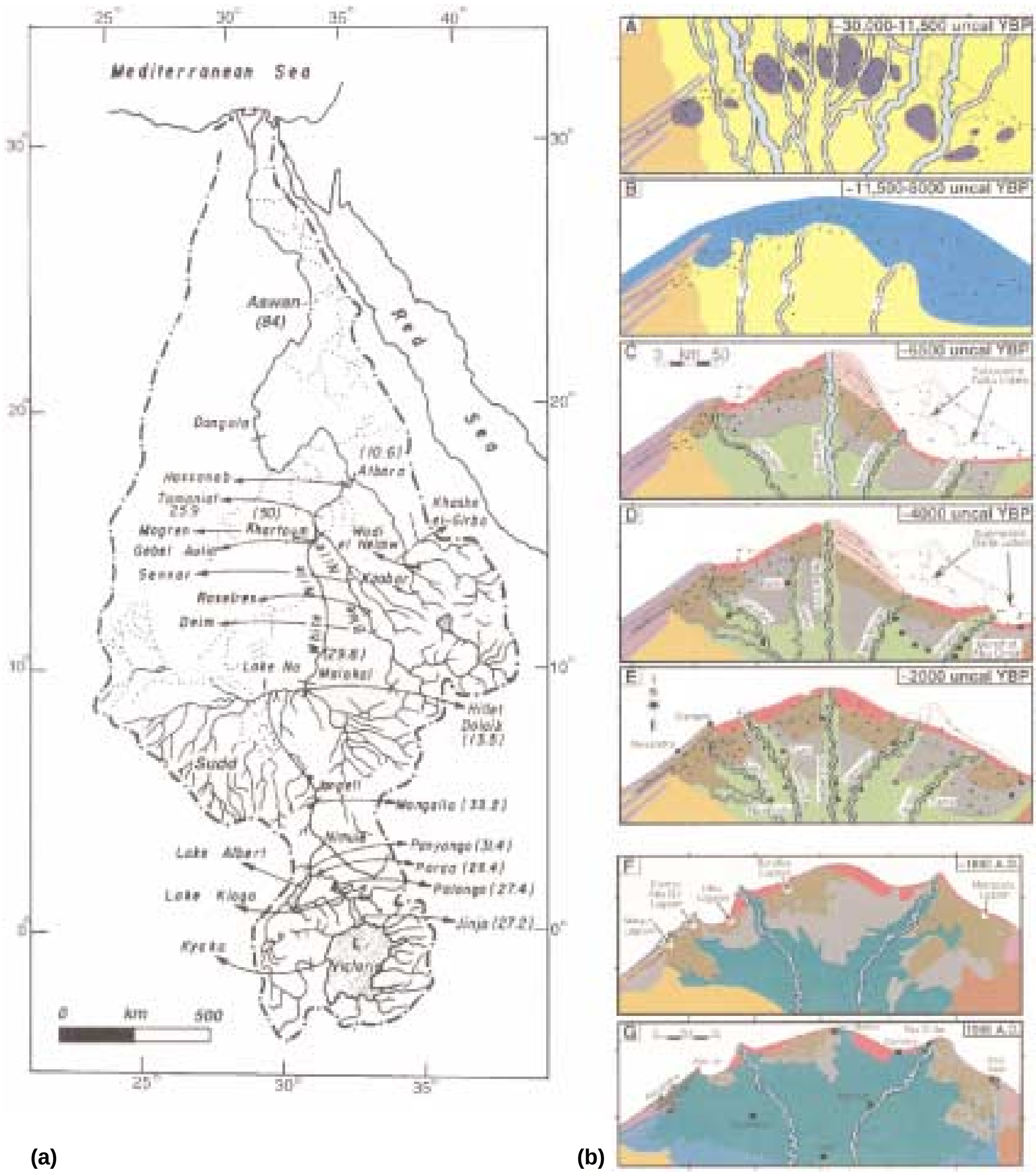
More than 6000 km long, the Nile is the longest river in the world. The map of its drainage basin (Fig. 1a), shows that the Nile valley extends approximately longitudinally, south to north so that its crosses different climatic zones: equatorial, tropical and temperate. It also drains very high mountains, some exceeding 4000m high in East Africa. This is very important with regard to the hydraulic regime of this river, and to its terrigenous influx offshore, during the different climatic epochs.

GEOLOGICAL EVOLUTION OF THE NILE VALLEY SINCE THE END OF THE MIOCENE

We know, thanks to the boreholes of the Assouan high dam (Chumakof, 1973), located more than 1000 km inland, that at the end of the Miocene, during the Messinian epoch, the Nile valley deeply cut, over 2 km deep, the African crystalline basement. In parallel, far offshore, the late Miocene palaeo-Nile river formed a very huge old fan called by Ryan (1978) the “Alexandria Fan”. This old fan appears very deeply entrenched by the Messinian erosion just before the deposition of the Messinian evaporitic series. After this event, some seismic data from oil companies, show that during the entire Plio-Pleistocene epoch, the Nile deep-sea channel networks were widespread all over the Egyptian continental margin.

HISTORICAL EVOLUTION OF THE NILE CONTINENTAL DELTA

Stanley and Warne (1998) showed, thanks to very numerous drills, that the present Nile continental delta has been built during the decrease and the stabilization of the sea-level rise, that is to say approximately 8,500 years BP. The Nile delta is the result of active sedimentary construction since this period of decreasing and stabilization of the sea-level rise. At that time, the Nile had four to five branches working simultaneously or successively (Fig. 1b). But the delta morphology changed radically about 2,000 years ago. From a “river dominated” type before 2.000 years, it became a “wave dominated” type, with only two main branches functioning, the Rosetta branch on the West and the Damietta branch on the East, both artificially maintained by man. A dramatic increase of this “wave and current domination” occurred very recently, with the starving



(a) **(b)**

Fig. 1. **(a)** Map of E-central and NE Africa showing Nile river drainage basin and 1920-1982 average discharge in billion cubic meters (in brackets) of river water. Mean annual flow to Egypt during the 20th century is 84 millions m3 (after Said, 1993). **(b)** Time-slice paleogeographic map depicting the evolution of the northern Niledelta from -30,000 years BP to present (modified from Stanley and Warme, 1998).

of the terrigenous sedimentary influx offshore, due to the Assouan dam construction. This leads actually to an important and catastrophic retreat of the coastline.

During the Pleistocene low sea-level, it is noteworthy that numerous branches of the Nile river existed. That is to be correlated with the widespread repartition of the Plio-Pleistocene deep-sea channels at this epoch as deduced from the seismic data.

THE NILE CONTINENTAL SHELF

The shelf is large, about 60 km wide. It is covered, especially in the inner shelf, by terrigenous muds, sands and silts, and, in the outer shelf, by bioclastic calcareous sediments (maerl, coralline reefs, etc). Three main characteristics noticed in this shelf can be with important consequences for the fan construction. First, this shelf is submitted to a strong eastward current, part of the

Mediterranean cell, transporting the sediments, and even the coarse sands, along the coasts of Egypt and Israel. Secondly, it is deeply cut by the submarine canyon connected to the Rosetta branch of the Nile. And thirdly, the outer shelf is submitted to important mass wasting processes.

THE NILE DEEP-SEA FAN

Only two regions (Fig. 2) display very fresh networks of deep-sea channels : the western and the most eastern region (Levantine region).

The western region displays mainly three main nets of channels, themselves branching into secondary channels, that can be followed downslope, very far. The easternmost channels of this domain appear rather old since their course is often interrupted locally by mass flow deposits.

The westernmost channel appears to be the most recent. It is in direct connection with the still active Rosetta canyon. This channel branches into two channels, the eastern branch appearing inactive since it is sealed by remobilized sediments, very close to the branching.

The western branch of this main channel is therefore the most recent. It is very continuous and meanderous. At one point, it is branching into three E-W trending channels, and thanks to the very good precision of the multibeam sounder Simrad 300, it was possible, in this branching region, to analyse the different stages of channel evolution as well as their main controlling factors. First an old and very large abandoned meander is seen just before the branching, showing several parallel ridges on its outer left levee, representing probably migrating waves due to the action of overflowing turbidite currents.

The southern channel of the three branches appears to be the oldest since it is no longer connected to the main channel. As for the intermediate channel, it has been clearly subjected to migration processes towards the south, since several slides, marked by very clear scars, affect its old right levee. So, the collapse of the levees appears to be one of the main factors controlling the channel migrations. This can be illustrated by several cross sections showing clearly the morphology of the scar, and the corresponding deposit of the destabilized sediments, forcing the channel to migrate towards the south. As for the northernmost channel, the most recent in appearance, it is very sinuous and very continuous. Very far downslope it branches into two channels but here we reach the limit of the performance of the Simrad 300. However a special processing

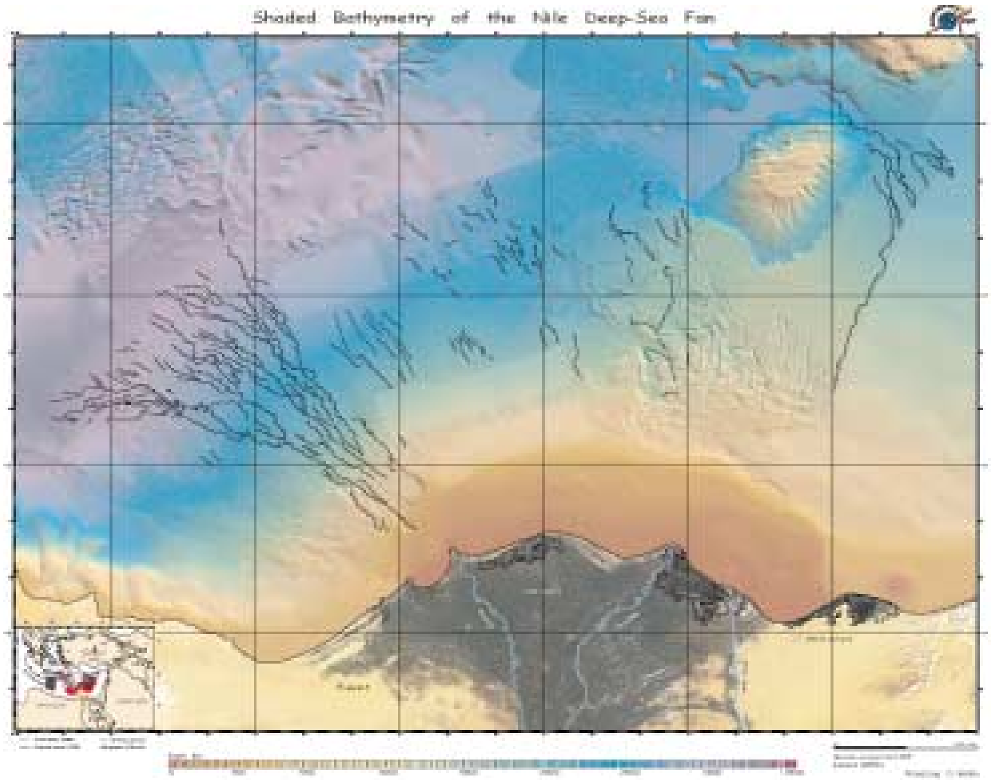


Fig. 2. The present network of Nile deep-sea fan deep-sea channels

of the data, made by Olivier Sardou and Jean-Marie Augustin, still permits to recognize, in the bathymetry, the lobe deposits linked to this channels : in this very distal sector, where the water depth exceeds 3000 m, their altitude is less than 5 m. But these lobe deposits are very clearly recognized in the acoustic imagery map showing, in dark tones, the large extension of the sediment discharge of the channels in the distal zones.

The channels of the central and eastern area. Although they have been widespread in all this sector during the Plio-Pleistocene times, these channels presently appear very scarce, discontinuous and disrupted. This can be explained by recent tectonic movements (especially salt tectonics) and by a recent covering of all this region by pelagic sediments, and mass flow deposits.

In the Levantine region located east of the Suez canal and of the Eratosthène Seamount, we can observe a very long, fresh and sinuous channel, trending NNE East of the Eratosthène Seamount, this channel merges with another network of sinuous channels that seem to originate from the easternmost part of Egypt, Israel and Lebanon. The whole network merges NE of the Eratosthene Seamount and the sediment discharge occurs in the basin located between Eratosthene and Cyprus.

Unfortunately the data do not permit to determine from which region exactly these channels originate, since the upslope areas have not been surveyed. However if we refer to a study by Almagor and Hall (1984), the long NNE evidenced channel is connected to a network of channels originating from the Sinaï peninsula. The other channels are to be connected both to the El Arish canyon and wadis, also located in the Sinaï peninsula, and to channels originating from the Gaza strip, Israel and Lebanon. A confirmation is given from the map of the Plio-Pleistocene channels established by the oil companies.

One is struck by the freshness of these channels, and particularly of the Sinaï channels, with respect to the actual extreme dryness of this region. Presently the Sinaï is drained only by some dry or episodic wadis. But during some periods of the Pleistocene and also the beginning of Holocene, this desertic region was luxuriant. So, either we have to admit that these channels can be reactived from time to time, by recent catastrophic floods, or we must admit that the morphology of the channels can remain unaltered during very long periods of time.

The Nile deep-sea fan construction

It is possible to have some indications about the age of the building of the Nile deep-sea fan thanks to the two long piston cores sampled during the Fanil cruise in the most recent channel and in the lobe.

The core sampled in the lobe shows that the Holocene is represented by the superficial layer, from the top to about 70 cm. It is made of very light colored deposits, with a succession of pelagites, sapropel (>S1) and turbidites layers, This whole unit, and even the turbidites, is very rich in carbonates with values reaching 70%. The underlying deposits are made, on at least 7m length, of terrigenous turbidites with a very low content of carbonates. The core sampled in the most recent channel shows approximately the same facies except that the Holocene deposits are thicker (1,50 m).

The occurrence of Holocene turbidites rich in carbonates means very probably that the Nile deep-sea fan is still continuing to be built, even during the actual high sea-level environment. An explanation could be that during the Holocene, the carbonated sediments of the shelf are remobilized by the currents and by mass wasting processes, and shed directly into the Rosetta canyon, where they are channelled until the distal parts of the fan.

More sampling and analyses are needed, but a first conclusion would be that, as other deep-sea fans in the world, it is essentially in an low sea-level environment, during the glacial epochs of the Pleistocene, that the Nile deep-sea fan has been mainly and actively constructed, by turbidites made of Nilotic siliceous sediments. This construction is alternating with the delta construction, occurring rather during the high sea-levels periods. However, in the case of the Nile, the fan construction is still in progress, since the feeding canyon is deeply entrenching the shelf, itself submitted to active sediment remobilization.

New data from the easternmost Nile system : the GEMME project

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In order to investigate the tectonic and sedimentary setting of the southern Levantine continental margin as well as the Late Quaternary paleoceanography of the outer Nile Cone a geophysical and geological survey was carried out in the eastern Mediterranean between 4 February and 7 March 2002 (Fig. 1). For the so called Gemme project the German research vessel *Meteor* (cruise M52/2) operated for five weeks in the territorial waters of Israel (Leg A; 4-25 February) and Egypt (Leg B; 26 February to 6 March). The data set includes two refraction lines (15 OBS, 5 OBH on each line) and about 2500 km multichannel seismic data (44 profiles, Fig. 2). A magnetometer (gradiometer) was deployed along the reflection seismic measurements. Gravity and hydroacoustic data have been collected continuously on a 24/7 schedule. About 3500 km of relevant potential field data have been gained. About 30 piston cores including multicorers have been collected along four selected profiles, the sample sites have been carefully selected from the hydroacoustic systems, which include swathsounder data (Hydrosweep) and 4 kHz narrow beam echo sounder data (Parasound). The multicorer samples and gravity corer samples permit the investigation of the complete Holocene sequence.

The first objective of the geophysical part of the program was to reconstruct the Plio-Quaternary evolution of the continental margin of southern Israel by means of sequence stratigraphy, including interpretation of seismic data during the first project period, and modeling in the second one. The Post-Messinian sediment prism is considered to represent the easternmost deposition center for Nile derived sediments. This analysis should assist in understanding local as well as regional stratigraphic and tectonic features like strike-slip movement and constrain quantitative parameters such as subsidence, sedimentation rates and sea-level changes. Correlation of local sequence boundaries with global and Mediterranean events may provide age constraints to the processes mentioned above. The second objective was to create a 3D-model of the entire crust consisting of crystalline basement, pre-, syn-, and post-Messinian layers. This model, which will be based on potential field, refraction seismic and industry reflection seismic data, represents the tectonic frame and is crucial for any subsidence analysis. The specific scientific questions were:

1 - How did channel levee complexes evolve on the outer Nile Cone?

2 - How did the Post-Messinian sediment prism off reflect the interplay between sediment input, transport mechanisms, uplift and subsidence, halokinetics, and sea level and climate?

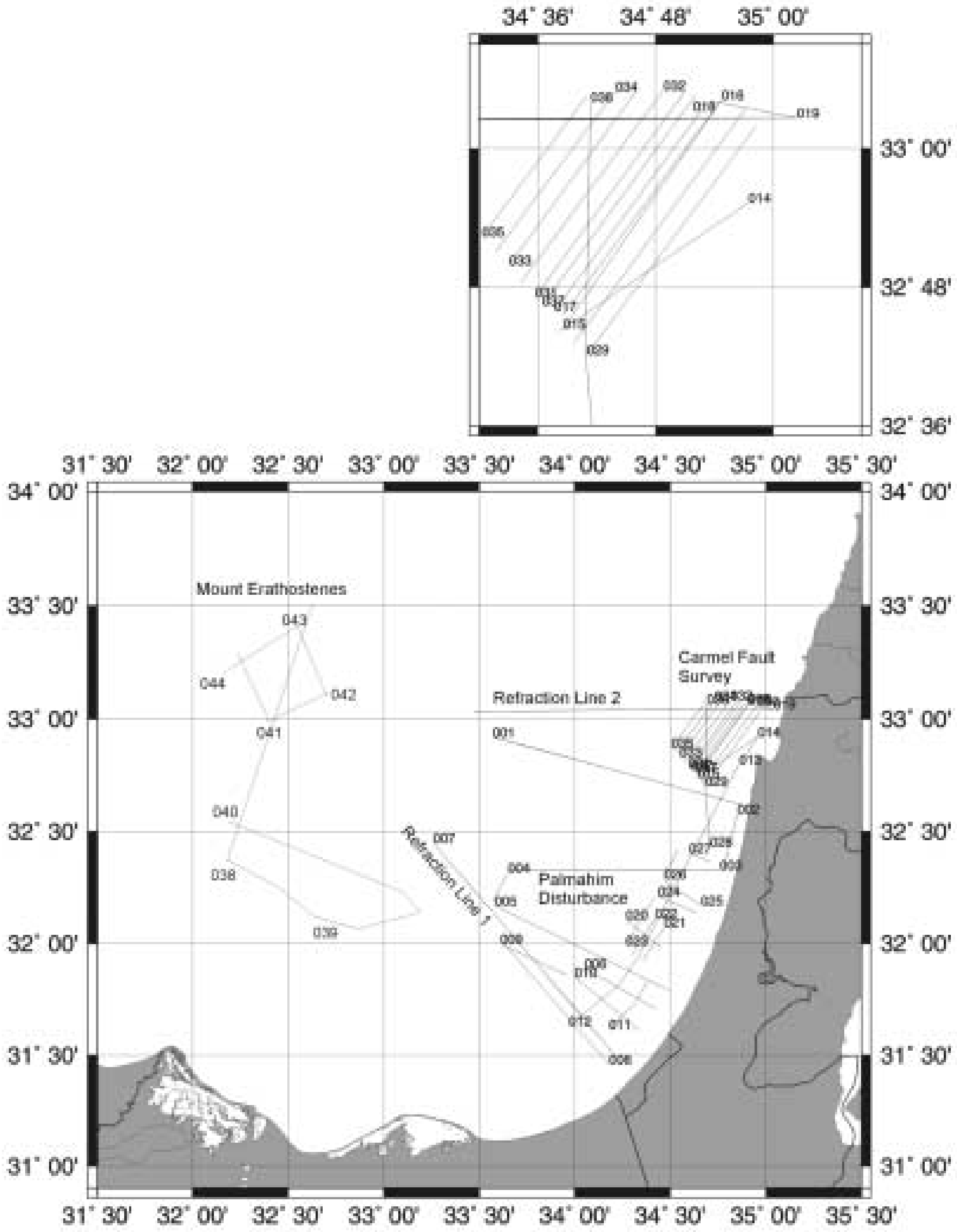

Fig. 1. Seismic lines of the GEMME project (RV *Meteor* cruise M52/2)

3 What is the source of gassy clastic sediments above the basal Pliocene unconformity?
4 - What is the relation between chemoherms, faulting, and gas/fluid migration?
5 - What caused the dominant disturbances (Gaza, Palmahim, Dor) along the continental slope off Israel? Do they reflect sedimentological or tectonical processes?
6 - Of what kind is the transition from south to north of the Carmel fault in terms of basement and sediment structures?
7 - How important is the Pelusium lineament regarding the dynamic of the ocean-continent boundary? Is it an elongated basement structure or a local sediment feature?
8 - Where is the transition between oceanic and continental basement in the eastern Mediterranean, and what is the relation to the Dead Sea Transform Fault?

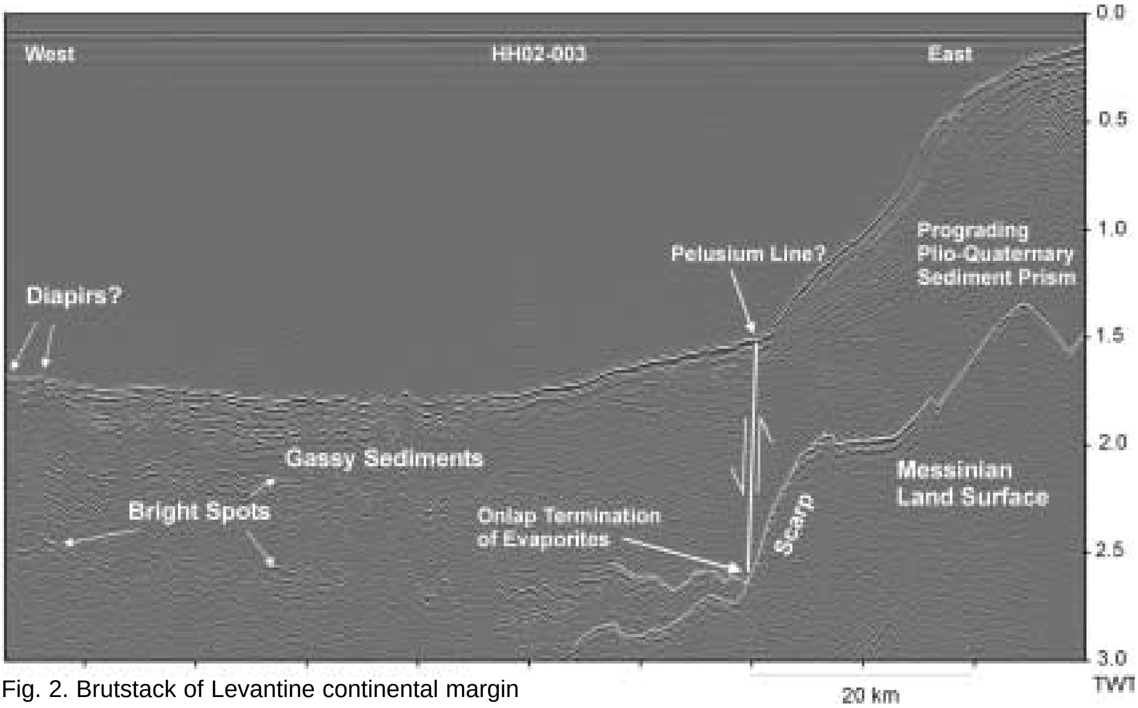

Fig. 2. Brutstack of Levantine continental margin

A striking observation in the reflection seismic data was that the landward termination of Messinian evaporites coincides with faults in the Plio-Quaternary sediments above. At the northern margin, where the termination is located beneath the slope, faults have been produced within the prism. Frequently pinnacle like structures can be observed on the seafloor in the vicinity of the faults. To summarise the occurrence of pinnacles it can be stated that they occur above faults or slumps. We assume that slumping or faulting interrupts stratigraphic seals, which prevent upward gas migration. At the seafloor carbonates may be produced when calcium is taken from the water column and carbon from methane. Off Haifa we investigated the tectonic activity of the Carmel (Yagur) fault with 18 MCS lines. A newly discovered active fault proves the tectonic activity of that region. The landward prolongation of this fault aims at the region south of Mount Carmel and was not known before. The final seismic profile grid covers the transition from the southern Eratosthenes Seamount to the Nile Cone. Messinian evaporites and the Nile derived Plio-Quaternary cover sequences stop abruptly at the southern flank of the seamount at the so-called Nile Scarp. A magnetic and gravity anomaly, indicating basement structures and the presence of low-density salt respectively mark the northern Nile Cone. All together five MCS lines cross the Nile Scarp to investigate tectonic activity of this region.

The paleoclimate history of the Nile deposits will be studied from the extensive sediment core collection. Four different sediment profiles were covered, i.e. three core transects representing the three different provinces (western, central, eastern) of the Nile fan and one core transect across the continental margin of southern Israel. High resolution dating by AMS ^{14}C will reveal detailed chronologies in proximal and distal provinces of the marine Nile fan. A set of high resolution logger methods (color, MSCL-Data, XRF-Scanner) will be used to establish sedimentological and geochemical chronologies of the Nile fan sedimentation. High resolution geochemical (C_{org}, $CaCO_3$) and stable isotope chronologies ($\delta^{18}O$, $\delta^{13}C_{CaCO3}$, $\delta^{13}C_{Corg}$, $\delta^{15}N$) will reveal climatic and oceanographic changes in the southeastern Mediterranean under the impact of the Nile. Special emphasis will be given to reconstruct the late glacial and Holocene climatic record and to compare it with the terrestrial archives of African and Middle East climate change (Nile delta deposits, African lake deposits, cave deposits in Israel, evaporitic deposits of the Dead Sea). These climatic reconstructions will contribute to the overall collaborative project by adding new high quality sediment core records to the ongoing research on the Nile fan. The overlap and combination of multicorer and gravity corer cores will enable us to study an undisturbed sediment sequence from recent sedimentation to the last glacial period. It will be also possible to reconstruct changes in sedimentation in post-Aswan dam times. To better understand land-ocean interactions it will be necessary to link our high resolution marine sediment records with terrestrial paleoclimate archives. We also expect an improved understanding of the impact of short term global climatic changes (i.e. Little Ice Age, Medieval Warm Period, mid-Holocene termination, 8.2 ky event, Younger Dryas) on the deposition of Nile sediments and the climate of the south-eastern Mediterranean.

Evidence of fluid escape structures, mud volcanoes and gas chimneys on the Nile Deep Sea Fan

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At continental margins, geochemical fluids are emitted into the ocean via the sea floor using most of the time tectonic features (thrusts, faults) as conduits. The forms of their emissions vary, however, from diffusive fluid flow to focused flow through seeps and vents, commonly associated with over-pressured mud constructions (mud volcanoes).

Until recently most of discoveries and studies of fluid seepages have been made on active margins, where fluid emissions on the sea floor are believed to relate to compressive stresses generated in such a setting (Milkov, 2000). For example numerous mud volcano fields and associated fluid seeps have been described, sampled (Ivanov *et al.*, 1996) and analyzed directly in situ (MEDINAUT/MEDINETH, 2000) on the Mediterranean Ridge (and surroundings), a large accretionnary prism. in the eastern Mediterranean basin (see discussion in Huguen, 2001).

Increasing developments of researches on the deep offshore, particularly at passive margins, using swath mapping and 3D seismic techniques, have now demonstrated that mud volcanism and fluid seepages are also a widespread phenomenon in this setting. Mud volcanoes have recently been discovered and studied for example off Norway and in deepwater Nigeria (Graue, 2000).

Systematic swath mapping (bathymetry and backscatter images) and seismic profiling (including some oil industry 3D seismic data) recently recorded in deepwater Egypt, over the Nile deep sea fan, have also revealed the presence, on the sea floor, of many morphological features interpreted to be evidences of fluid escapes and/or associated mud flows. Data show that these features are variably expressed as pock-marks, mud volcanoes and/or important sub-circular and flat mud “cakes” (Loncke *et al.*, 2001 a and b). These data have shown that the Nile cone can be subdivided, on the basis of its morphostructure, in several contrasted provinces (see Loncke *et al.* and Bellaiche *et al.*, this volume).

In the north-western province, characterized by a widespread active channel-levee system, an extensive field of small cones (few hundred meters in diameter for only few tens of m in elevation) has been discovered on the lower continental slope, at depths ranging between 2600 and 3000 m. One of these conlets has been sampled by coring and has yielded, below a thin hemipelagic and turbiditic cover, a grey, bubbly, and structureless mud indicating recent mud expulsion. In the same slope area, a few sub-circular, caldera-like, subdued depressions (up to 8 km in diameter and only few meters. deep for the biggest one) are detected on the sea floor.

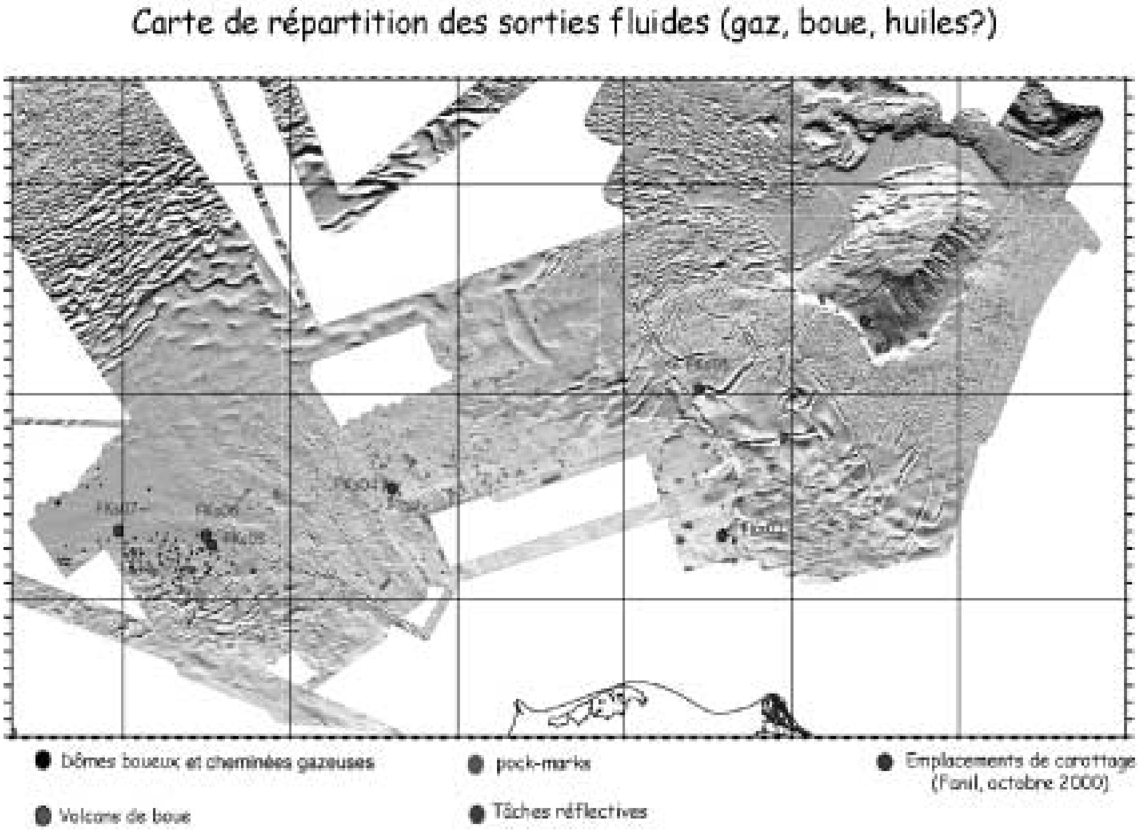

Figure. Distribution of pock marks, mud volcanoes and gas chimneys on the Nile deep sea fan as deduced from swath bathymetry, backscatter images and a few industry data.

These features are believed to result from sedimentary collapse following the emission and flow of a large volume of underlying, over-pressured shale and mud. This mud volcano field is clearly associated with a belt of growth faults that cut across this area of the continental slope, and are triggered by downslope displacement of underlying mobile Messinian salt layers. Sediment overloading is suggested to be the mechanism responsible for fluid migration and associated eruption on the sea floor of overpressured muds, whose stratigraphic levels are still unknown. Seismic data support that fluids and shales are likely using the growth faults as conduits to the sea floor.

Clusters of sub-circular large mud volcanoes, and a few isolated important “mud cakes”, are detected in several regions of the upper slope, around 800-1000 m of water depth. These features, which reach diameters up to 3/4 km, are characterized on seismic data by transparent or chaotic signatures. They are often surrounded by circular subdued depressions and may occasionally show evidence of lateral mud flows. A seabed core, from one of these mud volcanoes from the eastern Nile deep sea fan province, has yielded several meters. of strongly degassing, bubbly and grey mud indicative of gas uprising. These mud volcanoes and/or gas chimneys are either associated to deep anastomosed fractures, well imaged on 3D seismic data, or to sets of bathymetrically expressed faults, particularly in the eastern domain of the Nile cone.

Finally pock-marks, barely expressed morphologically, but well revealed by specific backscatter signatures, appear quite widespread in several domains of the deep sea fan, particularly within its central province, where there is evidence of important sedimentary slumps and debris flows.

On the Nile cone the distribution of fluid releasing structures and associated mud constructions seems to be not accidental (Mascle *et al.*, 2002) : (1) Clusters of large mud volcanoes and /or gas chimneys are always located on, or nearby, sets of active faults or fractures, cutting across the sedimentary cover of the upper continental slope. These tectonic features, apparently triggered for some of them by underlying salt displacement, are likely acting as conduits for fluid and mud emissions. (2) Surprisingly, the north western province of the cone appears to be the only one where a large field, including numerous small mud volcanoes and a few caldera-like features, is seen on the lower continental slope. These features are believed to be associated to sedimentary overloading, itself a consequence of growth fault activity on fluid-rich underlying sediments. (3) A relationship between fluid emissions on the seabed and the presence, or not, of Messinian evaporites at dept is suggested by the distribution of all these fluid releasing features, pock marks/mud cones/gas chimneys (Fig. 1) which appear particularly in areas where Messinian evaporitic formations are not detected.

River Danube-Black Sea geosystem. Birth and development.

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The River Danube-Black Sea geosystem represents one of the largest river-ocean systems in Europe; it is geologically and environmentally of first order of importance at continental scale.

THE RIVER DANUBE

The first term of the system, the River Danube is the most important European waterways, flowing 2,857 km across the continent from the Schwarzwald (Black Forest) Massif in Germany down to the Black Sea.

According to its geographical layout and geological structure, the Danube basin can be divided into three major units:

(1) The upper Danube, from springs in the Black Forest Mountains to the Devin Gate (Hungarian Gate), east of Vienna. The morphology of the valley varies from canyon-like to low, sometimes marshy landscape.

(2) The middle Danube basin from the Devin Gate, connecting Leitha Massif with the Little Carpathians, to the Southern Carpathians, at the Iron Gate Gorge. The middle section of the Danube basin is encircled by mountains and embraces the South- and East-Slovakian Lowland (Little Alföld - Alföld means plain in Hungarian) and the Hungarian or Pannonian Depression (Great Alföld), with the low chain of the Western Carpathians and the Trans-Danubian Mountains between the two plains. Except the Visegrád Gorge where the Danube passes through this chain, the morphology looks like a flatland river, with low banks and braided course.

(3) The lower Danube basin is situated downstream from the Iron Gates, where the river crosses the South Carpathian Mountains. The basin is formed by the Lower Danube Plain (Romanian Plain) and Bulgarian Lowlands, by the surrounding uplands and mountains (Carpathians and Balkans), the Dobrogean territory, the Siret and Prut basins and the Bugeac plateau (Moldavian and Ukrainian territories). Beyond the Iron Gates, the lower Danube flows across a wide plain, the river becoming shallower and broader. The last section of the lower Danube is represented by the Danube Delta, where the river splits into three main channels: Kilia, Sulina and St. George.

The River Danube is a typical example of a so-called “polygenetic valley”. The river links a series of basins, former lakes or inland seas, separated by mountainous chains: Vienna basin in the upper part, Little Plain (Little Alföld) and Great Plain (Great Alföld or Pannonian basin) in the middle part of the river and Dacian Plain (Vallachian or Lower Danube Plain) below the Iron Gates.

In its run towards the sea, the river has to cross the most significant mountain barrier in Central Europe - the South Carpathian Chain. How, why and when did the Danube manage to

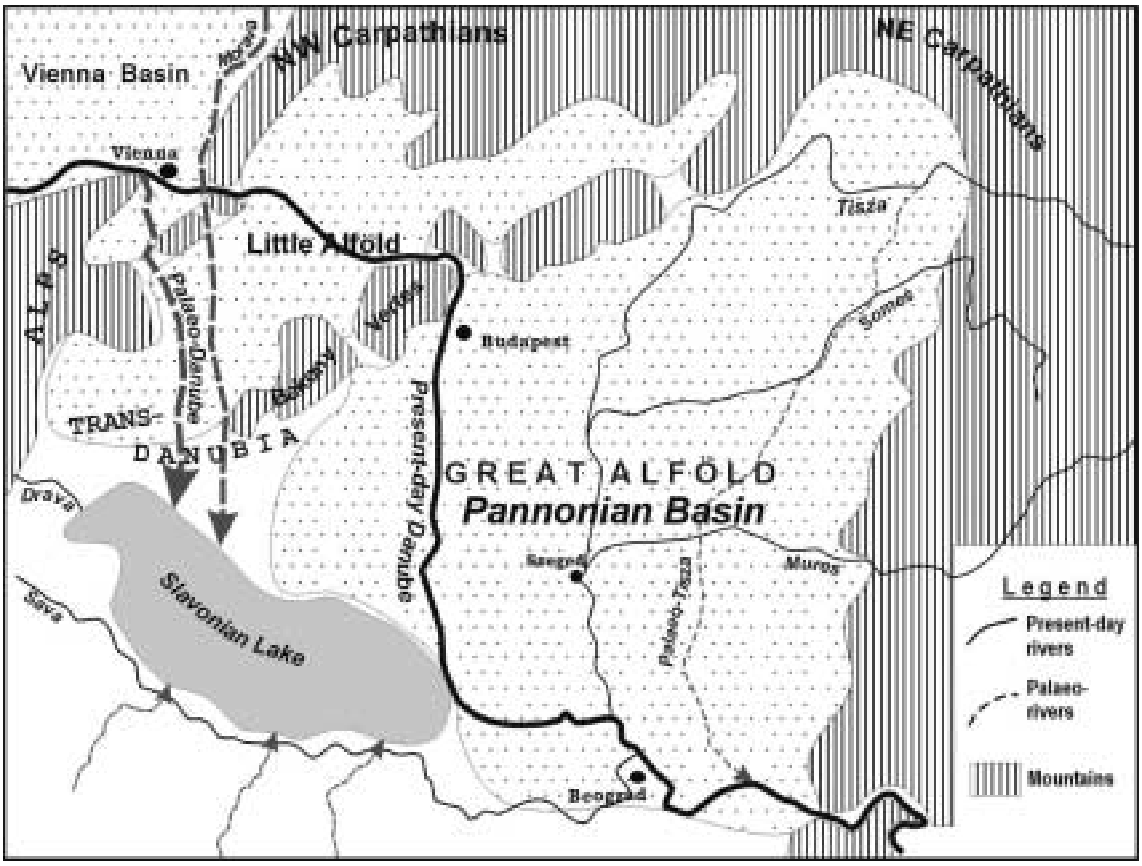

Fig.1. The evolution of the River Danube in the Middle part of its cours (modified after Gábris, 1994).

penetrate the mountains through the Iron Gates or Djerdap Gorge, the largest and most spectacular gorges in Europe? The Iron Gates connects the Pannonian and Dacian (Vallachian-Pontian) basins. The gorge is more than 100 km long and consists of several alternating relatively wide reaches (Liubcova, Donji Milanovac and Orsova are the main ones) and narrows (Golubac, Gospodjin Vir and the Small and the Great Cazane).

The newest data (Posea, 1964; Marovic *et al.*, 1997a,b) suggest that almost the entire Early Quaternary (Eopleistocene) Danube break-through route in the Iron Gates section is controlled by faults. Displacement along faults in different geological periods led to the formation of several small basins (Liubcova, Donji Milanovac, Orsova etc.), which were ingressed from the Pannonian basin.

Once the crossing of the Carpathian Mountains had been effected, the River Danube flowed into the Dacian Basin area, towards the Black Sea. The evolution of the Dacian Basin during the Pliocene-Pleistocene was strongly dependent on Black Sea level variations at that time.

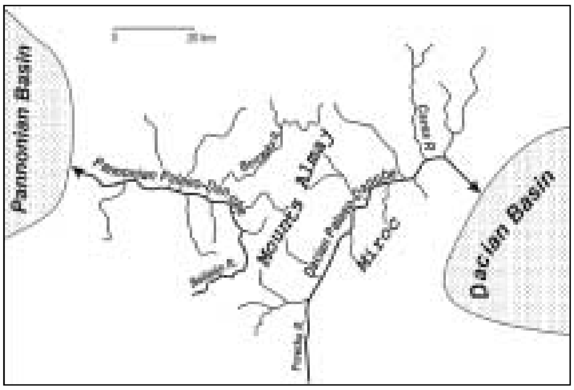

Fig. 2. The The paleohydrographical network at the crossing of Carpathian Mountains (after Marovic *et al.*, 1997).

In conclusion, the River Danube Basin appears as a succession of basins descending down to the Black Sea: Vienna basin, Little Alföld, Great Alföld, Dacian basin. The river had its own development in each of these basins and finally reached its present-day course late in the Quaternary – geologically speaking the Danube is a latecomer to the Black Sea. Probably before being as today there was a hydrographic network tributary to the Black Sea coming from the Carpathians and draining the eastern part of the Dacian basin. Let us call it "Paleo-Danube"; its existence is confirmed by important depo-centres in the deep part of the Black Sea with sedimentary bodies dated much earlier than the time when the present-day Danube started to flow into the sea. Confronted with a multitude of conflicting ideas we attempt here to present the state-of-the-art on this subject.

Hydrological characteristics of the river.

The Danube drainage basin extends to 817,000 km^2; more than 15 countries share the Danube catchment area. Some 120 medium and large size tributaries, more than 30 of which are navigable, constitute the Danube basin hydrographic network.

Recent computation and statistical processing of data collected over almost 130 years (Bondar, 1991, 1993) estimate the multi-annual water discharge of the River Danube into the Black Sea at QD = 6.047 m^3.s^{-1} with a tendency to slight increase. The extreme water discharge values recorded till now are: $Q_{max.\ 1970\ year}$ = 15,540 m^3.s^{-1} and $Q_{min.\ 1954\ yea}$r = 1,610m^3.s^{-1}.

The average annual suspended sediment discharge before the building of the Iron Gates dam was 2,140 kg.s^{-1} (67,5 millions t/year), out of which sandy alluvia formed approximately 10%. Accordingly to Bondar (1991, 1993), the multi-annual sediment discharge at the River Danube mouths was: R_D = 51.7 millions t/year, with a decreasing multi-annual tendency. After 1970, following the building of Iron Gates I dam (942.95 km from the Black Sea) and the hydrotechnical amelioration works along the Danube tributaries, the sediment discharge decreased by approximately 10-20%. In 1983, the second barrage (Iron Gates II), at Ostrovul Mare (864 km), was built up and this new closing of the Danube induced a really catastrophic decrease in the sediment discharge: in all the stations the measured sediment discharge dropped by 35-40 % compared to the mean value of pre-damming sediment flux regime. At present, therefore, one can estimate that the Danube total average sediment discharge cannot be larger than 30-40 million t/yr., out of which 4-6 million t/year are sandy material. This is the only amount of sandy sediment contributing yearly to the littoral zone sedimentary budget, which since 1970 became severely reduced, with the beaches suffering catastrophic erosion, up to 15-20 m/year in certain sections. It is also obvious that the present day sediment load of the Danube originates mainly in the eroded bottom sediments of the river course and this is affecting the entire ecosystem as well as the civil engineering works along the river.

THE DANUBE DELTA

The second term of the geosystem is represented by the Danube Delta, which is situated in the north-western part of the Black Sea, between 44°25' and 45°30' northern latitude and between 28°45' and 29°46' eastern longitude, being bordered by the Bugeac Plateau to the North and by the Dobrogea orogenic area to the South.

The three major depositional systems of the Danube Delta are characterised as follows: the delta plain, with a total area of about 5,800 km^2, including the marine delta plain area of 1,800 km^2; the delta front with an area ca 1,300 kkm^2, divided into delta front platform (800 km^2) and delta-front slope (ca 500 km^2), extending off-shore to a water depth of 30-40 m; the prodelta lies off-shore at the base of the delta-front slope to 50-60 m depth, covering an area of more than 6,000 km^2.The Danube Delta development and morphology are controlled by the River Danube high sediment input (as mentioned above ca40.10^6 t/y, of which 4-6.10^6 t/y sandy material), the prevalence of winds from the northern sector, the predominance of southward trending of marine

Fig. 3 - The Danube Delta evolution during the Holocene and corresponden coastline position changes (modified after Panin & E. and G. Ion, 1997).

Fig. 3. The Danube Delta evolution during the Holocene and correspondent coastline position changes (modified after Panin *et al.*, 1997).

currents, the long shore sediment drift directed also towards the south and the relatively important values of wave power, etc.

The Danube Delta overlaps the Predobrogean Depression which, in its turn, lies mainly on the Scythian Platform. The boundary of these units to the North Dobrogea Orogen is represented by the St. George fracture zone which otherwise influences the trending of the Danube course in the Galatzi - river-mouth sector. The sequence of deposits covering the Scythian Platform which constitute the filling of the Predobrogean Depression displays six sedimentation cycles (Pãtrut *et al.*, 1983), as follows: (a) pre-Mesozoic cycle (Paleozoic), calcareous -dolomitic; (b) Lower Triassic cycle, of considerable thickness (400-2,500 m), slightly unconformable over subjacent deposits and consisting of red continental detrital deposits with interlayered effusive rocks; (c) Middle-Upper Triassic cycle, transgressive, marine, built up of carbonate rocks at the lower part (350-450 m limestones and 500-600 m dolomites) and of detrital rocks (450 m) at the upper part; (d) Jurassic cycle, transgressive, marine, consisting of detrital deposits at the base (Middle Jurassic, 500-1,700 m thick) and carbonate ones at the top (Upper Jurassic, 1,000 m thick in the southern area); (e) Lower Cretaceous cycle, overlying Jurassic deposits, consisting of red continental deposits of varying thickness (ca 500 m); (f) Sarmatian-Pliocene cycle, overlying different Mesozoic deposits and consisting of alternating clays, sand and sandstones (200-350 m thick).

The Danube Delta is thus situated in an area of high mobility of the Earth crust, repeatedly affected by strong subsidence and important sediment accumulations. The deltaic conditions were settled here during the Quaternary, when the Danube started flowing into the Black Sea basin.

The Danube Delta edifice is formed by sequence of detrital deposits of tens to 300-400 meters thick. The important Quaternary changes of the sea level have strongly influenced the Danube Delta evolution. The Würmian regressions, and especially that of the Neoeuxinian stage of the

Black Sea (about 18,000-16,000 years BC), when the sea level lowered to ca -100 m brought about the intense erosions of the delta deposits. Probably much of the old Quaternary deposits were thus removed. One can still recognise deposits assigned to the Karangatian and Surojian stages (Würmian interstadial), located eastward of the Letea-Ceamurlia-Caraorman line and preserved behind some erosion relics of the predeltaic relief. The Danube Delta edifice was therefore formed mainly during the Upper Pleistocene (Karangatian, Surozhian, and Neoeuxinian) and the Holocene.

The development of the Danube Delta during the Holocene is marked by the following main phases (Panin *et al.*, 1983; Panin, 1996, 1997):

1. “Letea-Caraorman initial spit” phase (11,700-7,500 yr. BP): the coastline was represented by a spit located at the entrance into the “Danube Gulf” at about 25-30 km West of the present delta shoreline;

2. The first delta of the River Danube -“St. George I Delta” was formed by the first Danube distributary - the Paleo-St. George branch in the 9,000 -7,200 yr. BP period. In about 2,000 yr. the Delta St. George I has prograded seaward by about 8 km;

3. The following phase (7,200-2,000 yr. BP) is represented by the development of a new distributary - Sulina and its deltaic lobe-”Sulina Delta”. The maximum progradation was of 30-35 km from the “initial spit"”, the delta-front advanced beyond the present-day shoreline by 10-15 km.

4. At the same time (3,500-1,500 yr. BP) in the southern part of the delta area, a little secondary delta-the “Cosna-Sinoie Delta”, was formed by a secondary distributary named Dunavãt. Its front line prograded at least by 5 km offshore from the present shoreline.

5. The next phase (~2,800 yr. BP - present) is represented by the formation of two new deltaic lobes: “Kilia Delta” in the North, built up by a new Danube distributary - Kilia, and “St. George II Delta” in the South, corresponding to a reactivation of the St. George distributary. By then the Sulina distributary was partly clogged and the Sulina Delta gradually eroded. Thus, during the last ~2,800 yr. the new lobes have prograded by 16-18 km, while Sulina Delta coast line regressed by about 10-12 km. The same process of erosion and coast regression (by few km) has been recorded at the “Cosna-Sinoie Delta” within the Portita-Periboina section of the littoral zone.

THE BLACK SEA

The last term of the system, the Black Sea is one of the largest enclosed seas in the world: its area is about 4.2×10^5 km^2, the maximum water depth -2.212 m, the total water volume of 534,000 km^3 and the volume of anoxic deep water contaminated with H2S (below the depth of 150-200 m) 423,000 km^3. The connection of the Black and Mediterranean seas is limited to the Bosphorous-Dardanelles system of straits. The Bosphorous is a rather narrow (0,76-3,6 km large) and shallow strait (presently 32-34 m at the sill) restricting the two-way water exchange between the brackish Black Sea (the salinity of the Black Sea water is about 17‰ at the surface and 22‰ at the bottom) and the very saline Mediterranean Sea (38-39‰).

The surface outflow of the less saline Black Sea water is estimated at about 600 km^3/yr. (~ 20.000 m^3/s), while the under current of saline Mediterranean water flows towards the Black Sea and supplies it with almost 300 km^3/yr. (~10 000 m^3/s). The influence of the River Danube and the Ukrainian rivers (Dniester and Dnieper) is determinant to the sedimentation on the north-western and western Black Sea area. In Holocene the River Danube remained the only sediment supplier because the Ukrainian rivers sediment discharge is blocked in lagoons where they are flowing into. After 1970, following the building of the Iron Gates dams, the Danube River sediment discharge diminished, as mentioned above, by 35-40% of its previous value. At the end of a 12,000 year evolution, marked by active progradation, the Danube Delta became mainly inactive over the last few decades mainly due to intervention of man-made origin. The deficit of sediment influx led to the intense erosional processes of the deltaic littoral.

On the Black Sea north-western shelf as it is today, two main sedimentary environments have been identified: the internal, Danube sediment-fed shelf and the external, sediment-starving shelf. The modern highstand sedimentary history of the north-western Black Sea deep area is marked by the cessation of the Danube deep sea fan active development.

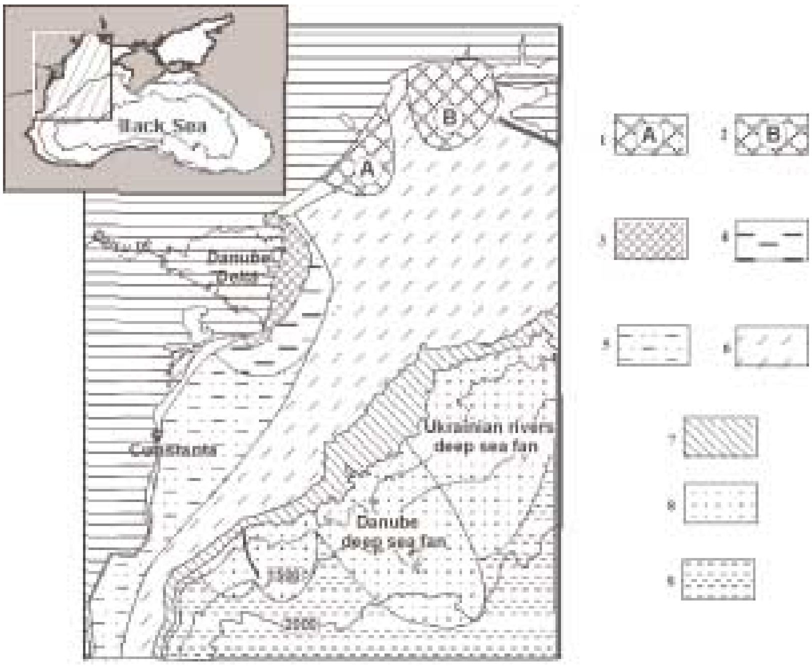

Fig. 4. The sedimentary units in the NW Black Sea.
1 and **2** : zones of influence of Dniester and Dniepr rivers.
3 : Danube delta front
4 : Danube prodelta.
5 : Danube bom sediment drift area.
6 : Sediment starving continental shelf.
7 : Continental slope.
8. Deep-sea fan complex.
9. Deep-sea zone.

The sediment-fed area in the neighbourhood of the Danube Delta includes the delta front unit (about 1,300 km^2) and off-shoreward, at the base of the delta front to 50-60 m depth, the prodelta covering an area of more than 6,000 km^2. Its southern boundary is more difficult to define on account of the strong southward drift of fine grained sediment load discharged into the sea by the Danube, which is stumping the prodelta limit.

Situated outside the area covered by the Danube fed sediment flux the external, eastern part of the continental shelf represents an area practically deprived of clastic material. Within this sediment starving shelf area, the condensed sediment accumulation is of biogenic origin, producing an organic thin cover on relict sediments or concentrations of shells. The Danubian sediments seldom reach the shelf area north or Northwest of the Danube mouths. Dniester and Dnieper, the main rivers north of Danube Delta, are themselves, as already mentioned, not significant suppliers of sediment for the north-western Black Sea shelf. Consequently, the sediment starving status characterises almost all of the whole Black Sea continental shelf west of the Crimean Peninsula.

Beyond the continental shelf, in the deep zone of the western Black Sea, during the Upper Quaternary, in correlation with the sea-level fluctuations of this period in time, very large accumulations of sediments were formed. These accumulations are represented by distinct but interfingering fans fed by the River Danube and by the Dniester and the Dnieper. The structure and the evolution of these fans are discussed in a number of presentations in this volume.

The character of recent turbiditic sedimentation on the south-eastern Crimean slope and the Pallas Uplift

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Geophysical and sedimentological data acquired during the 6th Training-through-Research cruise of R/V *Gelendzhik* on the base of the southeastern Crimean slope and adjacent Pallas Uplift (Fig. 1) show evidence of recent density flows activity in the area. Two sediment cores collected from the base of the slope in the Sorokin Trough area recovered sequence of fine-grained turbidites interbedding with the most recent Black Sea hemipelagic sediments forming units I and II (Ross and Degens, 1974; James and Gagnon, 1994) (Fig. 2). Most of the turbidites are muddy and often contain larger fragments of reworked sapropel at the base. The presence of turbidites increases the sedimentation rates for units 1 and 2 in the study area from 25 to 75 cm/ky. The database of 72 sediment cores collected in the area over last the 20 years shows that such turbidite sequence is common for the part of the Crimean slope southeast of Yalta.

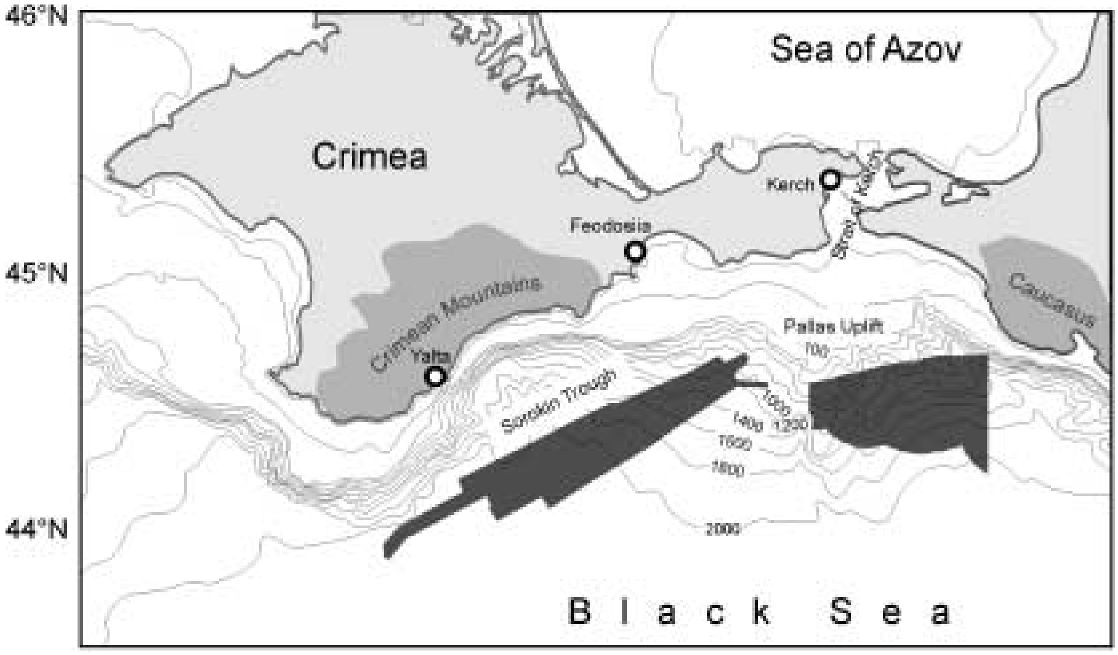

Fig. 1. Location map of the study area. Simrad EM12S multibeam echosounder coverage areas are shown.

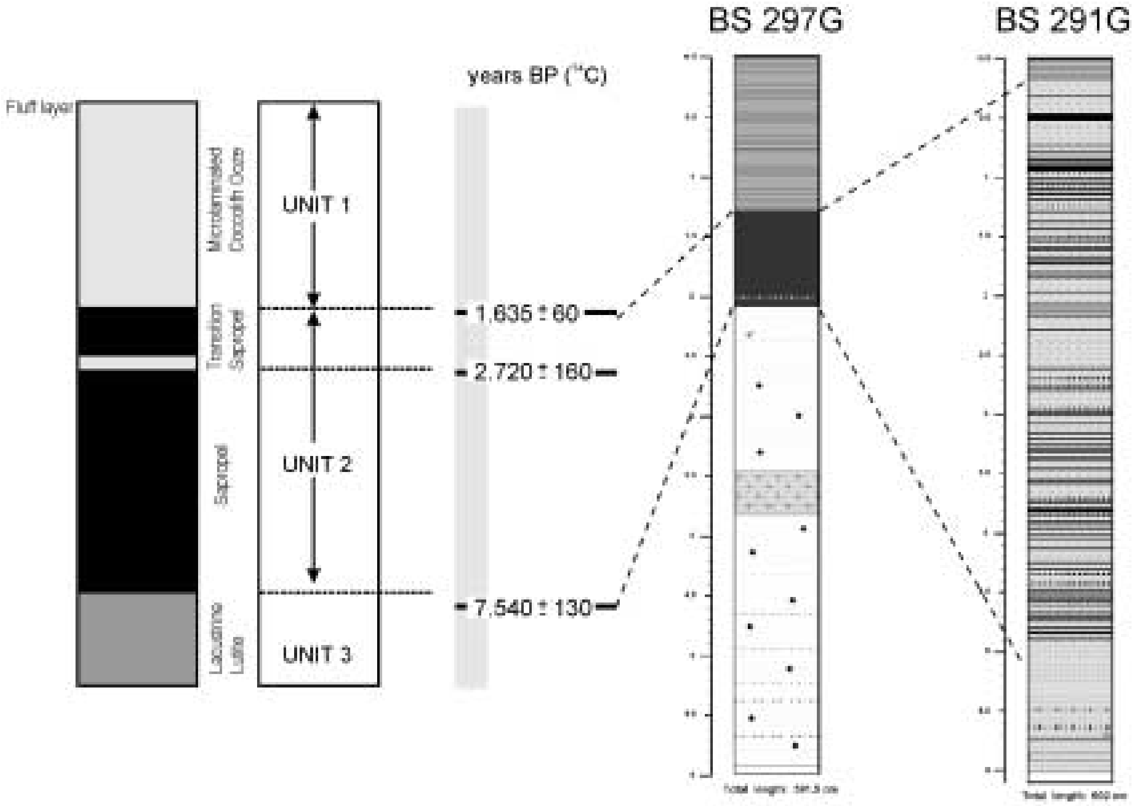

Fig. 2. Lithostratigraphy and chronology of laminated Black Sea sediments (Ross and Degens, 1974; Jones and Gagnon, 1994) and different types of sequences of Holocene sediments recovered in the study area.

The bypassing turbidity currents have formed a system of narrow channels seen on bathymetry and acoustic images of the seabed (Fig. 3). These channels are less than 10 m in depth and have little expression on the profiler records. Higher upslope the channels are connected with larger canyon system dissecting the upper part of the slope. A 3.5 kHz profile record across one of the channels near its junction with a canyon showed the presence of debris flow deposits on its floor. Sediment cores collected from canyon thalwegs also recovered debris flow deposits. At the base of the slope channel distribution is affected by diapiric ridges common in the area, which cause channels to deflect to the southwest.

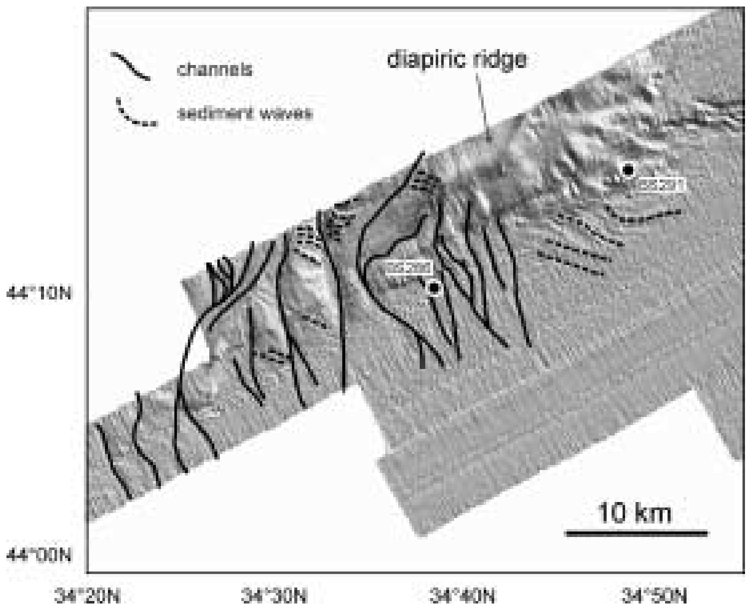

Fig. 3. EM12S shaded relief representation of the bathymetry of the base of the slope southeast of Yalta showing a system of turbidite channels. Locations of cores recovered Holocene turbidite sequence are indicated.

Composition, grain-size and thickness of the turbidites suggest that the flows are very diluted and do not exceed several meters in thickness as some of the cores taken in the vicinity of turbidite recovery sites but on higher locations contain undisturbed units 1 and 2. As the turbidites are contained within lithological units with well-dated boundaries it is possible to estimate the frequency of density flows. According to our calculations an event resulting in the formation a density flow which would reach the base of the slope can occur once in 90 years. Most of the Holocene turbidites recovered in the study area are composed of muddy hemipelagic sediments of units 1 and 2 which suggests that the slope sediments are prone to frequent failures which source these density flows. A typical density flow in the area would consist of a debris flow moving and freezing within canyons and an associated turbidity current capable of reaching the basin plain. Seismicity data accumulated in the period from 1900 to 1986 (Pustovitenko and Panteleeva, 1990) show a particularly high concentration of earthquake epicentres on this part of the slope, which explains the high frequency of the slope failures recorded in the Holocene sedimentary sequence.

On the northeast of the study area, towards the Feodosia Bay and the Strait of Kerch, the sedimentation has a different pattern as the survey enters a shallower part of the slope occupied by an apron formed by Quaternary sediments of the paleo-Don / paleo-Kuban rivers, also known as the Pallas Uplift (Tugolesov *et al.*, 1985). The slope above 1200 m is characterised by the presence of well-developed canyon systems. Some of the canyons are deeply incised into the shelf edge, have a V-shaped profiles and sinuous thalwegs. In the part of the Uplift adjacent to the Sorokin Trough canyons interact with diapiric ridges and, as a result, can loose their morphological expression on the seabed (Fig. 4). Large intraslope failures are common for the area to the south of the Strait of Kerch. EM12S reflectivity image shows that canyon floors are characterised by high backscatter which also extends beyond canyon mouths, indicating pathways of active sediment transport. A 30 kHz sidescan sonar and subbottom profiler line running across several canyons indicated seabed erosion along their thalwegs, and sediment accumulation on the inter-canyon areas. Sediment cores obtained along the line confirmed this conclusion, recovering from thalwegs sequences with eroded Holocene units 1 and 2. Cores from inter-thalweg areas recovered full sequence of the recent Black Sea sediments. Fields of mud waves were observed in different location of the mid-lower slope (below 1400 m) on the bathymetry, reflectivity and seismic data. They have a wavelength up to 1 km and height of 15-30 m and are similar to mud waves described from other deep-water depositional systems (e.g. Migeon *et al.*, 2000; Wynn *et al.*, 2000). The waves are usually found beyond canyon mouths and along sediment transport pathways (Fig. 4) and have a distinct sigmoid signature on seismic profiles. At some places, waves are draped by the sediments of units 1 and 2 but in others these sediments are also involved into wave formation indicating the recent development of these bedforms. 30 kHz sidescan sonar and subbottom profiler line crossing one of the sediment pathways displayed a variety of smaller scale bedforms such as sediment waves, chevron-shaped dunes and seabed lineatiation, all sug-

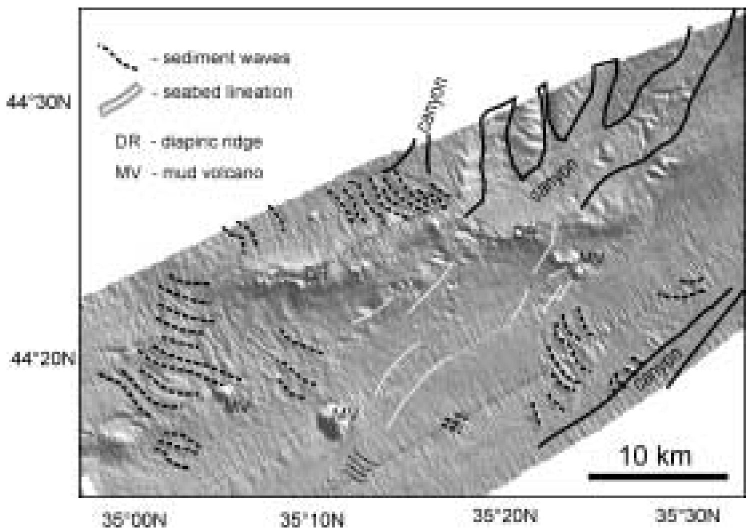

Fig. 4. EM12S shaded relief representation of the bathymetry of the southwest portion of the Pallas Uplift showing interaction of canyons, diapiric ridges and fields of sediment waves.

gesting a recent activity of the density flows along the pathway. The active status of the system is believed to be due to continuous sediment supply from the shelf area and neotectonics.

Some of the features observed on the recent seabed can be also recognised in the older sequences on seismic records. A seismic line shot along the base of the slope of southeastern Crimea across the lower reaches of the Yalta canyon system and towards the Pallas Uplift clearly showed cycles within the sedimentary cover formed as a response to major sea-level changes during glacial-interglacial periods. Each cycle is represented by a sequence with an acoustically transparent thick mass-transport complex, which probably is formed during the sea-level drop. It is overlayed with a sedimentary wedge usually formed during lowstand intervals. The sequence is topped with a characteristic package of sigmoid reflectors, which indicates the development of mud wave fields on the seabed which occur during highstand intervals.

Submarine valleys and canyons in the Black Sea - a case study of the Bulgarian part of the sea

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The first data about the existence of submarine canyons in the Black Sea date back at 1868. Captain lieutenant Kumani found the canyons in the east area of the Black Sea at the time of deep-sea measuring with the *Lioness* corvette. More information about the underwater canyons was obtained in the 1950's. During echo measurement with R/V *Vityaz* in 1949, a deep-sea canyon was found opposite the mouth of the Danube, today bearing the name of its founder ship. The first extensive researches of the bottom relief and continental slope were carried out by Goncharov *et al.* (1972), Leontiev and Safyanov (1973), Shnyukov (1978) and others.

The knowledge of submarine valleys and canyons is of major importance for the oil- and gas prospecting, laying of tubes and cables on the sea floor and other underwater economic activities. In this reference, detailed echolocate and seism acoustic investigations were made in 1980 to 1990 for the purpose of charting and genesis study. On the basis of completed bathymetric of the Black Sea in the scale 1:500000, Melnik (1986, 1995) accomplished cartographic generalization of the submarine valleys and canyons in the scale 1:1250000 (Fig. 1). Detailed study of submarine valleys and canyons and abyssal floor was made in the east and south areas of the Black sea in relation with the gas-pipeline project of Russian and Turkey (the Blue Stream project).

The submarine valleys and canyons are traceable along the shelf in the form of buried river valleys and they are directly related to the contemporary inland river valleys. From the crossing point of the shelf edge and upper part of the continental slope down to depths of 1200 to 1800 m, these are defined as canyons. Below this depth, the canyons resume their valley character and form deep-sea fans on the abyssal plain. There is a direct relation between the valley-canyon system and inland river systems, the paleo valleys and deep-sea tectonic structures, which predefine the orientation of submarine valleys and canyons.

The lithological composition and physical and chemical properties of floor sediments accumulated in the axis areas and slopes of submarine valleys and canyons point to extremely dynamic processes. Strongly expressed gravity slides trigger suspension fluxes. The speed of turbidity currents at canyon axes at depth of 1500-1700 m may reach up to 4.5 m/s (Melnik, 1986).

General characteristic of the Bulgarian part of the Black Sea

The upper boundary of continental slope crosses the Bulgarian continental shelf at depth of 125 m. The lower boundary reaches deeper at direction NE-SW from 1100 to 1800 m in the Rezovo valley canyon system area. The average slope gradient is 1.5-2º. The underwater valleys and canyons predominate in relief of the continental slope. There are 12 valley-canyon developed systems in Black Sea's Bulgarian part (Table 1). The continental rise situation varies between 1800 and 2125 m of depth.

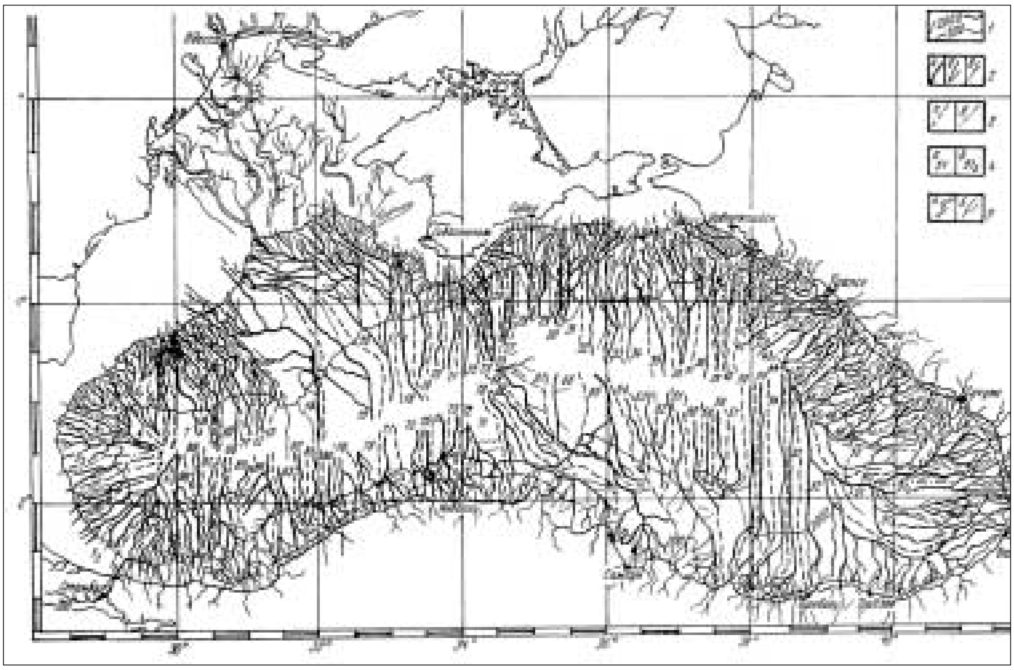

Fig. 1

Table 1. Valley-canyons system and valleys of the west part of the Black Sea

Number and name of the system and main valleys	**Subsystems**	**Valleys and their names**	**Length of main valleys in [km]**
1	2	3	4
I. Danube system	-	-	145
II. South-Danube system	-	a, b c	150
III. Portit valley -	-	110	
IV. Babadag system	IV.1 IV.2	a, b, c, d e, f	119
V. Midia valley -	-	115	
VI. Touzla system	-	a, b	115
VII. Touzla valley	-	-	104
VIII. Shabla system	VIII.1 VIII.2	a, b, c, d, e f, g, h, k, l	110
IX. Varna system	IX.1 IX.2	a.Kaliakra b. Balchik c. Albena d. Frangen e. Varna f. Bliznak g. Shkorpil h. Byala k. Obzor	110
X. Bourgas system	X.1I X.2	a.Kochan b. Emine c. Bourgas d. Sozopol e. Korakya	74
XI. Sredets system		a.Primorsko b. Sredets c. Ahtopol	64
XII. Rezovo system	-	a.Rezovo b. Server	72
XIII. Bosporus system	XIII.1 XIII.2	a.Kasatur b.Chiling c.Terkos d. Roumeli e. Bosporus f. Booder g. Hadjider h. Dogan	106

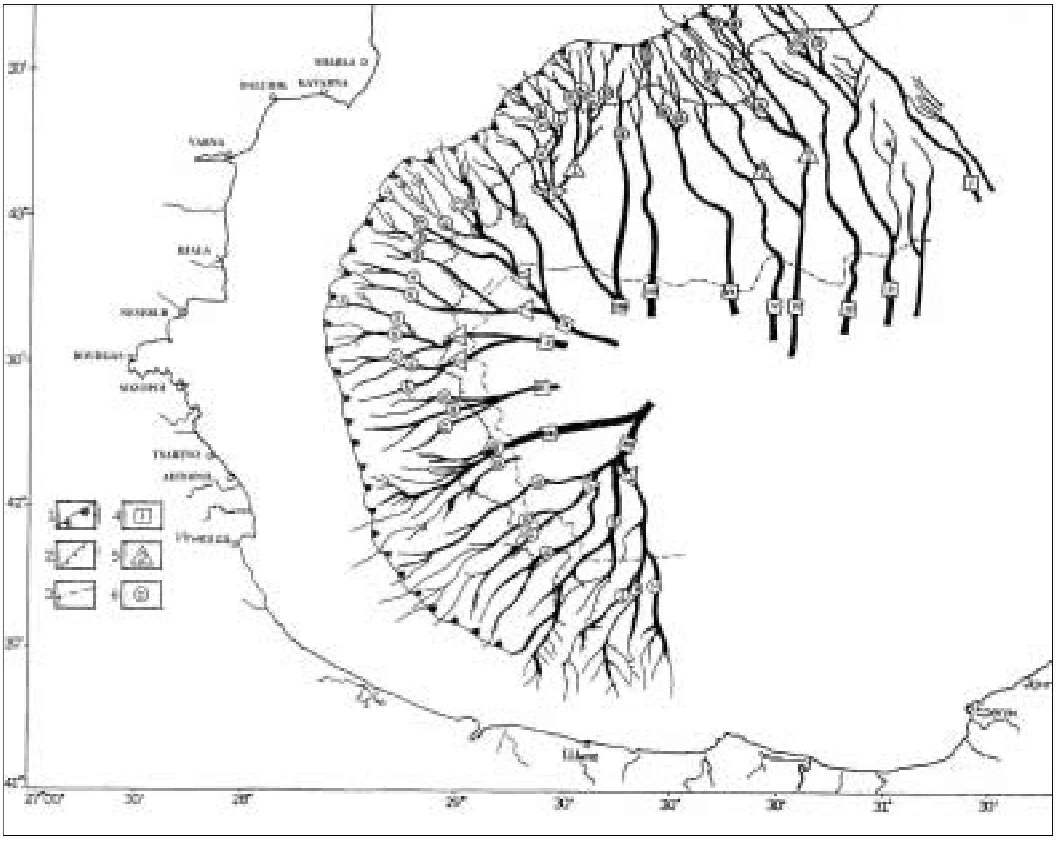

Fig. 2

The continental rise is a big accumulative cone formed on the base of inter flow of foot deltas in mouthparts of underwater valleys.

The main forming factor for these slightly expressed foot deltas is the avalanche sedimentation, which is being periodically revealed in the form of saturated turbidity currents along thalwegs of the underwater valleys. Their surface is gently inclined hilly plain complicated by shallow erosion incisions and height of 10-15m accumulative bars (Krustev *et al.*, 1990).

The average slopes of the continental rise vary from 0.3 to 0.9º as predominant slopes are 0.5-0.7º. The transition between continental slope and abyssal bottom is smooth and hardly visible. The basin bottom is abyssal plain with very gentle inclination to the deepest part of the Black Sea - 2245m.

The thickness of Quaternary sediments varies from 400-500m at the upper part of the continental slope to more than 1000m at the Continental rise. The thickness of Pliocene-Quaternary complex increases basin bottom and is assessing to 3.6-3.8 km. These sediment thickness values are determined according to geophysical investigations.

In 1983 while investigating of Rezovo submarine valley, the speed and direction of currents in the bottom layer at depth of 970 m were measured by RCM-4. The results showed that the currents' speed varied from 1-2 to 10 cm/s at the valley axes. The prospecting showed the absence of contemporary and Holocene sediments at many points along the axes and slopes, especially in the areas of steeper downward slopes. Similar results were obtained in the research of Varna canyon with the Russian Argus done in July 1985 (Aybulatov*et al.*, 1990). Active slides of Holocene sediments were observed at the valley axis at depth of 380-500 m (sapropel and cocolite muds) settled on the surface of the lower thick New Euxinus lake mud (Fig. 3).

At the slightest touch of the Argus to the bottom, suspension stream was formed, which spread down the slope like smoke curtain. Obviously, the gravitation-, turbidite- and suspension fluxes are not an uncommon event in the submarine canyons. Quite often mud volcanoes and methane torches are observed in the submarine axes at depths of 200-700 m. During investigations of

Fig. 3

Danube-, Rezovo - and Bosphorus valley- and canyon systems, considerable accumulations of diatom seaweed of thickness up to 5-6 m were found. Diatoms typically develop in contrasting hydro-chemical environment, i.e. at river-sea barriers and sea-fresh waters.

The canyon and valley system in the Black Sea was probably formed at the border of the Pliocene and Pleistocene and the process of formation was active through the transgressive and regressive cycles of the Quaternary. The geocatastrophic events on the border of the Pliocene and Pleistocene 7,500 years ago led to the final formation of the contemporary canyon and valley system on the Black Sea floor.

The maps of submarine canyons and valleys facilitate the solution of a number of issues related to the geological history of the Black sea as well as of ecological and technological problems.

Viteaz Canyon, the only sediment pathway of the Black Sea shelf ?

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A comprehensive swath bathymetry and high resolution seismic reflection data set obtained during a joint French-Romanian survey (BLASON) of the north-western Black Sea, reveals that the Late Quaternary development of the Danube progradational margin results from an interplay between turbidity current channel-related and mass-wasting processes. The Danube continental margin is mainly fed by the terrigenous input from the Danube, Dniepr and Dniestr rivers. Sediments supplied by the Danube were transported to the deep basin through the Viteaz canyon (Fig. 1), which was directly connected to a leveed turbidity current channel on the middle slope (Popescu *et al.*, 2001).

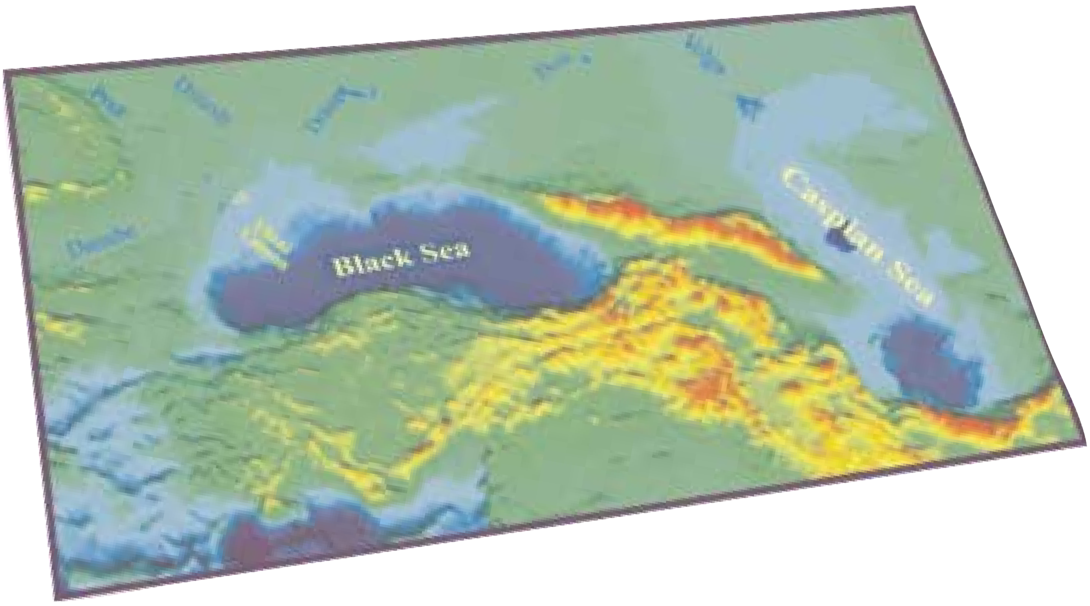

Fig.1. Location of the Viteaz canyon in the Black Sea.

Many authors (Flood *et al.*, 1999; Winguth *et al.*, 2000; Wong *et al.*, 1994) have recognised that sedimentation in the Black Sea was influenced by eustatic sea level changes driven by global glaciation and deglaciation. However, most of these recent studies have not recognised that the water level of the Black Sea was controlled by eustatic changes only to a certain extent. It has long been recognised that the Black Sea was isolated from the Mediterranean Sea during glacial intervals when the levels of the Black Sea and the Mediterranean dropped far below the level of the Bosphorus sill (e.g., during the last glacial, about 20-18 ky BP, the level of the Black Sea dropped to -130 m). Once separated from the Mediterranean basin, the level of the Black Sea fluctuated according to the regional climate and water supply independently of changes in the global oceans. The post-glacial warming and melting of ice caps which started 17 ky BP resulted in a global rise of sea level. Several hypotheses attempt to explain the independent behaviour of the Black Sea water-level during this period of time:

1 - It has been postulated that the supply of water to the Black Sea from glaciers covering the Russian Platform and the Carpathian Mountains was extremely high and that around approximately 12 ky BP, the water level rose to the level of the Bosphorus sill much more rapidly than in the Mediterranean basin. A large flux of freshwater flowed through the Bosphorus-Dardanelles towards the Aegean Sea. When the Mediterranean and the Black seas reached the same level (close to the present day level) some 9 ky BP, a two-way water exchange was established and the process of transformation of the Black Sea into an anoxic brackish water body started. This hypothesis has been supported by scientists from riparian countries (Romania, Bulgaria, Ukraine and Russia) since the late 1970s, (Stanley and Blanpied, 1980) and more recently by Aksu *et al.* (1999).

2- Ryan *et al.* (1997) proposed a new hypothesis for the changes in the level of the Black Sea in the upper Pleistocene-Holocene. They suggested that beginning about 12 ky BP, the retreat of the ice front on the Russian Platform temporarily redirected melt water towards the North Sea. In this way the Black Sea was deprived of melt water during the Younger Dryas (~11 ky BP) up to 9 ky BP, and under the influence of an arid and windy climate, experienced a new sea level fall (-100 m). At the same time the Mediterranean continued to rise, reaching the level of the Bosphorus sill by 7.5 ky BP, and thereby generating a massive influx of salt water into the Black Sea basin. (Ryan *et al.*, 1997) suggested that the water flux was strong enough to fill up the basin in a very short time (within a one to two year period).

Stratigraphic analysis of the north-western margin of the Black Sea using swath bathymetry (Fig. 2) and high resolution seismic reflection data (Fig. 3) can be used to refine our understanding of base-level variation in the Black Sea during the Late Quaternary. Submarine canyons, like the Viteaz Canyon, are known to evolve due to the influence of sedimentation, slope failure, sediment-gravity flow erosion, and topography (Pratson and Coakley, 1996). Recent models describe how submarine canyons and deep-water clastic deposits are generated and how their formation can be related to

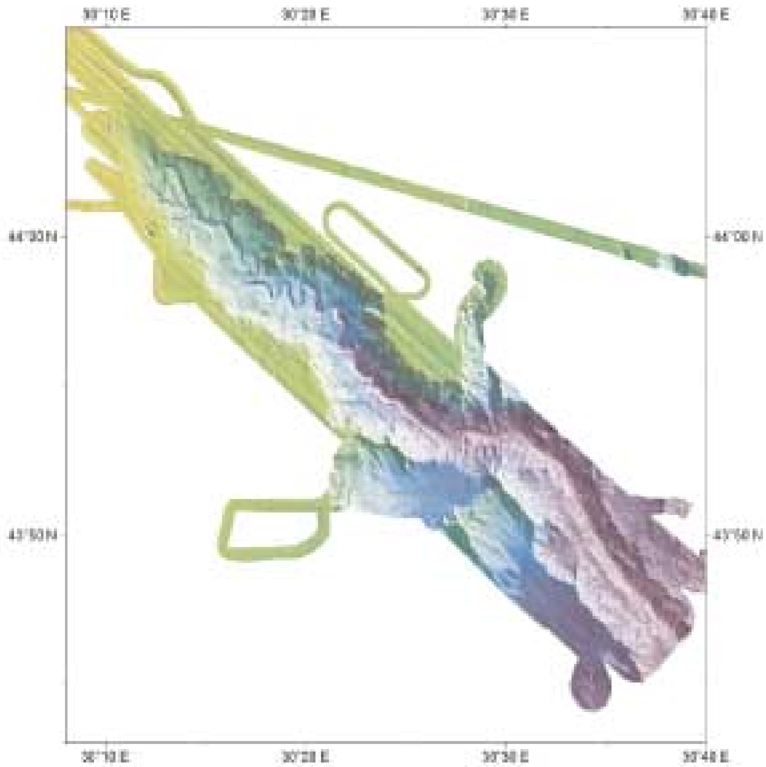

Fig. 2. EM 1000 DTM of the Viteaz canyon bathymetry.

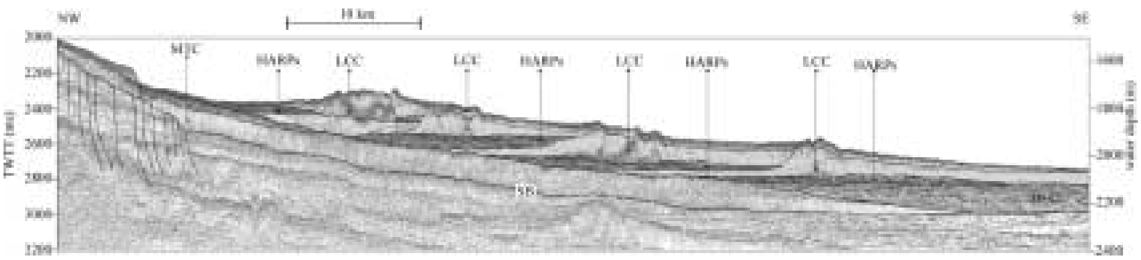

Fig. 3. Part of BLASON 24-Channel sesimic ligne 7 (from Popescu *et al.* 2001).
MTC = Mass transport Complex, DLC = Distributary channels and Lobe Complexes, LCC = Leveed Channel Complexes.

base level fluctuation (Beaubouef and Friedmann, 2000; Beaubouef *et al.*, 1998a; Garfield *et al.*, 2000). Building upon the Exxon Lowstand Fan Model (Vail and Mitchum, 1977), these authors propose a three-stage lowstand model: (1) during early lowstand, falling sea-level induces slope failures caused by pressure-related destabilisation of slope muds and erosion by sediment-gravity flows. Continued erosion by turbidity currents, focused upon the incipient topographic lows and further deepening and widening by marginal slumping and knick point migration lead to the development of canyon scale slope valleys. These mass wasting processes on the slope are associated with mass transport complex (MTC) deposition (slumps, slides, debris flows) downslope; (2) during middle lowstand, coarse sediment that bypasses the exposed shelf is transported through canyons and slope channels and deposited in distributary channel and lobe complexes (DLC) within the basin-floor fan beyond the toe of slope; (3) during the late lowstand/early transgression, coarser bed load sediment begins to be trapped on the shelf. Muddier suspended load sediment and more limited sand-grade sediment continues to be transported downslope by low-concentration turbidity currents. Overbank spillover and flow stripping processes common to low-concentration turbidity current channels contribute to the development of levees and leveed channel complexes (LCC) which are prevalent at this time. These develop above and landward of the sand-rich distributary channel and lobe deposits of the basin-floor fan.

The sequence stratigraphic model described above can be related to 4th and 5th order base-level cycles (Beaubouef and Friedmann, 2000; Beaubouef *et al.*, 1998b). Repetitive seismic facies stacking patterns, consistent with this high-frequency sequence stratigraphic model, are observed in the Danube Fan (Fig. 3). Low amplitude, chaotic seismic facies are overlain by an extensive high amplitude continuous to semi-continuous seismic facies unit which is in turn overlain by gull-wing seismic facies. These gull-wing facies are interstratified with thin, areally restricted high amplitude reflection packages (HARPs). These seismic facies associations are comparable to the lowstand depositional succession of muddy mass transport complexes (MTC), sand-rich distributary channel/lobe complexes (DLC) and leveed channel complexes (LCC) observed in other areas (Beaubouef *et al.*, 1998b; Flood *et al.*, 1994; Pirmez *et al.*, 1998). The fact that most of the Danube deep-sea fan sedimentation took place in freshwater suggests that hyperpicnal processes may have contributed to the generation of the turbidity currents that deposited the leveed channel and distributary channel and lobe deposits.

At least two distinct depositional cycles are observed below the water bottom and are interpreted to be Late Quaternary in age. The uppermost cycle is imaged in Fig. 3 and given the following depositional interpretation. Gull-wing seismic geometries represent leveed channels which are seen on the water bottom today. Three distinct leveed channels are observed in a landward stepping or retrogradational stacking pattern. These are interpreted to have been deposited during the Holocene base-level rise. The relatively thin and areally restricted high amplitude reflection packages (HARPs) interstratified with the large muddy levees are interpreted to be channel-mouth distributary channel and lobe deposits. These interstratified leveed channel complex and HARP units are stratigraphicaly younger and distinct from the extensive distributary channel/lobe deposits lying beneath them. The latter represent the updip portion of a large basin floor fan which extends at least 150 kilometres further into the basin beyond the image captured in Fig. 3. Leveed channels are also seen to cap the distributary channel/lobe deposits of the basin-floor fan in the underlying depositional cycle (not shown). In both cycles the levees are better developed in a landward direction. The extensive distributary channel/lobe facies that lie beneath the levees in the upper two depositional cycles represent a much larger sediment volume, and are interpreted to be sand rich based on acoustic impedance properties. The interpreted higher sand content, greater sediment volume and further basinward extent of these facies suggest that they formed during periods of maximum base-level fall when sediment flux and shelf bypass were at a maximum. These deposits most likely formed when the Black Sea was isolated from the global ocean. The chaotic mass transport complexes that underlie the basin-floor distributary channel/lobe complex facies in both depositional cycles lie above erosional uncomformities and were deposited in a toe of slope position, pinching out landward of the overlying distributary channel/lobe deposits. These facies are interpreted to be comprised of remobilized slope muds due to seismic geometry and acoustic impedance properties. Mass wasting processes associated with the formation of the Viteaz Canyon during periods of falling base-level are interpreted to have contributed to the development of these chaotic mass transport complexes downslope of the canyon.

Based on these observations and interpretations, we believe the Viteaz Canyon and its related deep-sea fan represent a large lake fan system developed during at least two 4th or 5th order Late Quaternary base-level cycles. Base-level fluctuation appears to have played a primary role in the erosion of the Viteaz Canyon and in the development of the cyclic facies architecture of the deep-sea fan, even during periods when the Black Sea was isolated from global sea-level fluctuations.

Architecture and recent sedimentary evolution of the Danube deep-sea fan (Black Sea)

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INTRODUCTION

The Danube deep-sea fan is a large passive-margin mud-rich fan and consists of stacked channel-levee systems intercalated with mass transport deposits. The main specificity of the Danube fan lies in its development under lacustrine conditions. This is due to the peculiar water-level history of the Black Sea controlled by the link to the Mediterranean through the Strait of Bosphorus and the Sea of Marmara. When the Mediterranean water level fell below the Bosphorus during glacial periods, the Black Sea was isolated from the world ocean and its level oscillated synchronously with the climatic cycles in Eurasia. At the same time, the Black Sea catchment areas were enlarged redirecting part of the meltwater discharge southward (Archipov *et al.*, 1995). Temporary absence of marine water influx together with large freshwater inputs from the Danube and other major rivers changed the Black Sea into a freshwater lake during times of fan activity. A re-establishment of the connection to the Mediterranean during highstands was associated with a rise in the water level of the Black Sea and interruption of fan activity, but also resulted in an increase in salinity, the Black Sea becoming a highly stratified marine basin with anoxic conditions in the deep zone. Recent geophysical survey on the north-western Black Sea slope reveals patterns of channel-levee systems on the seafloor and preserved within continental slope deposits. This survey, conducted as part of the BLASON French-Romanian Project, combined high-resolution seismic-reflection profiles and chirp profiles with piston cores and, on the upper slope, multibeam bathymetry. This study focuses on the evolution of the Danube channel, the youngest channel-levee system in the Danube fan, and it complements the recent study of the channel avulsions in the lower part of this system (Popescu *et al.*, 2001).

GENERAL MORPHOLOGY

The Danube channel (Fig. 1) is directly connected to the large shelf-indenting Danube canyon (also known as Viteaz canyon). The Danube canyon cuts into the shelf margin for 26 km landward of the shelfbreak up to the -100 m isobath and consists of a 3-6 km wide, northwest-south-

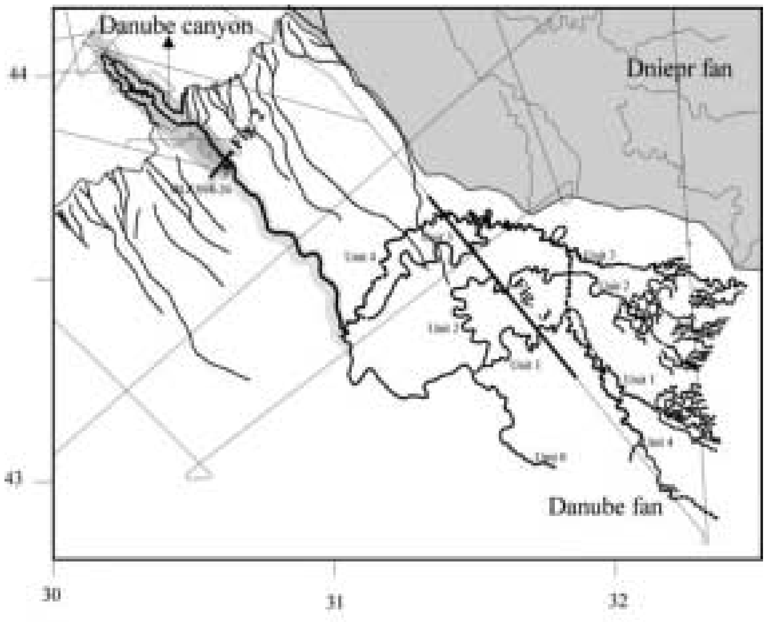

Fig. 1 Morphology of the Danube channel and location of BLASON seismic lines and core station BLKS98-26.

east trending main trough with steep flanks and a meandering thalweg cut into the flat canyon floor. On the upper slope (between the Danube canyon and ~1400 m water depth) the system consists of a single slightly sinuous channel with well-developed asymmetric levees. The channel is partially filled and incised by a thalweg channel.

Below ~1400 m depth the fan morphology is modified by the bifurcation of this single channel; several highly sinuous channels developed as a result of avulsions. The onlap relationships between these channels indicate that only one channel was active at a time. Basinward of the avulsion points, the channels followed a stable sinuous path with diminishing height and width of the levees. In the distal zone, the channels became unstable and migrated laterally.

SEDIMENTARY STRUCTURE

a. The upper Danube channel

The upper Danube channel is slightly sinuous and has undergone significant overbank deposition, as attested by the well-developed levees. The levees are strongly asymmetrical, being higher and wider on the right-hand side looking downstream. This type of asymmetry is rather common in deep-sea fans, and is generally attributed to the Coriolis effect (Menard, 1955). The top of the levee crests is commonly affected by crescent-shaped scarps concave towards the thalweg, indicating sites of former slump. An exceptionally large slump scarp (4.5/2.4 km) can be identified at the top of the right levee in the upper zone, and seems to be associated with a gas seepage zone (Popescu, in prep.).

The fan valley is 4.5-5 km wide, partially filled and incised by a thalweg channel that is connected to the meandering thalweg of the Danube canyon. The valley fill shows several phases of deposition separated by uncomformities (I to IV, Fig. 2). The lowermost unconformity cuts into the high channel levees, which indicate that the deposition of the valley fill is posterior to the channel levees formation. For this reason, they will be mentioned as “initial levees”.

The erosional surfaces within the valley fill are associated with distinct terraces in the bathymetry, more or less parallel along the main trough axis (see Fig. 2 of Lericolais *et al.*, this volume). Deposition inside the valley was more important on the right side, like the initial levees. As a result, the terraces are better developed on the right side of the valley fill. Still, this asymmetry is not associated with a lateral migration of the successive erosional trough axis inside the valley.

The uppermost discontinuity is the modern entrenched thalweg channel, locked into the confines of the larger fan-valley and contributing no sediment to the high levees. It is a narrow channel (~300 m wide at the thalweg floor) with steep walls (20-30°). The thalweg floor has a concave

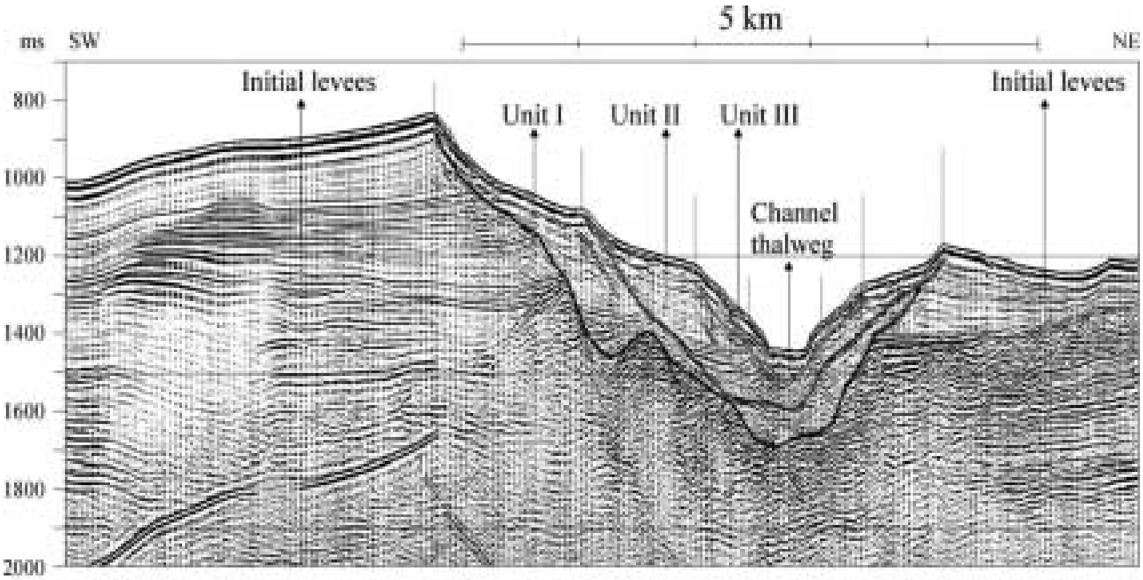

Fig. 2. Part of BLASON 24-channel seismic line 25.

upward, graded longitudinal profile and seems to represent an erosional feature. The gradient ranges from 0,71° (near the canyon-channel transition) to 0,18° (~ 20 km downward, at the end of the bathymetric survey area). This type of entrenchment was already described on the surface of the Rhône Fan, where it was interpreted to be an erosional thalweg (O'Connell *et al.*, 1995) or a depositional/erosional channel (Torres, 1995; Torres *et al.*, 1997). Basinward of the last avulsion point, the thalweg continues as a small channel-levee system (unit 4, Popescu *et al.*, 2001).

The sedimentary structure of the valley fill indicate that the Danube channel was built by a succession of depositional phases, interrupted by major erosional events. The initial channel was a typical channel-levee system with high levees and high amplitude reflectors (HAR, Kastens and Shor, 1986) at the channel axis, still visible in the deeper part of the basin where not removed by the subsequent erosional events. Three major uncomformities (I, II, III) can be identified within the valley fill, each overlain by a depositional unit. The channel thalweg is interpreted to represent a fourth erosional feature.

In the upper part of the channel, depositional units consist of a transparent MTD-like facies covered by a bedded facies. This bedded facies is also present in the lower part of the channel where it is in lateral continuity with HAR deposits, partially preserved under the subsequent erosional surface. Sampling of the bedded facies by a piston core in the upper channel showed it consists of typical thin turbidites levee facies.

The valley fill in the Danube channel seems to represent a succession of channel-levee systems confined (entirely or partially) within the previous relief. This relief is the result of major erosional events at the channel axis.

b. the lower Danube channel

On the middle slope below 1400 m, the Danube channel bifurcates through repeated avulsions. As a result, several highly meandering channels developed (Fig. 1). The onlap relationships between these channels indicate that only one channel was active at a time. Four main phases of avulsion were identified, each of which resulted in the deposition of a unit (1 to 4). A depositional unit consists of a basal unchannelized lobe defined as High Amplitude Reflection Packets (HARP, Flood *et al.*, 1991 for the Amazon fan) that underlies a channel-levee system (Fig. 3). The deposition of HARPs was associated with the readjustment of the longitudinal profile of the channel after the breaching of a levee, which resulted in remobilization of upslope channel deposits and eroded levees (Pirmez *et al.*, 1997). HARP deposits were sampled in a piston core in the distal zone, and consist in fine sand with mud-clasts, also described as a HARP facies in drillings on the Amazon fan (Normark, Damuth *et al.*, 1997).

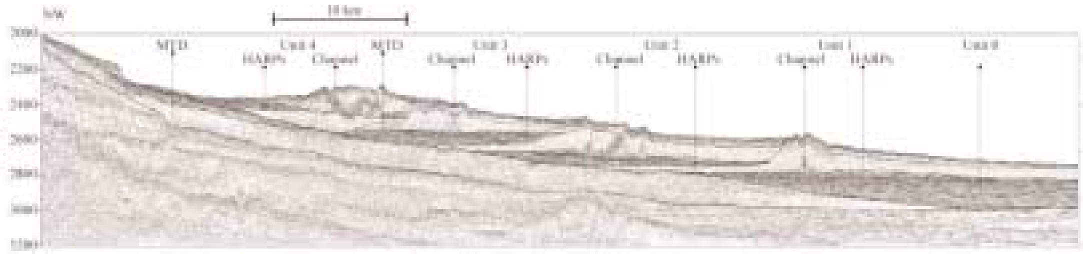

Fig. 3 Part of BLASON 24-channel seismic line 7 (after Popescu *et al.*, 2001).

Each phase of avulsion followed the same pattern (Popescu *et al.*, 2001): (1) breaching of the lower and narrower left levee, possibly due to major sediment failure in the feeder Danube Canyon or in the upper channel; (2) building of HARPs basinward of the bifurcation point by the unchannelized flow, while the former channel was abandoned; and (3) initiation of a new meandering leveed channel. The northward migration of the resulting units (1 to 4) through repeated bifurcations is influenced by the asymmetry between levees, hence by the Coriolis effect.

After bifurcation, channels followed a stable highly sinuous path basinward with diminishing height and width of their levees. In the lower fan where the levees became too low to maintain a stable pathway for the turbiditic flows, channels became unstable and migrated laterally (Fig. 1).

Locations of HARPs and channels after avulsion are controlled by the pre-existing bathymetry. Sedimentary deposits resulting from the repeated avulsions are confined between the high levees of unit 0 (the initial phase of this youngest channel-levee system) to the south, and the steep relief of the Dniepr fan, to the north.

CONCLUSIONS

Structure of the fan valley fill indicate that the erosional surfaces inside the upper channel (I to IV) could be formed in response of successive avulsions (1 to 4).

Four major erosional surfaces and their equivalent terraces can be followed inside the valley fill, down to the last bifurcation point. Two phases of avulsion originated in this zone (and resulted in units 3 and 4, Popescu *et al.,* 2001). Basinward of this avulsion zone, only two erosional events are recorded in the sediments of the main fan valley, almost entirely filled up. These events may be correlated with the avulsion phases that generated units 1 and 2.

Valley fill deposits (where not removed by the subsequent erosional event) show an axial high amplitude reflector (HAR) seismic facies, with lateral lower amplitude continuous reflectors consisting in a levee facies, as proved by sampling. This indicates that filling up was associated with flow within the channel, and not with interruption of fan activity. Therefore, depositional units of the valley fill seems to represent a succession of channel-levee systems confined within the previous relief

Consequently, it seems likely that erosional surfaces in the upper fan are associated with the adjustment of the channel longitudinal profile following the breaching of a levee wall, and to the deposition of a HARP unit basinward of the avulsion point. When this adjustment was complete, a channel-levee system developed downward of the bifurcation, overlying the HARPs, but also upward of this point, as a confined channel-levee system inside the erosional trough of the fan valley. Deposition of each unit generated by avulsion contributed to fill up the bathymetric depression that constrained its location, diminishing the gradient of the local topography. This could have been associated with a faster adjustment of the upper channel to the equilibrium profile, which possibly explains the partial preservation of each depositional unit under the subsequent erosional surface.

Northwestern Black Sea: Upper Quaternary water level and sedimentation

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THE DANUBE-DNIESTR FAN COMPLEX

Two overlapping deepsea fan complexes occur in the northwestern Black Sea: (1) the slightly inter-fingering Danube-Dniestr Fan complex fed by the River Danube, the Dniestr and possibly the Southern Bug, and (2) the Dniepr Fan built up by the River Dniepr (Fig. 1). The thickness and facies distribu-tions of eight seismic sequences were mapped in the former fan complex, of which four can be subdivided into parasequences. The two lower-most se-quences (sequences 1 and 2) consist mainly of unchannelized mass transport deposits (slumps, slides, debris flows), while the six upper sequences with their typical channel-levee systems as well as overbank and mass transport deposits make up the deepsea fan complex itself (Wong *et al.*, 1994, 1997; Winguth *et al.*, 2000).

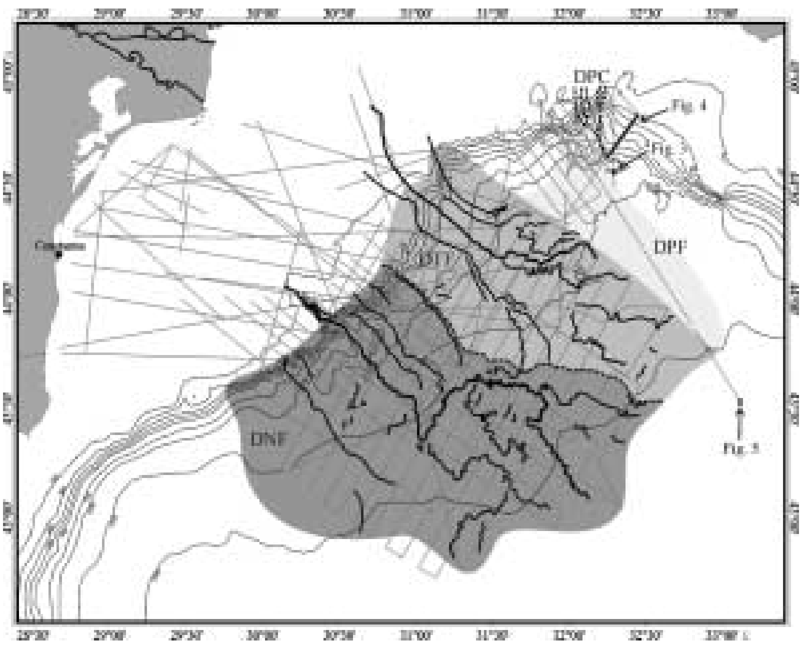

Fig. 1. Map of the northwestern Black Sea showing the locations of the main channels on the Danube-Dniestr Fan complex (**DNF** = Danube Fan and **DTF** = Dniestr Fan) and the upper Dniepr Fan (**DPF**). Dashed lines give the schematic boundaries between the fans. Grey lines show profile locations, with the profiles given in Figs. 3 and 4 marked in black. Thin black lines are the 100, 200, 300, 400, 500, 750, 1000, 1500 and 2000 m isobaths. **DPC** = Dniepr Canyon. Modified after Wong *et al.* (1994, 1997), Winguth *et al.* (2000) and Popescu *et al.* (2001).

In the Danube-Dniestr Fan, channel displacement occurs within a sequence as well as from sequence to sequence. This is probably due to activation and/or clogging of river arms or to channel breaching (Winguth *et al.*, 2000; Popescu *et al.*, 2001). Despite these dis-placements, the major channels did not migrate significantly, indicating that the sediment-contributing paleo-rivers flowed into the Black Sea approximately at their present mouths.

UPPER QUATERNARY WATER LEVEL CURVE FOR THE NORTHWESTERN BLACK SEA

Lowstands on a first regional water level curve for the northwestern Black Sea during the past 900 ky were reconstructed by identifying and mapping paleo-terraces and coastal onlaps on the shelf (Fig. 2). Corrections for sediment compaction, isostatic sub-sidence due to sediment load, thermal subsidence as well as vertical tectonic movements were applied. Ages for the water level cycles identified were assigned by correlating the water level curve with the global SPECMAP $\delta^{18}O$ curve (Imbrie *et al.*, 1984) as well as correlating the seismic sequences to commercial drill holes. Subsequent correlation of the fan sequences with the regional water level curve suggests that the Danube Fan was con-structed during the past 900 ky (sequences 3a to 8), and the Dniestr Fan during the past 800 ky (sequences 3b to 8).

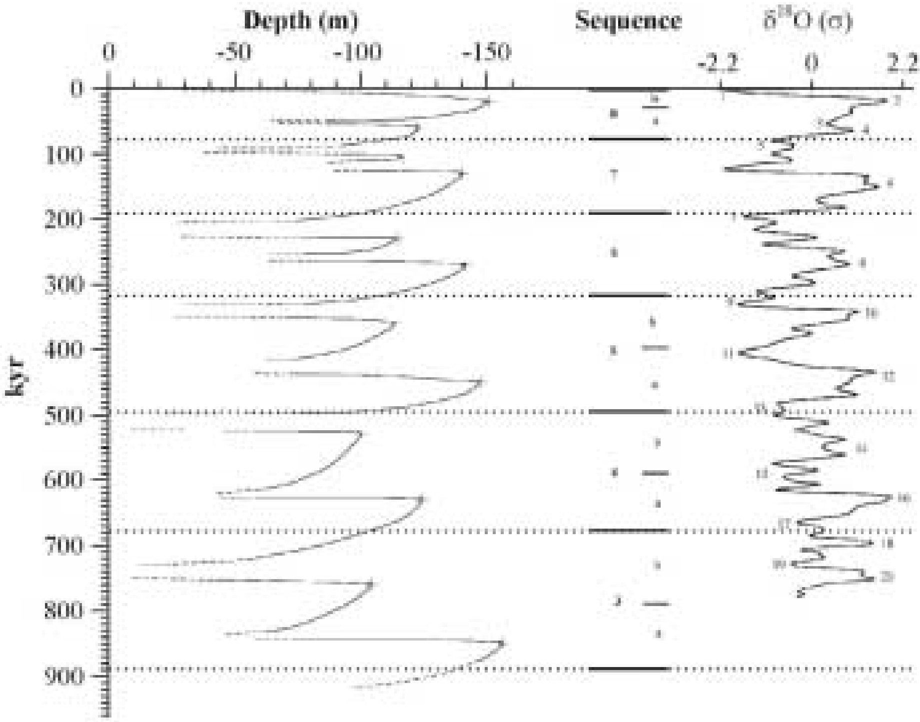

Fig. 2. (Left to right) Regional water level curve for the northwestern Black Sea; sequence correla-tions; SPECMAP $\delta^{18}O$ curve of Imbrie *et al.* (1984) (after Winguth *et al.*, 1997, 2000).

Deviations of our regional water level curve from the global sea level curve are due to isola-tion of the Black Sea from the global oceans during sea level lowstands, so that its water level could develop independently. Only during transgressions and highstands was the Black Sea re-connected to the Mediterranean via the Sea of Marmara, leading to freshwater outflow from and later saltwater inflow into the Black Sea. Timing of subsequent sapropel formation in the eastern Mediterranean Sea correlates well with the trans-gresssions presumed in our Black Sea water level curve. The water level lowstand during marine isotope stage 16 in the Black Sea is not as pronounced as in the world oceans, which may be a result of more humid conditions. The low-stand of -150 m during the LGM in the Black Sea is about 30 m lower than the eustatic lowstand of the world oceans. This hints at a dry regime in the Black Sea region during the last glaciation, when evaporation was presumably higher than precipitation and fluvial water influx.

The duration of the water level cycles identified in the northwestern Black Sea varies between 50 and 130 ky (except parasequence 8b which is still developing). Thus, they are 6th and 5th order cycles and are correlatable with the Milankovitch eccentricity and obliquity cycles.

EVOLUTION OF THE DANUBE-DNIESTR DEEP-SEA FAN COMPLEX

Development of the Danube-Dniestr Fan complex is controlled by the Black Sea water level (Weimer, 1990). During highstands, the deltaic regions are far removed from the shelf edge and function as depocenters for much of the fluvial sediment input. The slope and basin are sediment-starved. As the water level begins to fall, the river mouths advance towards the shelf edge and canyon formation begins. Mass transport processes lead to important deposits on the continental slope and rise. During a regression, when the retrograding canyons become connected with the fluvial valleys incised into the shelf, channel-levee systems start to form. At lowstands, the fan system becomes the main site of deposition. Coarse material is confined to the channels or it forms lobes at the channel terminations, whereas finer material is swept onto the levees and beyond to form overbank deposits. As the water level rises to a highstand, the deltaic system retreats towards the coast and the incised channels are filled. Thus, one cycle of water level fall and rise is responsible for the formation of a typical fan sequence.

Our seismo-stratigraphic interpretation implies that the Danube reached the Black Sea for the first time about 900 ky ago. This is consistent with the assumption that the Danube and the Ukrainian rivers reached the Black Sea only in the Chaudian. In the Upper Quaternary, the Danube system drained probably into the Dacian Lake, which was separated from the Black Sea by a basement high except for an outlet (Spânoche and Panin, 1997). Breaching of this lake led to direct drainage into the Black Sea. In contrast, the Dniestr Fan started to form only about 800 ky ago. A higher subsidence rate on the northern shelf may have caused the water level here to recede beyond the shelfbreak later than in the Danube area. Alterna-tively, the Danube Fan may have formed earlier than the Dniestr Fan because of its higher water and with it higher sediment discharge compared to the Ukranian rivers.

Computed average sedimentation rates range between 1.19 and 2.19 m/ky for the Danube Fan and between 1.07 and 2.03 m/ky for the Dniestr Fan (Winguth *et al.*, 2000). The corresponding rates for sediment accumulation calculated by assuming a sediment density of 2.4 g/cm^3 are 68-141 t/yr and 41-82 t/yr respectively. Mean denudation rates in the drainage areas are computed to be 0.027-0.105 mm/yr for the Danube basin and 0.017-0.127 mm/yr for the Dniestr-Bug-Dniepr drainage basins.

THE DNIEPR CANYON AND UPPER FAN

The Dniepr Canyon (the Dniepr Fan valley in the sense of Normark and Piper, 1969) is incised into the shelf and especially into the upper slope west of the Crimean Peninsula. It is floored by coarse-grained lag deposits and flanked by finer-grained levee and overbank sediments laid down during overflow of the canyons. The Dniepr Fan starts at a water depth of about 300 m and extends to the abyssal plain, possibly overlapping the Dniestr Fan. It consists of a series of vertically-stacked, laterally displaced channel-levee systems. It was deposited during water-level lowstands when the shelf was exposed and sediments were transported to the deep sea via channelised flow along the canyon, thus bypassing the shelf. Meandering and channel avulsion led to stacking of channel-levee systems.

The area east of the Dniepr Canyon is characterized by drift sedimentation. The sediment drifts are aggradative and cyclic. They form stacked individual units separated by distinct uncomformities that are sometimes accompanied by a moat (Fig. 3). They are laid down possibly as the northward-directed near-bottom slope current becomes focused by the levee morphology. Flow intensification causes the sediment particles to deflect upslope by the Coriolis force. On settling out, they form deposits with a convex-upward cross-section and confer a gentle gradient to the upper slope. West of the Dniepr Canyon, mass wasting dominates the steep upper slope, while mass transport deposition is prominent on the gentler lower slope. The middle slope at an average depth of ca 700 m represents a break in the gradient and a site of slide and slump deposition. From 750 m water depth to about 1300 m, debris flow deposits dominate.

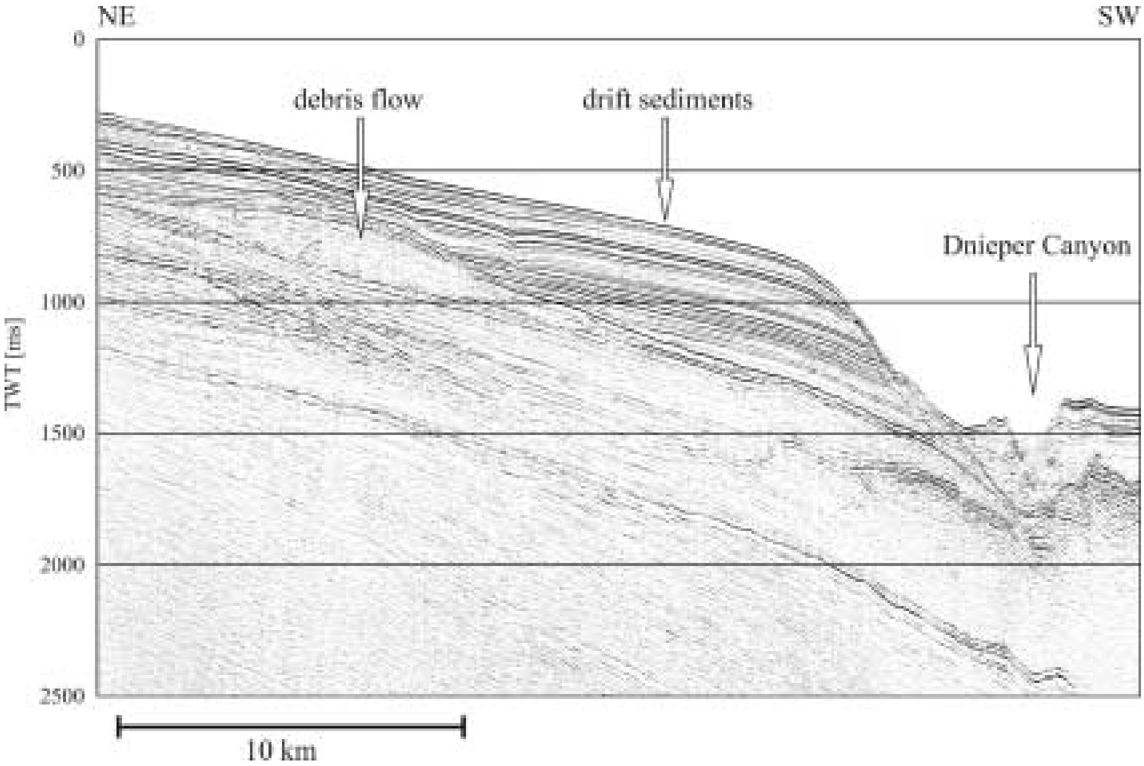

Fig. 3. Drift sediments and debris flows northeast of the Dniepr Canyon. See Fig. 1 for profile loca-tion.

A bottom simulating reflector (BSR), reported here for the first time in the Black Sea, occurs between water depths of 700-1500 m southwest of the Dniepr Canyon. It is a high-amplitude reflector that runs sub-parallel to the seafloor. Occasionally, it intersects the sediment stratifica-tions but has always a polarity that is opposite to that of the seafloor reflection (Fig. 4). It marks the lower boundary of the thermobaric gas hydrate stability zone, in which gas hydrate can exist

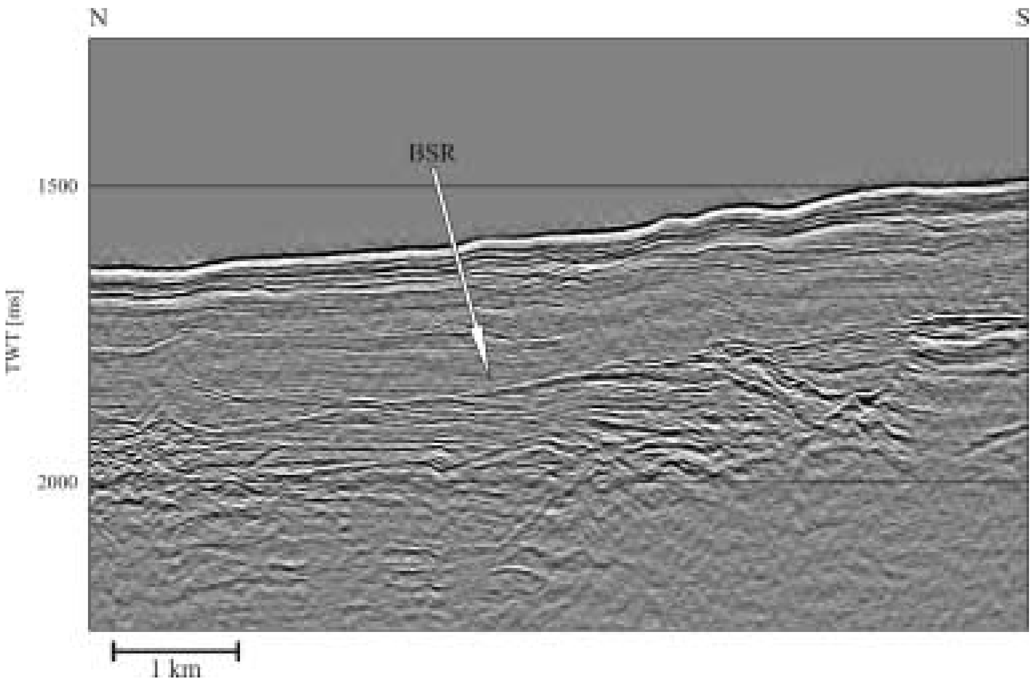

Fig. 4. Profile showing the occurrence of a bottom simulating reflector (BSR) characterized by a polarity that is opposite to that of the seafloor reflection and by intersections with the sediment strati-fication. See Fig. 1 for profile location.

as cement in the sediment. A BSR is absent where drift deposits occur, probably because these sediments are intrinsically gas-poor (low Corg content), or the gas generated in situ has already escaped during transport by bottom currents. A BSR is also absent in the distal fan. Here, gas concentrations below the gas hydrate zone (if one exists) is presumably so low that the impedance contrast is insufficient to produce a BSR. In addition, sediments in the lower Dniepr Canon have probably a permeability high enough to allow an upward migration of gas and fluids into the hydrate stability zone to allow the formation of gas hydrates. By assuming that the total pressure at the BSR depth is equal to the sum of the hydrostatic and lithostatic pressures, and that the methane hydrate stability conditions in seawater of Dickens and Quinby-Hunt (1994) applies, the heat flow distribution can be deduced by mapping the BSR depths. The resulting heat flow pattern is compatible with values from the Global Heat Flow Database of the International Heat Flow Commission.

The estimated total volume of gas associated with gas hydrates in the study area is of the order of $3x10^{11}$ m^3. This value is 5 orders of magnitude lower than the global reservoir of methane from gas hydrates layers, which is $2\text{-}4x10^{16}$ m^3 (Kvenvolden, 1998). Seismic refraction measurements made by GEOMAR show a velocity inversion at the BSR, with velocities of 1850 m/s for the gas hydrate layer, and 1400 m/s for the underlying gas-bearing sediments (Dr. Matthias Zillmer, per. comm., 2002).

Upward mud and fluid migration in the central Black Sea southeast of the fan area is documented in mud volcanic activity such as that at the MSU Mud Volcano (Fig. 5).

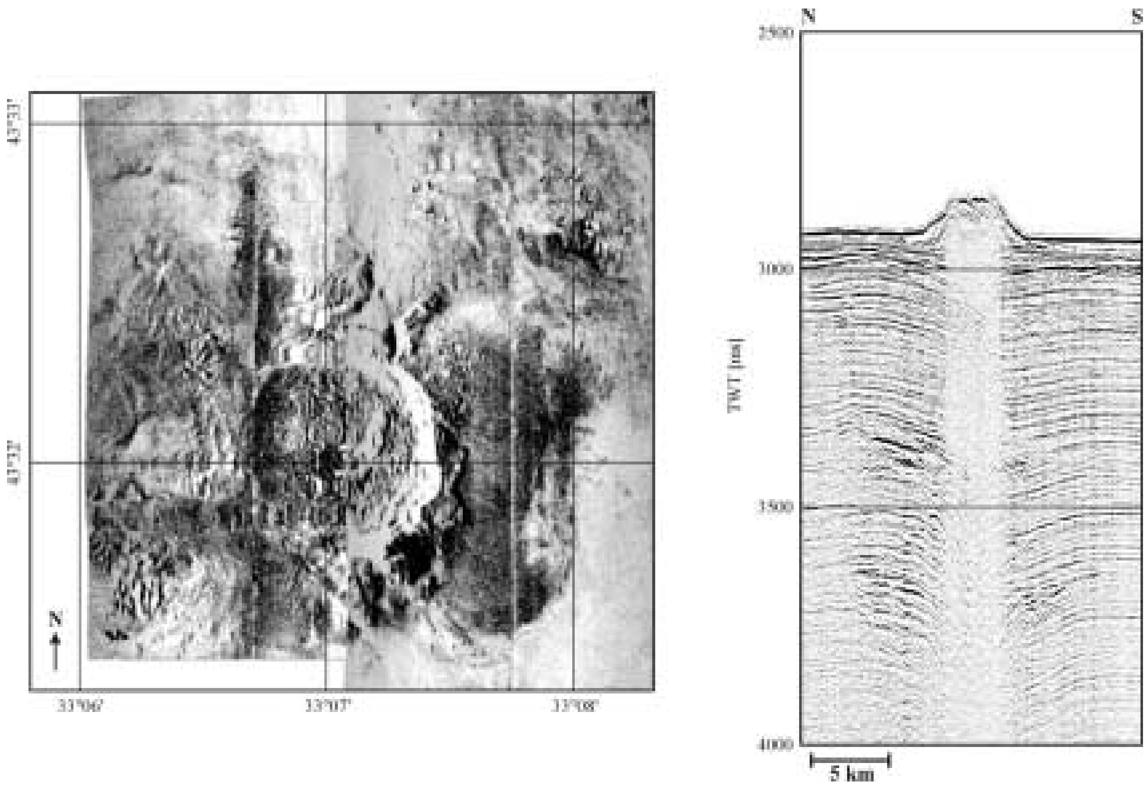

Fig. 5. (a) Sidescan mosaic of the MSU Mud Volcano, showing a round crater with rim, eruption centres within the crater, and mud flows down the flanks. (b) Seismic reflection profile through the MSU Mud Volcano. See Fig. 1 for profile location.

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Seismo-acoustics evidence of gases in sedimentary edifices of the paleo-Danube realm

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During the Quaternary the lower courses of the paleo-Danube, Dnieper and Dniester, the main rivers that were flowing in the western Black Sea, have been extremely dynamics. This dynamics has been the result of the associated effect of large, repeated sea level variation and the great width of the western shelf of the Black Sea. In order to keep pace with the changing sea level, the external drainage of the paleo-Danube fluctuated accordingly. The sea level variation has been taken place with different speeds (Winguth at al., 2000), a fact which together with the active tectonic in the region, controlled the hydrological parameters of the lower paleo-Danube. This dynamics affected the entire western shelf and produced a large variability of the drainage pattern of the lower paleo-Danube; this variability influenced the development of marshes, lagoons and deltaic bodies, which later were partly covered by newer sediments.

In general, large quantities of organic matter are associated with marshes, lagoons and delta sediments. The fluctuation of the external drainage area of the Danube during the Quaternary has affected the production and disposition of the organic matter and the horizontal variability of sediment types. During the geological evolution, due to the reworking and transportation of sediments, the organic matter has been dispersed to deeper parts of the sea. These types of organic matter concentrations, are spots in the regional production and settling of biomass. Soon after deposition, the organic matter is mainly decomposed in carbon dioxide, hydrogen sulfate and methane.

The gases migrate in the surrounding sediments in relation with the local permeability and even in very small amounts (1% or less of pore space) dramatically affect the acoustic impedance of the sedimentary edifices in which they are temporarily imprisoned (Anderson and Hampton, 1980) and greatly modify the corresponding acoustic facies. The spatial disposition of gases in sediments is a valuable and direct information regarding the evolution of the paleo-Danube realm and its deep sea fan.

The multifold high resolution seismic data acquired by IFREMER during BLASON (Black Sea Over the Neoeuxinian), French-Romanian scientific campaign in the Black Sea in 1998, have clearly put in evidence the canyon of the Danube (Fig. 1). The canyon is cut in Dacian+Q, Pontian and older sediments. The canyon has been build and filled in several stages and then covered by a sedimentary blanket. The width and depth of the canyon and its burying depth below the sea floor are smaller near to the seashore and larger to the shelf break. Near the shelf break the canyon is hardly seen on the seismic lines due to the chaotic deposition and also due to the high pore pressure of the water in the fine grained sediments.

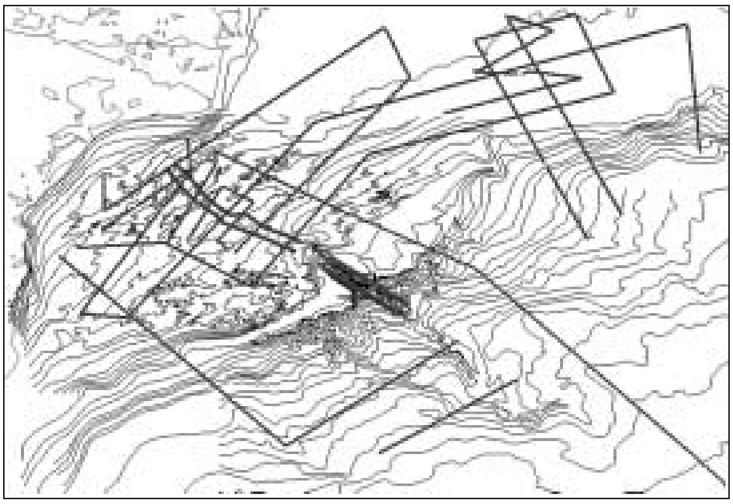

Fig. 1 The position of buried canyon of the paleo-Danube.

The 3.5 kHz data acquired by GEOECOMAR in the framework of the National Research Program between 1980-1990 show a multistage network of converging and diverging valleys to the main canyon of the paleo-Danube.

Based on these regularly spaced data, it is possible to separate sedimentary bodies specific of different paleo-geographic conditions, such as marshes, lagoons, abandoned streams and others specific features in which gases are present.

During the Blason cruise, GEOECOMAR using a chirp system collected very high-resolution seismic data, which work in the 2-16 kHz domain. The gas effect on seismic records is mainly controlled by the average diameter of gas bubbles and frequency of the signal. The frequency as instrumental controlling factor of the seismic response, plays a very important role.

There are frequency-gas bubble diameter couples for which the seismic effect of gases in sediments is maximum. Due to the wide frequency domain of the system, the chirp equipment has been very sensitive in detecting gases in shallow sedimentary structures. The decomposition of the organic matter is controlled by the depth of the sediments in which the process take place. At depths greater than 1000 m (Hovland and Judd, 1988), the methane is most likely to be of thermogenic nature. In the western part of the Black Sea, the Danube controlled the deposition, reworking and transportation of sediments on the continental shelf and slope and in the deep sea.

Taking into account the above mentioned considerations we searched for the gas presence in all three zones: continental shelf, continental slope and deep-sea area. We have correlated the pinger data with the multifold seismic information.

In the continental shelf area, the multifold seismics has mapped a lot of zones affected by the gas presence in sediments. In this case the effects of gases are reflected as columnar or local turbid facies and local or columnar bright spots. The columnar turbid facies are solitary or gathered in larger columns. The depth below the sea floor of the cap and root of the columnar features are variable. We observed the following cases:

- the gases are confined to a certain domain, no deeper than 1200 ms twt (two way time) and not reaching the sea floor;
- the gases are confined to a certain domain, no deeper than 1200 ms twt and reaching the sea floor;
- the gases come from deeper than 1200 ms twt zones and do not reach the sea bed, being limited to a less permeable horizon;
- the gases come from deeper than 1200 ms twt zones and reach the sea bed.

Sometimes the columnar zones are related with faults, which serve as permeable zones. In case the columnar features are not related with faults which serve as permeable zones, the gas rising could be related with more permeable tracts which were formed as a result of continuous supply with fluids during the sediment deposition.

We considered the columnar turbid seismic facies with roots deeper than 1400ms twt, to be of thermogenic origin. The shallow gases have been very well put in evidence on very high-resolution seismics recorded with 3.5 kHz and chirp pinger systems. On pinger sections the gas presence has been manifested as gas fronts, enhanced reflectors, acoustic turbid zones and acoustic windows. The general opinion is that the gases in shallow sediments are entirely of biogenic origin. It is not the general case for this part of the Black Sea.

A detailed comparison of these data with the multifold seismics information revealed in many cases a very good correlation. A good example of this situation is depicted in Fig. 2.

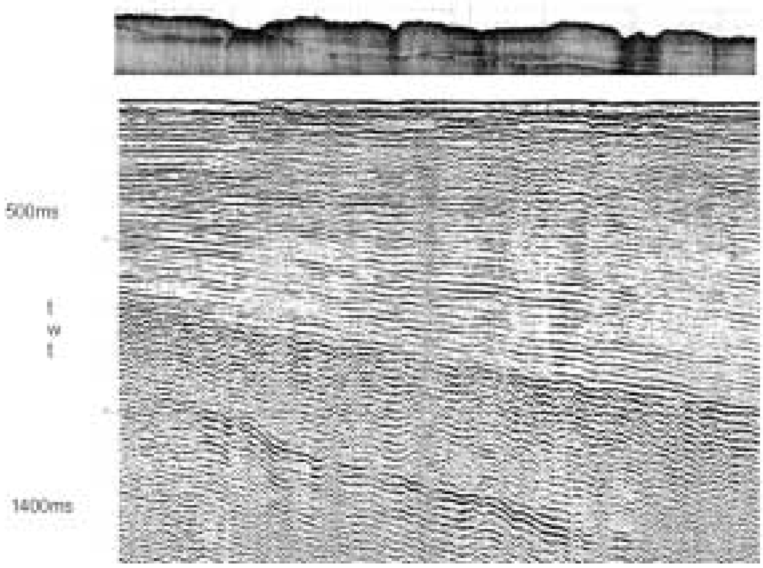

Fig. 2. Correlation of pinger and seismic data

In Fig. 2 one easily sees how several columnar seismic facies have their roots deeper than 1400 ms and how in some cases the bright spots are formed. In the upper sediments, the gases are spread, producing a large gas front, which is seen also on the pinger image. It is interesting to see how the low amplitude depressions (4-5m depth) observed on chirp data, are correlated with the main columns of gases seen on seismic information. It seems that expulsed gases from deep zones influenced the differential consolidation of the shallow sediments in zones of 200-700 m width. The depression on the right part of Fig. 2 has a central doming structure, which could be related with the gas expulsion trough the sea floor.

The same situation is encountered on a profile about 30 km off Razelm-Sf. Gheorghe coast line where columnar turbid facies and bright spots are present (see Fig. 1). In this area the canyon of the paleo-Danube is also present (see Fig. 3)

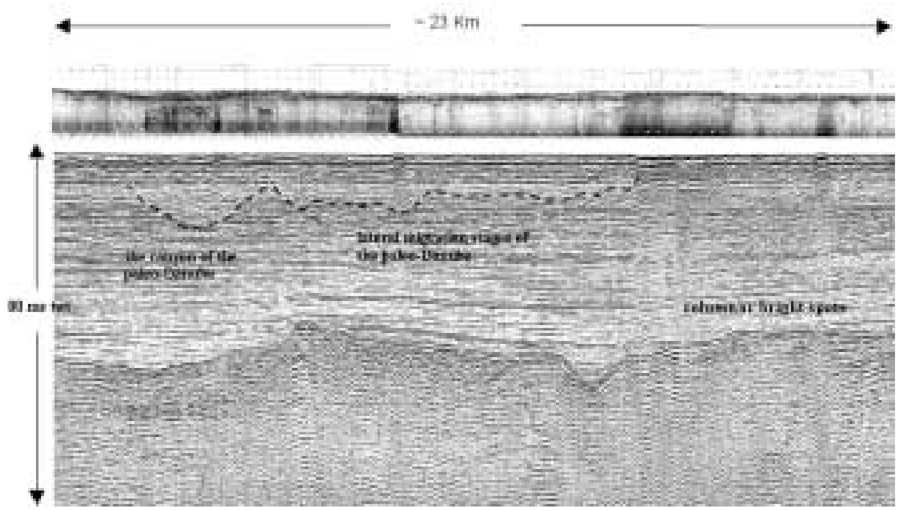

Fig. 3

Again, the columnar features reach the sea floor and go further in the water column. It is seen how the gas comes from deep zones and pass trough a major unconformity (Oligocene-Upper Cretaceous ?).

The columnar turbid zones on the corresponding chirp profile present a good correlation with the columnar gas expulsion zones seen on seismics. The chirp data suggest that the acoustic facies specific to the gas presence in shallow sediments are produced by both types of gas: biogenic and thermogenic.

There are a lot of areas on the western Black Sea continental shelf, where the acoustic facies related to the gas presence are entirely due to biogenic fluid production, which can be as deep as 1000 m, but usually shallower.

On the continental slope the data indicate a less important gas presence, probably due to the sediment dynamics on slope which disseminates the organic matter accumulations. It is quite common to record some gas accumulations along the flow faults, which are more permeable and constitute paths for fluids.

In the deep part of the Danube fan some morphologies appear linked to the fluid dynamics and gas presence.

In Figure 4 is presented an active mud volcano (see Fig. 1 for position), in 1650 m water depth area. The pool of fluids that feeds the mud volcano is deeper than 1000m below sea floor - bsf. The typical mud volcano morphology is preserved 40 ms twt bsf.

On the same line 53 km to the NE (see Fig. 1), a four level of bottom simulating reflectors – BSR (Fig. 5), can be distinguished. The BSR's are placed in the deep sea fan complex of the Danube and in water depths of 1500-1680 m and 400-600 ms twt bsf. We think that the first two

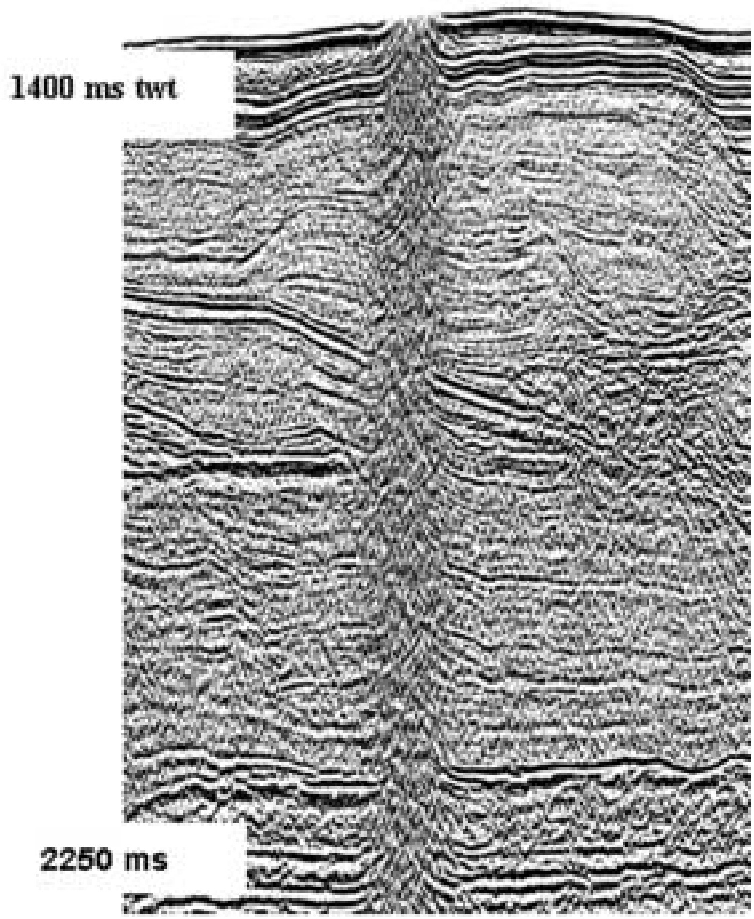

Fig. 4

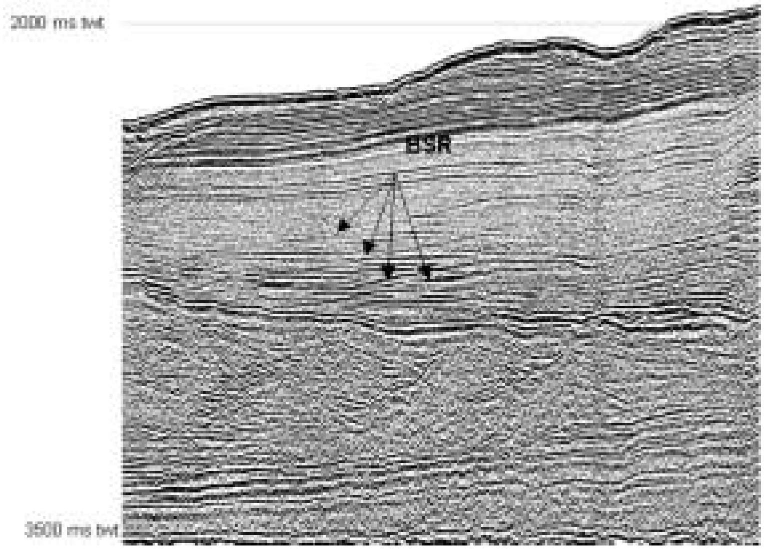

Fig. 5 BSR features

uppermost (A and B) BSR features are two layers with disseminated gas hydrates, without gas presence beneath them. The other two BSRs (C and D) appear to have basal fluids unless it is a single less

permeable layer with clathrates which have basal gas and water below gas. This quite uncommon association of BSR features could be the result of the vertical migration of the g-h stability zone, in response to the sea level variation during the Quaternary.

On another seismic line acquired during the Blason, outside of the paleo-Danube influence, a classical BSR feature was recorded (see Fig. 1 and Fig. 6).

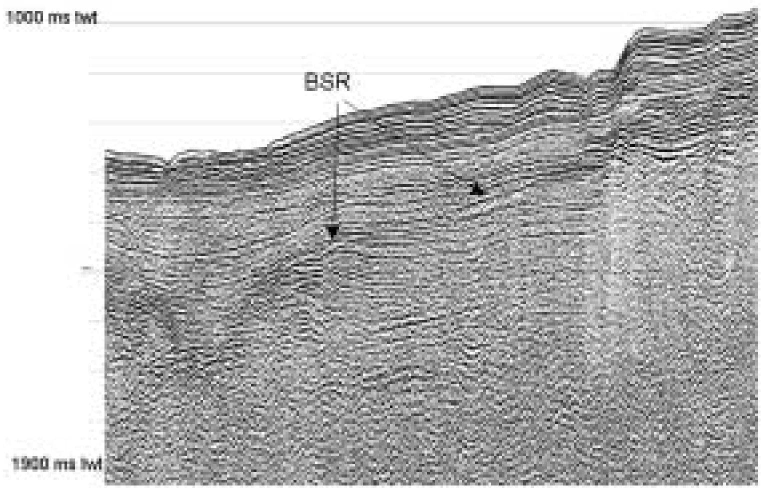

Fig. 6

In conclusion, the detailed analysis of the multifold seismics and pinger data reveal that the gas is present in the sedimentary features of the paleo-Danube realm, on the continental shelf and slope and in the deep sea zone. In the shelf area the biogenic gas is prevailing, but the thermogenic gas is also present. On the continental slope the gas signature on seismo-acoustic facies is less present. In the deep-sea area the gases in association with other fluids are present and produce mud volcanoes and BSR structures which have been reported for the first time in the Danube deep sea fan area.

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The Amazon-HARP Fan model: facies distributions in mud-rich deep-sea fans based on systematic coring of architectural elements of Amazon Fan

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Introduction

Although Amazon Fan is one of the largest deep-sea fans in the world, its architectural features are typical of "mud-rich" fans developed on passive margins, regardless of their size (cf. Bouma *et al.*, 1985). Because Amazon Fan is the only modern fan whose architectural elements have been systematically drilled and continuously cored, it is one of the most important modern analogs for understanding "mud-rich" deep-sea fans and their hydrocarbon reservoir potential. Prior to ODP drilling in 1994, architectural elements and distribution of sedimentary facies within Amazon Fan were inferred from high-resolution seismic, GLORIA side-scan sonar, SeaBeam swath-mapping and piston-core data (Damuth and Kumar, 1975; Damuth and Embley, 1981; Damuth *et al.*, 1983 a,b, 1988; Damuth and Flood, 1984, 1985; Manley and Flood, 1988; Flood *et al.*, 1991; Pirmez, 1994; Pirmez and Flood, 1995). In particular, these studies revealed that distributary channels have highly meandering planforms and are perched on natural levee systems. The aggradational channel-levee system is thus recognized as the basic depositional unit of the fan (Fig. 1). High-amplitude reflections (termed HARs) observed beneath the channel axis were interpreted as coarse-grained channel-fill deposits (Fig. 1). More laterally extensive high-amplitude reflections packets (termed HARPs) at the bases of channel-levee systems were interpreted as coarse sediment deposited either from flows spreading laterally outward from a channel mouth (i.e. depositional lobe), or from flows issuing through a crevasse in a levee during initiation of a channel-avulsion event (i.e. crevasse splays) (Figs. 1, 2). Although only one channel-levee system was active at any given time, repeated channel avulsion developed groups of overlapping, genetically related channel-levee systems, termed channel-levee complexes, across the upper to middle fan surface. In addition, large, regionally extensive mass-transport deposits overlying portions of channel-levee systems were recognized on the modern fan surface (Damuth and Embley, 1981) and seismic data showed that older levee complexes buried within the fan are also separated by similar thick, mass-transport deposits at many locations (Manley and Flood, 1988) (Fig. 1).

Results of Drilling during ODP Leg 155

ODP Leg 155 cored > 4 km of sediment from 17 drill sites on Amazon Fan. Excellent continuous sections were recovered from all major submarine-fan elements including: (1) levee/overbank deposits of channel-levee systems of a variety of ages, (2) channel-fill deposits (HAR units), (3) base-of-channel deposits (HARP units), (d) lower fan lobes, and (e) surficial and buried mass-transport deposits. Terrigenous sediments comprise the vast majority of the cored

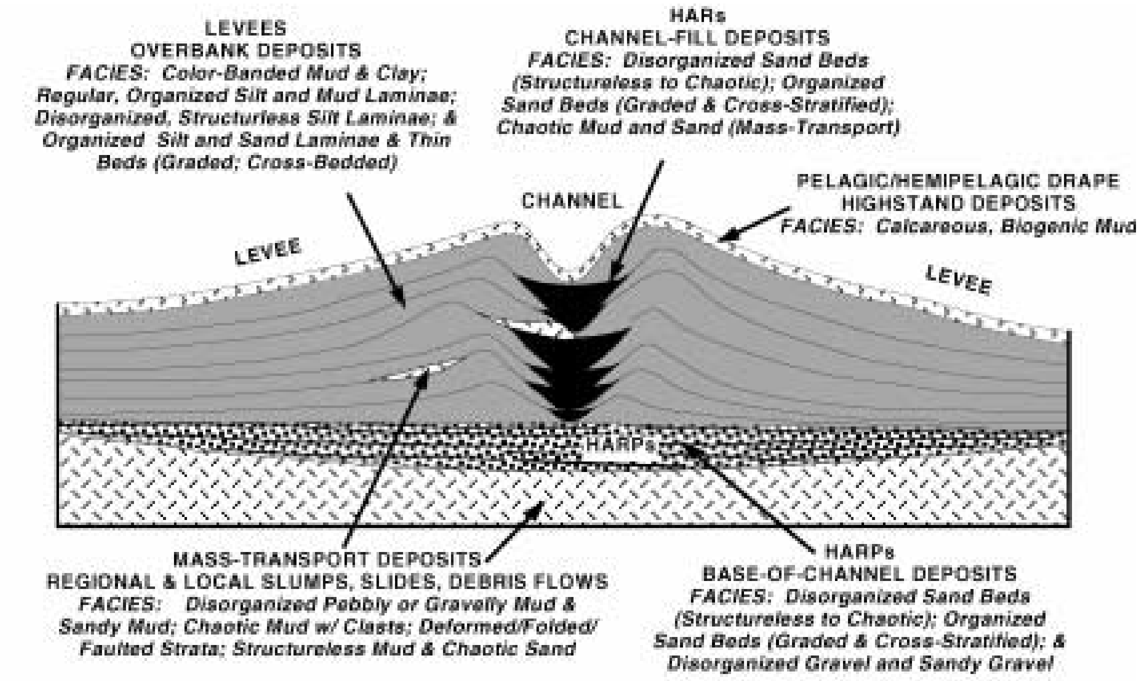

Fig. 1. Distribution of sedimentary facies within seismic units and architectural elements of a channel-levee system on Amazon Deep-Sea fan. The schematic diagram shows a typical channel-levee system which is the basic architectural unit of the upper and middle fan. Regional mass transport deposits separate channel-levee complexes in many parts of the fan (modified from Normark, Damuth et al., 1997).

intervals and display a number of discrete sandy and muddy facies (Fig. 1) (Normark, Damuth *et al.*, 1997). Wire-line logs in combination with Formation MicroScanner TM (FMS) images allowed interpretation of ~400 m of coarse-grained intervals of little or no core recovery (see Flood *et al.*, 1995; Flood *et al.*, 1997 for detailed results of Leg 155 drilling which are briefly summarized here).

The levee or overbank deposits are constructed of seven interbedded facies (Fig. 1). Color-banded mud and clay are most common. Interbeds of coarser sediment are rare to abundant and are predominantly organized (e.g. x-stratified, graded) and disorganized (structureless) silt laminae and thin beds (<10 cm); medium and thick silt beds are common to rare, respectively. Organized sand beds also occur, but are much less common than silt beds.

Sediments cored from beneath the axis of the modern Amazon Channel in the underlying HARP units are predominantly thick-bedded, coarse facies (Fig. 1). The most prevalent facies is disorganized structureless to chaotic, poorly sorted, fine-to-coarse sand; large mud clasts are common. Beds range up to several meters in thickness (net:gross = 30-75%). Medium-to-thick-bedded, fine-to-medium organized sands (e.g. graded, x-stratified) are also common to abundant. Some intervals of deformed to chaotic mud occur and apparently represent localized sediment failure of the levee walls, which produced small, localized mass-transport within the channels.

The coarsest and thickest sand beds occur in the thick, laterally extensive HARP units at the bases of individual channel-levee systems (Fig. 1) and in lower-fan deposits, which presumably represent coalescing depositional lobes (i.e. HARPs) extending downfan from the mouths of the leveed channels. HARP units are confirmed to contain thick, laterally extensive, medium-to-coarse sands commonly with mud clasts and rock granules. Wire-line and FMS logs and rare recovered pebbles suggest that some intervals of little to no core recovery are thick beds of disorganized gravel or sandy gravel (Pirmez *et al.*, 1997). More commonly, HARPs and lower-fan deposits contain medium-to-thick (up to 12 m) beds of disorganized structureless to chaotic sand. Poorly sorted medium-to-coarse sand with large mud clasts is common. Medium-to-thick organized sand beds (e.g. graded, x-stratified) of fine to medium sand are also common. These facies

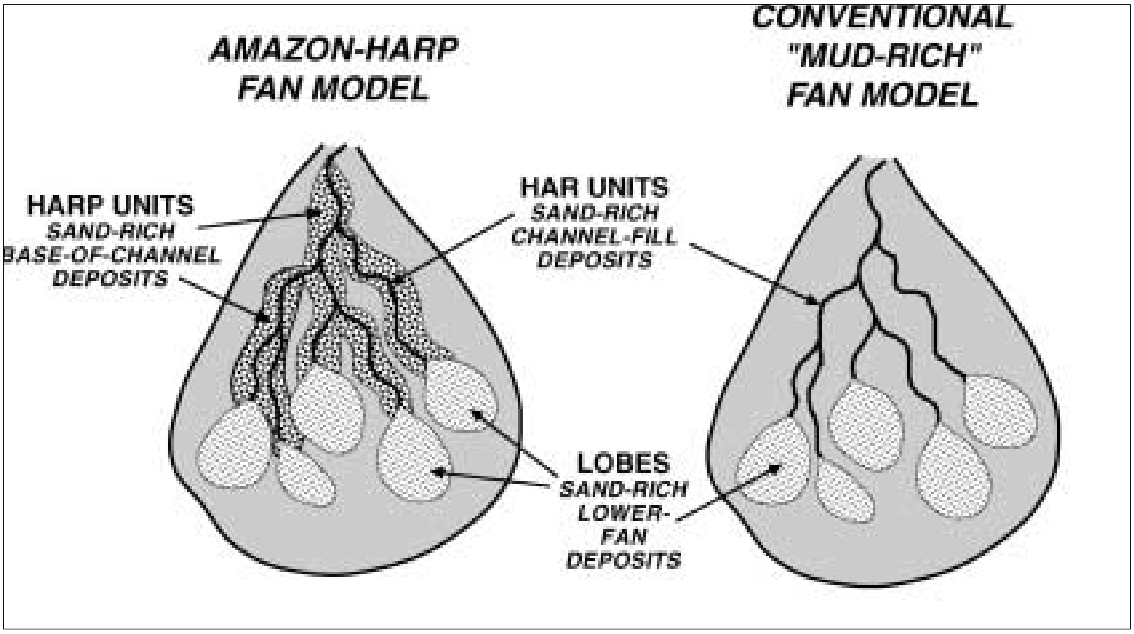

Fig. 2. **Left:** schematic diagram showing sand-rich architectural features of "mud-rich" deep-sea fans based on results of drilling on Amazon Fan. **Right**: previous conventional models for "mud-rich" fans did not recognize the sand-rich HARP units, which indicate that more extensive sand deposits exist in these fans.

support the interpretation (Flood *et al.*, 1991) that a HARP unit forms by deposition from turbidity and related gravity-controlled flows that issue from a crevasse in an active channel levee during the beginning of an avulsion event. The HARP unit is, in a sense, a laterally restricted (by inter-levee topography), end-of-channel lobe that progressively progrades down slope in front of the newly forming channel-levee system until it reaches the lower fan. The new channel-levee system, which was created by avulsion, progressively builds downslope and buries these coarse deposits to form the base-of channel HARP unit. Upon completion of channel-levee development, the HARP unit spreads laterally across the lower fan to form an end-of-channel lobe. In the upper and middle fan, HARP units thus form thick (>100 m), laterally extensive (tens of km) sand bodies (net:gross = 50-100%) that were not recognized in previous fan models.

The thick, regionally extensive mass-transport deposits on the fan surface and buried within the fan contain mainly chaotic muddy facies that clearly indicate large-scale sediment failure and mass-transport (e.g. slumps, debris flows) down-fan (Fig. 1). These deposits consist predominantly of thick intervals (tens of meters) of deformed or chaotic mud with mud clasts and blocks, or discordant, contorted, folded, faulted, and truncated beds. Thick intervals of disorganized pebbly or gravelly mud and sandy mud are common, and intervals of homogeneous, structureless mud (possibly undeformed blocks) also occur. Large scale sediment failures that led to these deposits were apparently initiated at various locations on the upper and middle fan by processes that are not yet fully understood (Piper *et al.*, 1997).

During periods of glacio-eustatic sea-level lowstand and early rise, individual channel-levee systems aggraded at very rapid rates (up to 30m per 1000 yrs), and entire levee complexes of multiple channel-levee systems formed during a single 100 ka (4th order) glacial/interglacial period. Thin intervals of pelagic and/or hemipelagic biogenic muds drape inactive channel-levee systems and lower-fan areas away from the active channel-levee system (Fig. 1). Holocene and previous glacio-eustatic sea-level highstands of the Quaternary have caused the entire Amazon Fan to become temporarily inactive for short periods (~10 k.a.) by forcing the locus of Amazon River sedimentation landward to the inner shelf, and thereby cutting off the large terrigeneous sediment supply to the fan. As a result, only a thin (< 1 m) layer of calcareous biogenic mud (Fig. 1) has slowly accumulated across the entire fan during the Holocene (Damuth and Kumar, 1975; Damuth *et al.*, 1988). Similar thin intervals of biogenic mud recovered deeper in the fan attest to previous periods of fan inactivity during older interglacials (Flood *et al.*, 1995). These biogenic mud intervals represent condensed sections equivalent to at least portions of transgressive (TST) and highstand (HST) systems tracts and maximum flooding surfaces (MFS) in the Vail/Exxon conceptual sea-level model.

CONCLUSIONS

The Leg 155 cores show that despite its classification as a “mud-rich” submarine fan, many elements of the Amazon Fan (HARs, HARPs, lower-fan lobes) actually contain very thick sand deposits (Fig. 1), some of which are laterally extensive and therefore form potentially good reservoir sands (Fig. 2). Stacked, coarse channel-fill deposits (HARs) in a channel-levee system can be >tens of meters thick, up to kilometers wide and extend for tens of km down fan. Coarse deposits that form HARP units beneath channel-levee systems (Fig. 1) and depositional lobes on the lower fan comprise much more laterally extensive sand deposits, which can contain stacked sand units 10's to 100's of meters thick and several tens of km in width and length (Fig. 2). The Amazon Fan demonstrates that some elements of so called “mud-rich” submarine fans can contain extensive coarse deposits, which should exhibit good lateral and vertical continuity and, thus, provide excellent reservoir potential. Such reservoirs would be enclosed in muddy levee/overbank and mass-transport deposits, which should provide good seals. Since drilling of Amazon Fan, many oil companies have utilized 3D seismic data to identify buried meandering channel-levee systems in continental margin deposits of the Gulf of Mexico, West Africa, Niger Delta and other locations, which show architectural elements (HARs, HARPs, levees) similar to those of Amazon Fan and are now providing good exploration targets.