I - EXECUTIVE SUMMARY
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 biostratigraphy, 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 on large scale features like salt ridges. Mud volcanoes, mud “cakes” or pockmarks are mesoscale features, whereas chemohemms 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 an 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.