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Title

LEBANESE SUBMARINE CANYONS AND THEIR ROLE IN SEDIMENT TRANSFER FROM SHALLOW TO DEEP WATER

Settore Scientifico Disciplinare GEO/04 GEO/02

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Abstract

Submarine mass movements and their consequences are of major concern for coastal communities and infrastructures but also for the exploitation and the development of seafloor resources. Elevated awareness of the need for better understanding of the underwater mass movement is coupled with great advances in underwater mapping technologies over the past two decades.

The seafloor in the Bay of Jounieh and Beirut North (Lebanon) is characterized by deep canyons, reaching one thousand meters depths in proximity of the coast. Signs of submarine mass movement instability related to these canyons create a connection between shallow and deep water. The presence of these canyons in a tectonically active area generates a particular drained mechanism to the sediment in form of mass movement and slumping.

Since this area is poorly explored, in the framework of an international project between Lebanese Navy Hydrographic Service, Lebanese National Center for Marine Sciences, University of Ferrara and Italian Navy Hydrographic Institute, we analyse the morpho-bathymetric and sedimentological characters of the coastal and shelf sectors. Multibeam echosounder and sub-bottom profiler acoustic systems calibrated with ground truths (sediment grabs) in accordance to the International Hydrographic Standards allow us to characterize the nature of seafloor and sub-seafloor. The detection of particular undersea features provides detail maps which are in support to littoral morpho-dynamics, coastal transport and sediment budget. This high resolution multibeam bathymetry dataset, integrated by the sedimentological characters, will provide useful constraints to the potential natural hazards that may be caused by active tectonics in the offshore and a high coastal risk in one of the most populated region of Lebanon.

The study aims to evaluate the role of the area's submarine canyons in the underwater mass movements, taking into account: 1) the evaluation of the environmental condition of the Jounieh Bay, 2) the sediment deposit dynamics along and across the Lebanese continental shelf and slope, and finally 3) the sediment movement inside canyons heads in the Jounieh-Beirut Basin.

The above studies allowed us to discover that although canyons in the research's area belong to the same continental margin, share more or less the same morphology and are located few kilometres apart, they display a relevant variability in their geometry, morphology, sedimentary processes, and where the SW current is the main governing cause of sediment movement, and to highlight the important role that the Jounieh-Beirut Basin plays in the Lebanese underwater dynamics, comparing its status in 2019 with a previous work achieved by Goedicke and Sagebiel (1976).

Riassunto

I movimenti di massa sottomarini con le loro conseguenze sono di un grande interesse per le comunità e le infrastrutture costiere e anche per lo sfruttamento e lo sviluppo delle risorse del fondale marino. L'elevata consapevolezza della necessità di una migliore comprensione del movimento di massa sottomarino è accompagnata da grandi avanzamenti nelle tecnologie di rilievi sottomarini durante gli ultimi due decenni.

Il fondale marino nella baia di Jounieh e del Nord di Beirut (Libano) è caratterizzato dalla presenza di profondi canyons che raggiungono mille metri di profondità in prossimità della costa. I segni dell'instabilità del movimento di massa sottomarino relativi a tali canyons creano una connessione tra acque basse e acque profonde. La presenza di questi canyons in un'area tettonicamente attiva genera un particolare meccanismo di drenaggio del sedimento sotto la forma di movimento di massa e di crolli.

Visto che l'area è poco esplorata, nel contesto di un progetto internazionale tra il servizio idrografico della Marina Libanese, il centro nazionale libanese per le scienze del mare, l'Università di Ferrara e l'istituto idrografico della Marina Militare Italiana, analizziamo i caratteri morfo-batimetrici e sedimentari dei settori costieri e della piattaforma continentale. Gli ecoscandagli multifascio ed i sistemi acustici "Sub-bottom profilers", calibrati con dati reali (raccolta di sedimenti), in conformità con gli standard internazionali dell'idrografia, ci permettono di caratterizzare la natura del fondale e del substrato. La detezione di morfologie sommerse particolari permette la costruzione di mappe di dettaglio a supporto di analisi di morfodinamica litorale, trasporto sedimentario costiero e budget sedimentario. Questi dati batimetrici da sistemi multifascio ad alta risoluzione, integrati con i caratteri sedimentologici, forniscono dati utili per la previsione di potenziali rischi naturali che potrebbero essere causati da tettonica attiva nella zona offshore, e per un alto rischio costiero in una delle regioni le più popolate del Libano.

Questo studio ha lo scopo di valutare il ruolo dell'area dei canyons sottomarini nei movimenti di massa sottomarini, considerando:

1- La valutazione della condizione ambientale della baia di Jounieh.
2- Le dinamicità del deposito sedimentario lungo e attraverso la piattaforma continentale e lo slope libanese e finalmente,
3- Il movimento del sedimento nelle teste dei canyons nel bacino Jounieh-Beirut.

Questi studi ci hanno permesso di scoprire che i canyons nell'area di ricerca nonostante la loro appartenenza allo stesso margine continentale, la condivisione più o meno della stessa morfologia e la loro presenza a pochi chilometri l'uno dall′ altro, mostrino una relativa variabilità nella loro geometria, morfologia, e processi sedimentari, la corrente SW è la causa principale che controlla il movimento del sedimento. Lo studio evidenzia il ruolo importante che il bacino di Jounieh-Beirut gioca nella dinamicità sedimentaria dei fondali libanesi, anche grazie al confronto tra il suo stato attuale (2019) e la situazione nel 1976.

Introduction

Sediment mass movements are linked to the formation of submarine canyons which is believed to occur as the result of at least two main processes: 1) erosion by turbidity current; and 2) slumping and mass wasting of the continental slope. Naturally, the erosion patterns of submarine canyons may appear to mimic those of river-canyons on land, but due to the markedly different erosion processes that have been found to take place underwater at the soil/water interface, several notably different erosion patterns have been observed in the formation of typical submarine canyons.

Submarine canyons and related mass movements are more common on the steep slopes found on active margins compared to those on the gentler slopes found on passive margins. They show erosion through all substrates, from unlithified sediment to crystalline rock. Canyons are steeper, shorter, more dendritic and more closely spaced on active than on passive continental margins where the walls are generally very steep and can be near vertical. These walls are subject to erosion by bio-erosion, or slumping. There are an estimated 9,477 submarine canyons on earth, covering about 11% of the continental slope.

My project is devoted to a geological characterization of the Lebanese seafloor in Eastern Mediterranean in the area between Jounieh and North Beirut with a hydrographic approach. This area is poorly explored; the offshore coastal strip is characterized by a very narrow continental shelf, crossed by deep canyons that, from a short distance from the coast, go down to depths of one thousand meters. The seabed topography is the continuation of inland geomorphology with its almost absent coastal plain on which the main Lebanese cities have developed, and a steep mountain belt exceeding in elevation 3000 meters, 20 km from the coast. The submarine canyons are nothing else than the continuation of steep inland valleys which correspond, more or less to active tectonic faults.

In the frame of the CANA project (2010), the CNRS National Centre for Geophysical Research (NCGR) conducted a bathymetric study in the area of coastal shallow waters, completing the studies already executed in 2003 by the French-Lebanese team and the IFREMER. The discovery of a complex intricate network of submarine canyons off the coast of Central Lebanon and the active deformation of the seabed that this complexity suggests, are revealing signs of the seismic risks associated with this peculiar geological situation of Lebanon. It has been demonstrated that the isolated high relief of Mount Lebanon, plunging almost vertically into the deep sea (an altitude change of 3000m within 20 km), and the deformation of the seabed are indicators of the active growth of this relief due to a tectonic thrust on its continental margin.

Mapping the topography of the seabed and producing a morpho-bathymetric map represent a priority for Lebanon in order to carry out a sustainable development of sea resources and reduce the coastal vulnerability. A detailed seabed mapping is produced and will be the main support to all scientific research dedicated to the area and primarily to detect the seafloor and sub-seafloor geological and geophysical features. One of the most important recent morpho-dynamics features are those connected to the submarine mass movement and slumping that have been poorly studied at the Lebanese continental margin. In general, triggering factors are, consequently, as diverse as sea-level fluctuations, earthquakes, high-sediment supply leading to the overload of under-consolidated deposits, fluid charging and more. Depending on their size and location on a margin, submarine failures could be responsible for various hazards including tsunami and destruction of infrastructures such as submarine cables. The interpretation of seafloor morphology in terms of mass wasting processes and the identification of the potential factors controlling sediment failure are of major importance for the geo-hazard assessment in a given area.

The superficial failures are mainly located in the areas surrounding the mouth of the mountain-supplied rivers and along the walls of canyons eroding the continental slope. The slope angle is known as an important factor controlling the location and volume of submarine failures. High sedimentation rates related to hyperpycnal flows and gradual basal erosion of canyon walls are thought to be the main trigger mechanism. Generally large scars are located at the base of the continental slope, between 1,500 and 2,000 m of water depth. Their location correlates with the presence of faults that are also the areas of highest earthquake activity.

The aim of this research is to define the morpho-bathymetric and sedimentological characters of the coastal and shelf sector referring to the seafloor dynamics in connection with deep water environment and drainage system. The presence of Jounieh-Beirut basin's canyons in a tectonically active area creates probably a particular drained mechanism to the sediment in form of mass movement and slumping. The methods in support to this goal are multibeam (MB) and sub-bottom profiler acoustic systems calibrated with ground truths (sediment grab) to characterize the nature of seafloor and sub-seafloor with particular detail to the geotechnical and geochemical properties of sediments and high resolution seismic-stratigraphy of the surficial layers. In particular, the use of acoustic data and backscatter signatures provide information of the seafloor morphology and nature with an areal sweep and also of the water column.

The first product of this research is the seabed mapping of coastal and offshore sector from Jounieh to North of Beirut while the final product will be a multilayer hydro-oceanographic map in accordance to the International Hydrographic Standards and nautical supports. The detection of particular undersea features will provide detail maps that fund the environmental assessment and protection (mapping freshwater karstic resurgence craters, marine habitat, wrecks and submerged remain), resource exploitation, coastal management and geo-hazard precautionary measures.

Results of the study highlight the sediment mass movement inside Jounieh-Beirut basin and the role of its canyons (Jounieh, Nahr El Kalb, and Saint Georges) as bypass of the deposited sediment, taking into account the environmental status of the Jounieh bay. Moreover, this result should be in support to littoral morpho-dynamics, coastal transport and sediment budget. The mapping of particular features imputable as the slumping phenomena is clear connection in the definition of the slope and seafloor stability aiming to define the role of slumping in the deposition and distribution patterns of the sediments in the Eastern Mediterranean basin. Recent studies have become of great practical value concerning the possible earthquake-triggered hazards. Finally, this high-resolution seabed mapping will devote to the interest in potential natural hazards that may be caused by active tectonics in the offshore and a high coastal risk where it is located the most populated area.

These new data (morpho-bathymetric and seafloor data) should integrate the previous data related to the sector to increase the resolution and information knowing that the technology of data processing and management is recently growing. Finally, I hope with this research's results to create an easy hydrographic workflow, to raise the awareness of potential areas where slope movements could be triggered. For this purpose, I created a very high resolution multibeam bathymetry dataset integrated by the sedimentological characters; the acoustic data sharing and its interdisciplinary uses are "bench marks", contributing in a rapid growing value with the use of standardized database to develop integrated tools.

This work is structured in seven chapters reflecting the temporal development of the study:

- Chapter 1: Introduction to Hydrography;
- Chapter 2: Principles of hydrographic surveying;
- Chapter 3: Seafloor Mapping along Continental Shelves;
- Chapter 4: Aspects of Submarine Mass Movement;
- Chapter 5: Environmental status of the Bay of Jounieh through the evaluation of its marine sediments' characteristics. This chapter is based on a published paper by Milad Fakhri, Abir Ghanem, Myriam Ghsoub and Afif Ghaith on Lebanese Science Journal, Vol. 19, No. 3, 2018, 373-388;
- Chapter 6: Sediment deposit dynamics along and across the Lebanese continental shelf and slope;
- Chapter 7: Sediment movements inside canyons heads of Jounieh-Beirut basin.

1. Chapter 1: Introduction to Hydrography

1.1. Brief history of hydrography

The oldest modern navigational chart known today is the Carte Pisane, so named as it was bought in 1829 from a Pisan family by the Bibliothèque Nationale in Paris. It was drawn on an animal skin towards the end of the 13thC, probably in Genoa where a school of marine cartography had been established; there was a similar school in Venice, while a third school was developed on the isle of Majorca. Known as "portolans" the charts produced by each of these schools were similar in style and content.

During the 16thC a school of hydrography was formed in Dieppe by the many sea pilots who sailed to distant shores. In 1661 Jean Baptiste Colbert became Chief Minister to Louis XIV and among his many tasks was that of revitalising the French Navy. He not only took over the Dieppe school but established similar hydrographic centres in a number of other French ports. This enabled him to have surveys made of the whole French coastline, every chart being directly connected to the national triangulation established by the Cassini dynasty. Colbert's cadre of hydrographers were working in New France and the mass of material coming from Quebec led to the establishment in Paris of the "Dépôt Général des Cartes et Plans", now recognised as the first national Hydrographic Office. Denmark was the next nation to establish a Hydrographic Office, followed closely by the British in 1795; a further twenty or so countries established such offices in 19thC.

About 1775 two British surveyors, Murdoch Mackenzie and his nephew of the same name were largely responsible for the invention of the station pointers, a device with which a vessel's position could be precisely plotted by the observation of two horizontal angles between three fixed marks onshore. This was a major technical advance which revolutionised sea surveying throughout the 19thC during which the demands for navigational charts both for war and peace increased dramatically. Even before World War I a number of national Hydrographers were considering how international cooperation could lead to the exchange of and the standardisation in chart design. With the end of the War the British and French Hydrographers jointly called for an international Conference at which delegates from 22 countries gathered in London in June 1919. Many Resolutions were adopted by the Conference concerning chart standardisation and finally a Resolution to form an International Hydrographic Office with three Directors.

H.S.H. Prince Albert I of Monaco, who had been kept in touch with the Proceedings of the Conference, generously agreed to provide a building in the Principality to house the Bureau where it remains.

The history of hydrography during the 20thC, during which there have been many technical developments, can be followed in the 75th Anniversary Commemorative Issue of the International Hydrographic Review dated March 1997.

1.2. Importance of hydrography

Firstly it is necessary to consider the IHO definition of Hydrography, which stands as follows:

That branch of applied sciences which deals with the measurement and description of the features of the seas and coastal areas for the primary purpose of navigation and all other marine purposes and activities, including –inter alia- offshore activities, research, protection of the environment, and prediction services. (IHO Pub. S-32)

Therefore, the development of a National Maritime Policy requires a well-developed capability to conduct all these activities which will allow the obtaining of basic knowledge of the geographical, geological and geophysical features of the seabed and coast, as well the currents, tides and certain physical properties of the sea water; all of this data must then be properly processed so that the nature of the sea bottom, its geographical relationship with the land and the characteristics and dynamics of the ocean can be accurately depicted in all zones of national shipping. In brief, Hydrography, as defined, is the key to progress on all maritime activities, normally of great national economic importance. To adequately address areas such as:

- Safe and efficient operation of maritime traffic control;
- Coastal Zone Management;
- Exploration and Exploitation of Marine Resources;
- Environmental Protection;
- Maritime Defence.

It is necessary to create a Hydrographic Service. The Hydrographic Service, through systematic data collection carried out on the coast and at sea, produces and disseminates information in support of maritime navigation safety and marine environment preservation, defence and exploitation.

1.3. Fields of competence associated with hydrography

1.3.1. Maritime Transport

More than 80% of international trade in the world is carried by sea. Maritime commerce is a basic element for a nation's economy. Many areas and ports in the world do not have accurate nor adequate nautical chart coverage. Modern nautical charts are required for safe navigation through a country's waters and along coasts and to enter its ports. A lack of adequate nautical charts prevents the development of maritime trade in the waters and ports of the concerned nations. The shipping industry needs efficiency and safety. Poorly charted areas and the lack of information can cause voyages to be longer than necessary, and may prevent the optimum loading of ships, thus increasing costs. The saving of time and money resulting from the use of shorter and deeper routes and the possibility to use larger ships or load ships more deeply may produce important economies for national industry and commerce. It is also very important to note that the SOLAS Convention Chapter V considers a ship unseaworthy if it does not carry up-to-date charts necessary for the intended voyage.

A solution to these problems would not be possible without the quality maps and charts produced and continually updated and distributed by a Hydrographic Service. These charts, produced by means of modern hydrographic surveys, are required to enable the larger ships of today to navigate through national waters and enter ports the access to which was formerly insecure and therefore are essential tools for the creation of coastal nations' incomes.

Modern charts also provide information required to create the routeing systems established by international conventions and to meet the economic interests of the coastal state.

1.3.2. Coastal Zone Management

Adequate coastal zone management includes items such as construction of new ports and the maintenance and development of existing ones; dredging operations for the maintenance of charted depths and for the establishment, monitoring and improvement of channels; control of coastal erosion; land reclamation from the sea; establishment and monitoring of dumping grounds for industrial waste; extraction of mineral deposits; aquacultural activities; transportation and public works projects including construction of near shore infrastructure.

Precise large-scale surveys provide the primary data essential for projects involving all items mentioned above. Due to the rapid changes to which shorelines are subject, these surveys must be updated with the frequency dictated by the monitoring and analysis process. The information collected by Hydrographic Offices about the coastal zone provides essential input to coastal zone GIS (Geographic Information Systems) which are increasingly being used for better overall management and decision-making with regard to conflicting uses within the coastal region. The users of hydrographic information go beyond the traditional user group, mariners, to include government agencies, coastal managers, engineers, and scientists.

1.3.3. Exploration and exploitation of marine resources

Although intended primarily to support safety of navigation, the extensive data-bases amassed over the years by Hydrographic Offices, together with their various products and services, are of considerable economic value in assisting the management and exploitation of natural marine resources. In recent years, it has become more evident that inadequate hydrographic services not only restrict the growth of maritime trade but also lead to costly delays in resource exploration.

Coastal and offshore sedimentary areas may contain mineral deposits, in particular hydrocarbons, which require adequate surveys in order to be identified. If the existence of these hydrocarbons is confirmed, this will lead to the coastal nation's undertaking development of hydrocarbon production which implies interpretation of the sea floor morphology; navigation safety for the transportation of these hazardous cargoes; safety of offshore platforms and related sea floor transmission systems and the placement of production wells and the laying of pipelines. Bathymetric, tidal and meteorological data provided by a Hydrographic Service is a fundamental element in the development of a hydrocarbon industry.

The fishing industry is also a source of national wealth. Fishermen need marine information not only for the safe navigation of their vessels but also for safe deployment of their fishing gear, which will prevent costly losses. In addition, oceanographic charts, compiled and produced by Hydrographic Offices, are now being extensively used by the fishing industry.
Fishery activities need detailed charts in order to:

- Avoid loss of fishing gear and fishing vessels on undetected or poorly charted obstructions;
- Identify fishing areas;
- Locate areas where fishing is limited or prohibited.

This kind of information is subject to frequent changes and therefore needs constant updating. Hydrographic surveying is essential to obtain timely and up-to-date information and should be periodically repeated.

The trend of modern fishery science is orientated towards habitat management; bathymetry and other ocean data will provide important input for proper species management and development.

1.3.4. Environment Protection and Management

An essential factor for the protection of the environment is safe and accurate navigation. Pollution caused by wrecks and oil spills are a major damage factor, the economic consequences of which are more devastating than is commonly imagined, but which, in some cases, have been estimated at US $ 3 billion for a single incident. The value of navigation services for the protection of the marine environment has been internationally recognized. In this respect, it should be noted that Chapter 17 of Agenda 21 of the United Nations Conference on the Environment and Development (UNCED), held in 1992, recognized that *"Hydrographic charting is vitally important to navigational safety"*

1.3.5. Marine Science

Marine science depends largely on bathymetric information. Global tide and circulation models, local and regional models for a wide variety of scientific studies, marine geology/geophysics, and the deployment/placement of scientific instrumentation and many other aspects of marine science depend on bathymetry provided by Hydrographic Services.

1.3.6. National Spatial Data Infrastructure

In the information age it is realised by governments that good quality and well managed spatial data are an essential ingredient to economic and commercial development, and to environmental protection. For this reason many nations are establishing national spatial data infrastructures, bringing together the services and data sets of major national spatial data providers, for example topography, geodesy, geophysics, meteorology, and bathymetry. The Hydrographic Service is an important part of the national spatial data infrastructure.

1.3.7. Maritime Boundary Delimitation

Good hydrographic data is essential to proper delimitation of the maritime boundaries as detailed in the United Nations Convention on the Law of the Sea.

1.3.8. Maritime Defence

Navies are major users of nautical chart products in that they must be prepared for deployment to many areas in the world and typically must maintain a large set of charts. The unique risks associated with the carriage of munitions and nuclear materials make it important for such vessels to have up-to-date information. The marine data and information provided by national Hydrographic Offices support a variety of products used in naval operations. Surface, submarine, anti-submarine, mine-hunting and aero-naval operations need nautical information products very different one from another. Hydrographic and oceanographic data necessary for the preparation of such products must be available if national investment in defence is to be optimised.

1.3.9. Tourism

Good charts are particularly important to the development of the economically important industry of tourism, especially involving cruise ships. The potential of the cruise ship industry is especially important to developing nations. Yet this important source of revenue cannot be properly developed if safe navigation to remote touristic landscapes is prevented or limited by a lack of adequate charts. Tourism is one of the major growth industries of the 21st Century.

1.3.10. Recreational boating

The recreational boating community represents a large percentage of mariners. It is generally not mandatory for leisure craft to carry charts and recreational mariners often do not update their charts; however, the advent of digital chart information is making it possible for the recreational user to have updated chart information readily available along with many types of value added information such as marina locations, etc. This development is likely to result in the recreational leisure sector becoming a significantly larger user of the hydrographic data as greater numbers of people become able to afford boat ownership. Again income from this sector is increasingly significant to many countries.

As it can be seen, it is extremely difficult to quantify the economic and commercial benefits which flow from a national hydrographic programme, but several studies by IHO Member States have suggested that the cost to benefit ratio is about 1:10 for major maritime nations. It is also true that volumes of maritime trade are growing continuously and, in the future, the exploitation and sustainable development of the national maritime zones will become a major pre-occupation of government and industry.

It should also be noted that, in economic parlance, the national hydrographic programme is regarded as a "Public Good". That is to say the necessary services required in the public interest will not be supplied at optimal levels by market forces alone. In every IHO Member State the provision of hydrographic services is a responsibility of central government, as an essential component of national economic development. This overall and important economic dimension of the work has sometimes been obscured by the emphasis on sector interests served by hydrographic services, and more recently by legislative or regulatory requirements. It is clear that the economic dimension of Hydrography deserves greater attention than it has received in the past.

2. Chapter 2: Principles of hydrographic surveying

2.1. Introduction

Hydrographic surveying deals with the configuration of the bottom and adjacent land areas of oceans, lakes, rivers, harbours, and other water forms on Earth. In strict sense, it is defined merely as the surveying of a water area; however, in modern usage it may include a wide variety of other objectives such as measurements of tides, current, gravity, earth magnetism, and determinations of the physical and chemical properties of water. The principal objective of most hydrographic surveys is to obtain basic data for the compilation of nautical charts with emphasis on the features that may affect safe navigation. Other objectives include acquiring the information necessary for related marine navigational products and for coastal zone management, engineering, and science (NOAA Hydrographic Manual, 1976). The purpose of hydrographic surveying (International Hydrographic Organization, P-13) is:

To collect, with systematic surveys at sea, along the coast and inland, georeferenced data related to:

- Shoreline configuration, including man made infrastructure for maritime navigation i.e. all those features on shore that are of interest to mariners.
- Depths in the area of interest (including all potential hazards to navigation and other marine activities).
- Sea bottom composition.
- Tides and Currents.
- Physical properties of the water column.

To process the information collected in order to create organized databases capable of feeding the production of thematic maps, nautical charts and other types of documentation for the following most common uses:

- Maritime navigation and traffic management.
- Naval operations.
- Coastal zone management.
- Marine environment preservation.
- Exploitation of marine resources and laying of submarine cables/pipelines.
- Maritime boundaries definition (Law of the Sea implementation).
- Scientific studies.

Mariners have unquestioning faith in nautical charts and where no dangers are shown, they believe that none exist. Nautical chart is an end product of a hydrographic survey. Its accuracy and adequacy depend on the quality of the data collected during the surveys ((NOAA Hydrographic Manual, 1976). A nautical chart is a graphic portrayal of the marine environment; showing the nature and form of the coast, depths of the water and general character and configuration of the sea bottom, locations of dangers to navigation, rise and fall of the tides, cautions of manmade aids to navigation, and the characteristics of the Earth's magnetism. The actual form of a chart may vary from a traditional paper chart to an electronic chart.

An electronic chart is not simply a digital version of a paper chart; it introduces a new navigation methodology with capabilities and limitations very different from paper charts.

The electronic chart has become the legal equivalent of the paper chart as approved by the International Maritime Organization. Divergences in purpose have led to the publication of various "new-generation" charts. Bathymetric charts developed from digital data or created from multi-beam sounding data allow the underwater relief to be visualised by means of varying blue tints and isobaths. Similarly, side-scan sonar mosaics have been published in the form of charts or atlases to characterise the large geomorphological structures. Such charts no longer have, as their object, the safety of navigation, but rather, the knowledge of the environment required for submarine navigation, oceanographic research or industrial applications, such as cable laying, seabed mining and oil exploitation.

Hydrographic surveying is undergoing fundamental changes in measurement technology. Multibeam acoustic and airborne laser systems now provide almost total seafloor coverage and measurement as compared to the earlier sampling by bathymetric profiles. The capability to position the data precisely in the horizontal plane has been increased enormously by the availability of satellite positioning systems, particularly when augmented by differential techniques. This advance in technology has been particularly significant since navigators are now able to position themselves with greater accuracy than that of the data on which older charts are based (International Hydrographic Organization, P-19).

2.2. Hydrographic surveying

2.2.1. Survey Specifications

Requirements for hydrographic surveys arise as the result of policy decisions, product user reports or requests, national defence needs, and other demands. The inception of a specific hydrographic survey project follows an evaluation of all known requirements and the establishment of priorities. Among the many objective and subjective factors that influence the establishment of priorities are national and agency goal, quantitative and qualitative measures of shipping and boating, the adequacy of existing surveys, and the rate of change of the submarine topography in the area (NOAA Hydrographic Manual, 1976).

To accommodate in a systematic manner different accuracy requirements for areas to be surveyed, four orders of survey are defined by IHO in publication S-44 5th Edition 2008. These are described in subsequent paragraphs. Table 2-1 summarizes the overall requirements but should be read in conjunction with the complete standard (International Hydrographic Organization, S-44).

Special Order: This is the most rigorous of the orders and its use is intended only for those areas where under-keel clearance is critical. Because under-keel clearance is critical a full sea floor search is required and the size of the features to be detected by this search is deliberately kept small. Since underkeel clearance is critical it is considered unlikely that Special Order surveys will be conducted in waters deeper than 40 metres. Examples of areas that may warrant Special Order surveys are: berthing areas, harbours and critical areas of shipping channels.

Order 1a: This order is intended for those areas where the sea is sufficiently shallow to allow natural or man-made features on the seabed to be a concern to the type of surface shipping expected to transit the area but where the under-keel clearance is less critical than for Special Order above. Because man-made or natural features may exist that are of concern to surface shipping, a full sea floor search is required however the size of the feature to be detected is larger than for Special Order. Under-keel clearance becomes less critical as depth increases so the size of the feature to be detected by the full sea floor search is increased in areas where the water depth is greater than 40 metres. Order 1a surveys may be limited to water shallower than 100 metres.

Order 1b: This order is intended for areas shallower than 100 metres where a general depiction of the seabed is considered adequate for the type of surface shipping expected to transit the area. A full sea floor search is not required which means some features may be missed although the maximum permissible line spacing will limit the size of the features that are likely to remain undetected. This order of survey is only recommended where under-keel clearance is not considered to be an issue. An example would be an area where the seabed characteristics are such that the likelihood of there being a man-made or natural feature on the sea floor that will endanger the type of surface vessel expected to navigate the area is low.

Order 2: This is the least stringent order and is intended for those areas where the depth of water is such that a general depiction of the seabed is considered adequate. A full sea floor search is not required. It is recommended that Order 2 surveys are limited to areas deeper than 100 metres as once the water depth exceeds 100 metres the existence of man-made or natural features that are large enough to impact on surface navigation and yet still remain undetected by an Order2 survey is considered to be unlikely.

2.3. Survey Planning

Survey planning covers a wide range of activities from the development of an idea for a survey within the Hydrographic Office and its subsequent issue as Project Instructions/Hydrographic Instructions (HIs), to the detailed planning and organisation of a surveying ship to fulfil a practical task. It covers inter departmental liaison at Government level, diplomatic cooperation and the allocation of numerous expensive resources. It also covers prioritization of resources and day to day running of a survey ship employed on surveying task. Survey planning involves blending of these activities into a coherent pattern aimed at the achievement of a specific task. A survey begins long before actual data collection starts. Some elements, which must be decided, are (Bowditch, The American Practical Navigator):

- Exact area of the survey.
- Type of survey (reconnaissance or standard) and scale to meet standards of chart to be produced.
- Scope of the survey (short or long term).
- Platforms available (ships, launches, aircraft, leased vessels, cooperative agreements).
- Support work required (aerial or satellite photography, geodetics, tides).
- Limiting factors (budget, political or operational constraints, positioning systems limitations, and logistics).

Table 2-1

Minimum Standards for Hydrographic Surveys

Reference	Order	Special	1a	1b	2
Chapter 1	Description of areas.	Areas where under-keel clearance is critical	Areas shallower than 100 metres where under-keel clearance is less critical but features of concern to surface shipping may exist.	Areas shallower than 100 metres where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas generally deeper than 100 metres where a general description of the sea floor is considered adequate.
Chapter 2	Maximum allowable THU 95% Confidence level	2 metres	5 metres + 5% of depth	5 metres + 5% of depth	20 metres + 10% of depth
Para 3.2 and note 1	Maximum allowable TVU 95% Confidence level	a = 0.25 metre b = 0.0075	a = 0.5 metre b = 0.013	a = 0.5 metre b = 0.013	a = 1.0 metre b = 0.023
Glossary and note 2	Full Sea floor Search	Required	Required	Not required	Not required
Para 2.1 Para 3.4 Para 3.5 and note 3	Feature Detection	Cubic features > 1 metre	Cubic features > 2 metres, in depths up to 40 metres; 10% of depth beyond 40 metres	Not Applicable	Not Applicable
Para 3.6 and note 4	Recommended maximum Line Spacing	Not defined as full sea floor search is required	Not defined as full sea floor search is required	3 x average depth or 25 metres, whichever is greater For bathymetric lidar a spot spacing of 5 x 5 metres	4 x average depth
Chapter 2 and note 5	Positioning of fixed aids to navigation and topography significant to navigation. (95% Confidence level)	2 metres	2 metres	2 metres	5 metres
Chapter 2 and note 5	Positioning of the Coastline and topography less significant to navigation (95% Confidence level)	10 metres	20 metres	20 metres	20 metres
Chapter 2 and note 5	Mean position of floating aids to navigation (95% Confidence level)	10 metres	10 metres	10 metres	20 metres

Notes:

1. Recognising that there are both constant and depth dependent uncertainties that affect the uncertainty of the depths, the formula below is to be used to compute, at the 95% confidence level, the maximum allowable TVU. The parameters "a" and "b" for each Order, as given in the Table, together with the depth "d" have to be introduced into the formula in order to calculate the maximum allowable TVU for a specific depth:

Where:

- a represents that portion of the uncertainty that does not vary with depth;
- b is a coefficient which represents that portion of the uncertainty that varies with depth;
- d is the depth;
- b x d represents that portion of the uncertainty that varies with depth.

2. For safety of navigation purposes, the use of an accurately specified mechanical sweep to guarantee a minimum safe clearance depth throughout an area may be considered sufficient for Special Order and Order 1a surveys.
3. A cubic feature means a regular cube each side of which has the same length. It should be noted that the IHO Special Order and Order 1a feature detection requirements of 1 metre and 2 metre cubes respectively, are minimum requirements. In certain circumstances it may be deemed necessary by the hydrographic offices/organizations to detect smaller features to minimise the risk of undetected hazards to surface navigation. For Order 1a the relaxing of feature detection criteria at 40 metres reflects the maximum expected draught of vessels.
4. The line spacing can be expanded if procedures for ensuring an adequate sounding density are used. "Maximum Line Spacing" is to be interpreted as the:
   - Spacing of sounding lines for single beam echo sounders, or the
   - Distance between the useable outer limits of swaths for swath systems.
5. These only apply where such measurements are required for the survey.

2.4. Survey planning continued

Once these issues are decided, all information available in the survey area is reviewed. This includes aerial photography, satellite data, topographic maps, existing nautical charts, geodetic information, tidal information, and anything else affecting the survey. The HO will normally undertake this strategic planning of surveys in cooperation with other organisations and, from this, Projects Instructions/Hydrographic Instructions (HIs) will be compiled by the Hydrographer and issued for compliance. Details provided in Project Instructions/HIs will include some or all of the following, depending on the type of survey required (Admiralty – GIHS, 1992):

- Survey limits.
- Data requirement and resolution.
- Method of positional control, together with the accuracy expected.
- Use to be made of sonar.
- How the survey report is to be rendered and target date if appropriate.
- A general, and at times detailed, description of the reason for the survey priorities, methods to be employed, particular observations to be made and other relevant guidance or instruction.

In addition, appendices to HIs will give instruction or guidance on the following:

- Horizontal datum, projection and grid to be used.
- Wrecks in the area.
- Tidal datum and observations required.
- Particular instructions regarding the collection of data in respect of oceanography, geophysics, sailing directions, air photography etc.

On receipt of Project Instructions/HIs, the survey planners then compile sound velocity information, climatology, water clarity data, any past survey data, and information from lights lists, sailing directions, and notices to mariners. Tidal information is thoroughly reviewed and tide gauge locations chosen. Local vertical control data is reviewed to see if it meets the expected accuracy standards, so the tide gauges can be linked to the vertical datum used for the survey. Horizontal control is reviewed to check for accuracy and discrepancies and to determine sites for local positioning systems to be used in the survey.

Development of a general survey plan and subsequent site specific survey plans will create a more efficient survey. The general survey plan addresses the way that surveys are planned, performed, and processed. This plan must be well thought out and robust to account for as many contingencies as possible. This plan includes training, software, equipment maintenance and upgrades, logistics, all data requirements, schedule, safety, and weather. The site specific survey plan will address local notifications, survey lines, datum, data density, and specific equipment and personnel that will meet the general survey plan requirements. Few are described below:

- Training of surveyors should be catered during a survey operation in order to ensure appropriate competencies are maintained.
- Data logging and processing software are critical in a survey operation. These should be user friendly and personnel employed on these need to be well conversant with its all functions.
- Suitable survey platform and equipment should be selected. Some equipment will lend itself to particular types of surveys and others will be more general in use. It is paramount that a proper selection is made.

- The purpose for the survey will usually dictate the data requirement (density, coverage, and precision). However, if there are no impact to cost and schedule, then as many requirements should be addressed as possible.
- Schedule is often a critical element in a hydrographic survey. The data requirement usually has as a specific deliverable date assigned, such that the survey data collection and processing occur within a very specific time frame. This requires that the personnel and equipment resources be adequate to meet this need. In some cases, if the schedule cannot be met, then the survey simply will not be requested and other sources will be used. Considering this, it is important to plan and analyse all aspects of a general survey plan with the ability to meet schedule as a prime element.
- Safety is the primary consideration. It is incumbent on the person in charge in the field to evaluate every situation for possible hazards. If there is an identified hazard, then it needs to be addressed before continuing with the activity.
- Notifications to the local authorities/harbourmaster office should be made with enough time to allow them to notify the local mariners.
- Survey lines for multibeam surveys should follow the contours of the harbour bottom. This will reduce the changes in bottom coverage created by different water depths. However, when using a single beam survey system, the lines should run perpendicular to contours. This will help in determining changes in the bottom relief. Multibeam survey lines also need to be spaced so as to achieve the proper amount of overlap or data density to meet the survey standard.
- An integral part of the data of a survey is the reference datum. It is required, by good survey practice, to clearly indicate by note on the published survey the actual vertical and horizontal reference used, and the procedures used to establish the datum for the survey. WGS-84 is being used worldwide.
- Data density will vary based on method of survey, water depth, and need. The method of survey will be determined by equipment available for the survey, the personnel, and survey site conditions. If only a single beam survey system is available, then data density will be less. With a multibeam system, the greater the water depth the less dense the data will be, unless multiple passes are made. The type of survey will dictate the data redundancy or data overlap requirements.
- It is important to standardize the equipment as much as possible to limit training, maintenance and overheads.

2.5. Data Gathering

Data gathering is dependent upon various factors. The survey requirements, the platform and equipment available and the time specified for a particular task will determine the amount of data to be collected. A large amount of data can be collected using latest hydrographic software's and tools like multibeam echo sounders. In particular, the purpose of the survey will usually dictate the data requirement (data density, data coverage, and data precision). However, if there is no impact to cost and schedule, then as many data may be collected as possible during field survey. The data collection is made in methodical manner starting from one side of the area ending on other.

It should be noted that data redundancy and data density are not the same thing. Data density is the number of soundings per unit of area, while data redundancy refers to data overlap or data collected at a different time at the same location. The type of survey defines data redundancy or data overlap requirements. Full coverage surveys deal more with data density insuring that all bottom features/obstructions have been located. These need to be clearly understood by those requesting the survey and those doing the survey to insure compliance with the standards specified by IHO.

2.6. Data Processing

Data processing must be done under strict quality control criteria. Hydrographic data is either collected by automated systems or converted into an automated format. Final data processing and plotting are accomplished using onboard or office-based computer systems. A standard approach for a hydrographic survey is the collect-process-collect methodology (Bourgeois et al., 1999). The data collected is processed and subsequently gaps and areas with questionable data re-surveyed. Most of the hydrographic systems are capable of performing "field-finish" operations, wherein survey data is collected, processed, plotted and analysed in the field. Comprehensive survey planning is required for an integrated approach that generates the base line for all real-time and post processing operation with the system. An example of such a model (Junni and Lindgren, 2005) is given in (figure 2-1).

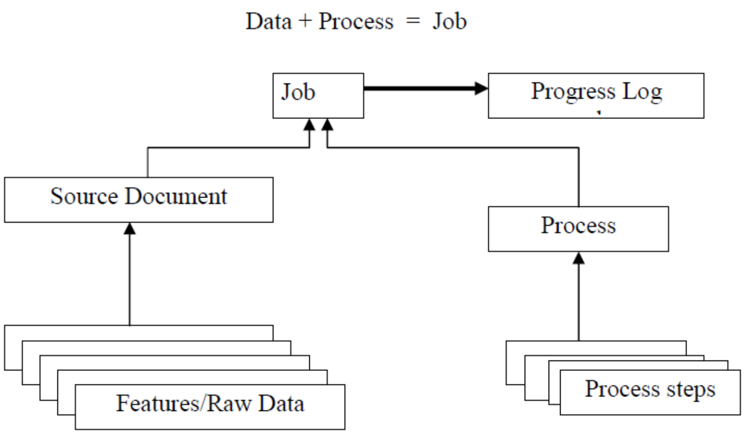


Fig. 2-1. Data Processing Model.

This model describes the different processes that can ideally handle the hydrographic information. The process contains several steps. The comments of each process step along with results, statistics should be recorded in a progress log. Further, the source and general quality information of any new data be described in source document which is stored in the database.

The core requirement of data processing is the generation of valid data; which has been sufficiently processed i.e. undergone through various procedures at various stages or represented so that evaluation can be made. These procedures/processing steps could be applied in real-time or during post processing but have to ensure that the final product meets the standards and specifications defined by IHO.

Care is to be exercised in processing the raw data. It is to be ensured that all errors have been eliminated and necessary corrections e.g. system calibration factors and sensor offsets, or variable values such as sound velocity profiles and tide values for the reduction of soundings, have been applied. The processing should strive to use all available sources of information to confirm the presence of navigationally significant soundings and quality data. Few processing steps outlined below are only to be interpreted as an indication, also with regard to their sequence, and are not necessarily exhaustive (International Hydrographic Organization, 2001):

- **Position:** Merging of positioning data from different sensors (if necessary), qualifying positioning data, and eliminating position jumps.
- **Depth corrections:** Corrections should be applied for water level changes, measurements of attitude sensors, and changes of the draught of the survey vessel (e. g. squat changing with speed; change over time caused by fuel consumption). It should be possible to re-process data for which corrections were applied in real-time.
- **Attitude corrections:** Attitude data (heading, pitch, roll) should be qualified and data jumps be eliminated.
- **Sound velocity:** Corrections due to refraction be calculated and applied; If these corrections have already been applied in real-time during the survey, it should be possible to override them by using another sound velocity profile with the advent of MBES, the application of SV has become critical.
- **Merging positions and depths:** The time offset (latency) and the geometric offsets between sensors have to be taken into consideration.

2.7. Data Analysis

The accuracy of the results of survey measurement should always be quoted to show how good or reliable they are. Since no equipment is entirely free of errors, therefore, errors are introduced in all observations. In addition, errors are introduced in computations by approximations in formulae or by rounding. Observational techniques are designed to eliminate all but small random errors, which can then be analysed by rigorous techniques to quantify the accuracy of the observations. Various errors, their sizes and procedures to eliminate are as under:

ERROR	SIZE	ELIMINATION
Blunder	Large	Training, care procedures.
Constant	Usually small, but fixed	Calibration or procedures
Periodic	Usually small, but variable	Procedure (repetition), even for large errors
Random	Usually small	Only reduced, by repetition

2.8. Data Quality

Quality is about "fitness for the use". It has to do with the extent to which a data set, or map output satisfied the needs of the person judging it. Error is the difference between actual and true data. Error is a major issue in quality. It is often used as an umbrella term to describe all the types of the effects that cause data to depart from what they should be (McGlamery, 2000). To allow a comprehensive assessment of the quality of survey data, it is necessary to record or document certain information together with the survey data. Such information is important to allow exploitation of survey data by a variety of users with different requirements, especially as requirements may not be known when survey data is collected. The process of documenting the data quality is called data attribution; the information on the data quality is called metadata. Metadata should comprise at least information on (International Hydrographic Organization, S-44):

- The survey in general as e.g. date, area, equipment used, name of survey platform.
- The geodetic reference system used, i.e. horizontal and vertical datum; including ties to WGS 84 if a local datum is used.
- Calibration procedures and results.
- Sound velocity.

- Tidal datum and reduction.
- Accuracies achieved and the respective confidence levels.

Metadata should preferably be in digital form and an integral part of the survey record. If this is not feasible similar information should be included in the documentation of a survey. Data quality can be achieved by effective quality control either by automatic or manual means (international Hydrographic Organization, 2001).

- **Automatic (Non-interactive) Quality Control:** In this, the coordinates (i.e. positions and depths) obtained should be controlled automatically by a programme using suitable statistical algorithms which have been documented, tested and demonstrated to produce repeatable and accurate results.
- **Manual (Interactive) Quality Control:** In this, the use of 3-D visualisation tools is strongly recommended. These tools should allow viewing the data using a zoom facility. The interactive processing system should also offer different display modes for visualisation, e.g. depth plot, error plot, single profile, single beam, backscatter imagery etc. and should allow for the visualisation of the survey data in conjunction with other useful information as e.g. shoreline, wrecks, aids to navigation etc; editing of data should be possible in all modes and include an audit trail. If feasible, data displays should be geo-referenced. The flags set during the automatic stage, which correspond to depths shallower than the surrounding area, should require explicit operator action, at least, for Special Order and Order1 surveys. If the operator overrules flags set during the automatic stage, this should be documented. If a flag is set by the operator, the type of flag used should indicate this.

2.9. The Guidelines

Various methodologies exist for the collection, processing and presentation of hydrographic survey information. Although the presentation of such information is largely determined by the end user, the fundamentals of hydrographic data collection remain the same: *Accurate measurement of the depth of water above a stated datum and the Position of this measured depth.*

For many years, the widely accepted means of obtaining depth data has been with a single-beam echosounder (SBES) with position provided by electronic ranging equipment. Subsequently, positioning has been made easier with the advent of GPS and more recently, DGPS. In the past 15 years, the introduction of Multi-Beam echosounders (MBES) with their ability to measure much greater areas of sea-floor (full sea coverage) at an increased level of detail, has seen an associated increase in the knowledge required to effectively use them.

2.10.Types and Frequency of Hydrographic Surveys – Risk Assessment

The varied nature of the ports, harbours and varied depths dictates that the frequency and methodology for hydrographic operations relating to them should be determined primarily by a risk assessment rather than by adoption of a set of rigid criteria. An important product of the risk assessment is a survey plan that describes the requirement for surveys including the type, extent and frequency. Hydrographic factors for consideration in risk assessments should take account of the stability of the seabed and depth of available water in relation to draught of vessels as well as intended development that will affect the navigable depth in a given area. Other considerations shall include (but not be limited to):

- Vessel type and operations (high speed, restricted in ability to manoeuvre etc.).
- Potential environmental impact of a hydrographic related event.
- Quality and reliability of existing hydrographic information.
- Complexity of area.
- Stability of seabed.
- Depth and width of navigable water in relation to vessel draught.
- Regional development.
- Chanel design.
- Investigation of a grounding or reported depth discrepancy (wrecks).
- Competency of person(s) responsible for the surveys (refer to Section 6 of this document).

2.11.Survey Equipment

Equipment to be used during hydrographic survey operations falls within the broad groupings of depth measurement equipment, positioning equipment and water level measurement equipment (e.g. automatic tide gauges). General considerations for the use of such equipment are covered in this section. Advances in survey equipment technology have significantly reduced the level of user input in normal modes of operation. It is however vital that users possess a reasonable understanding of the capabilities, and more importantly, the limitations of the survey equipment operated. In particular, it should be understood that manufacturers′ specifications rarely guarantee equipment performance unless the equipment is operated in accordance with strict parameters and under optimum environmental conditions. Regardless of stated manufacturers′ specifications, the fundamental good practice requirement of the surveyor to identify, eliminate or reduce, and quantify remaining sources of error in an appropriate error budget remains extant (refer Section 5.4.1).

2.11.1. Depth Measurement Equipment

Depth measurement is normally achieved using either Single Beam (SBES) or Multibeam (MBES) echosounders; the "order of survey" following S-44 publications is primordial to decide what type of echosounder should be used. Unless capital and operating costs reduce significantly, it is unlikely that MBES will replace SBES for routine surveys in the average port and/or harbour in the short term. We should notice that the alignment of lines′ survey when planning a hydrographic survey is perpendicular to bathymetry when using a SBES and parallel to bathymetry when using a MBES.

Single Beam Echosounder: SBES should be calibrated by bar checks to correct for index error, set the correct draught setting and ensure that the instrument records the depth below the sea surface and not below the transducer. A bar check should be conducted at least daily and on any change of survey area during the day to ensure consistency of data quality.

Multibeam Echosounder: The use of MBES as a hydrographic survey tool has significant advantages over SBES in the capability to detect small objects and achieve full bottom coverage. MBES require auxiliary equipment such as an appropriate motion sensor and gyro, which must be correctly integrated for correct operation. The ability to measure SVP profiles through the water column is also required to correct for the refraction of beams, particularly when using wide swath widths. Users should be aware of the expected performance of the system and employ robust methodology to prove this before accepting the system as operational. Careful calibration of MBES is required at regular intervals thereafter (refer Section 5). Inherent with the increased detail and coverage achieved with MBES is the ability to clearly see errors associated with incorrect vessel offsets, SVP or excessive vessel motion. The ability to "average" or "smooth" out such errors in subsequent processing is potentially misleading and should be avoided unless the magnitude of the change from the raw to the smoothed record is clearly stated. Such errors should be included in the calculation of the overall accuracy value accompanying the data.

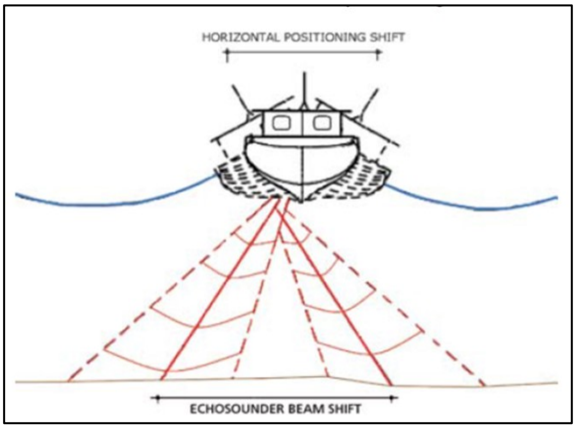
2.11.2. Positioning System Equipment

Differential GPS has been widely adopted as the primary method to fix vessel position during hydrographic surveys. The source of the differential corrections should be proven by comparison with a known mark, particularly if a local base station is established. GPS receivers should be configured to output position in the desired datum (normally WGS84) with associated quality tags. Close monitoring of position quality during sounding operations through examination of the number of tracked satellites and PDOP, and/or real-time comparison with a second system, is recommended. Kinematic GPS offers increased precision in terms of horizontal position, provided that the footprint of the echosounder in use is of a comparable dimension.

2.11.3. Motion Sensor Equipment (MRU)

Effects of vessel Roll, Pitch and Heave: Correcting observed depths for the superimposed effects of vessel roll, pitch and heave is perhaps the most difficult aspect of hydrographic surveying since all three conditions can occur simultaneously and at different periods. Roll and pitch introduce bias error in depth, resulting in a deeper reading over a level bottom (Figures 2-2 and 2-3). On side-mounted transducers, this bias error is compounded by the random up and down motion (heave) of the vessel. Unless reliable motion compensation devices are used (MRU equipment), the only practical method of minimizing vessel motion effects is to limit the maximum allowable sea states under which a particular "order of survey" may be performed.

Solution for undesired motions (Roll, Pitch and Heave): The demand for greater transparency in the derived accuracy of measured soundings obtained in swell conditions has seen the use of motion sensor equipment become standard in an increasing number of "shallow water" surveys. Standard motion sensing equipment is of the accelerometer type, ranging in complexity and the precision they are capable of achieving. The correct installation and definition within the vessel reference frame is vital and consideration should be given to obtaining assistance from the manufacturer if the user is unfamiliar with the equipment.



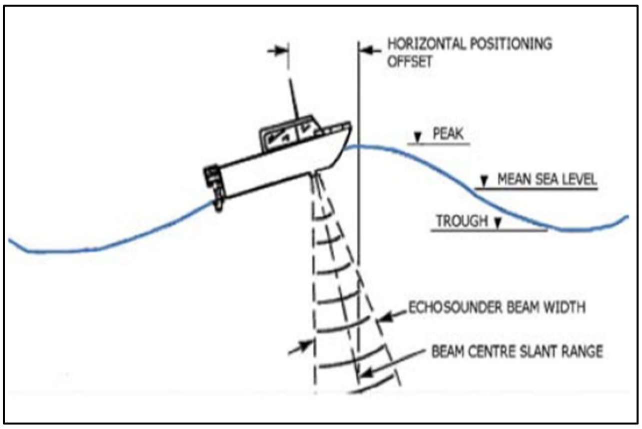


Fig. 2-2. The effect of vessel roll on depth soundings. Fig. 2-3. The effect of vessel pitch and heave on soundings.

The use of Kinematic GPS as a source of vessel motion corrections in conjunction with, or in lieu of, accelerometer based motion sensors is slowly increasing. Users of both types of motion sensors should take all practical steps to check their correct operation, preferably by some means of ground-truthing (e.g. quantifying motion error residual in data collected over a known flat seabed).

2.11.4. Tide Gauge Equipment

Sea level (tide) measurements of height and time are required to reduce collected soundings to Chart Datum and are subsequently used (as a continuous record over long periods not less than 28 days) to define tidal reference levels. Other methods used to obtain tidal information include manual tide pole (or staff) readings referenced to a recognized datum (normally chart datum) and, in recent years, using the centimetric precision achievable with Kinematic GPS in the vertical dimension. This latter method provides a source of total height measurement, including tide; however, the geode to ellipsoid difference must be accurately known and base station-rover range limitations clearly understood.

If Kinematic GPS is used in this manner, it is considered good practice to regularly correlate the results against tidal observations obtained by traditional (e.g. gauge) methods. Regardless of the type and method used, the equipment must be capable of measuring the tide to the required accuracy. If the method of tidal reduction requires interpolation between individual observations, the interval between observations must be such as to provide an adequate representation of the tide curve.

If automatic tide gauges are used, these must be regularly calibrated against a staff gauge to ensure their accuracy. The accuracy of the tide readings used to reduce soundings impacts directly on the overall accuracy of the survey.

Tidal Records: The hydrographic surveys in tidal areas should be referenced to a base elevation or chart datum, normally taken as the lowest astronomical tide level, or LAT also referred to as LLWS (Lower Low Water Spring) in some countries. This level is the result of the effect of celestial bodies only and does not include the additional effects of:

- Atmospheric pressure (low pressure increases tide level);
- Storm surge (increases tide level);
- Wind (landward wind increases tide level); and
- Heavy rainfall (increased flow in estuaries increases tide level).

In addition to the use of tide readings to reduce sounding data, a continuous record of tidal data is important for the maintenance of accurate predictions for the port. It is recommended that an unbroken record of tidal readings is maintained and archived (accompanied by relevant calibration records) for this purpose.

2.11.5. Survey Vessel – Equipment Offsets

The position of the various sensors on the survey vessel should be carefully measured in relation to a common datum point (Reference point - e.g. centre of gravity COG) and correctly applied within the survey acquisition software. This information should be included in the survey documentation.

2.12.Seafloor geomorphology (using multibeam techniques): the final stage

In the past, interpretation of undersea features would have been made from nautical charts or contour maps generated from bathymetric soundings. Now that full coverage data is more widely available the most common method for visualization of bathymetric data is through the use of shaded relief Digital Terrain Models (DTM). These may be combined with color shaded maps representing depth to give an overall picture of the seabed terrain

Whilst color shaded relief is popular as an end product, many experts prefer to use simple grey-scale shaded relief for interpretation of features. Shading may be achieved through the application of a variety of algorithms implemented in desktop mapping software, which provide either a single, multiple or moveable light source.

The type of light source employed, and whether or not the bathymetry is vertically exaggerated is a matter of personal choice for the interpreter, will depend to a certain extent on the dataset being considered. Software offering a three dimensional view of the data, with the opportunity to 'fly' around the seabed is also employed by some scientists for interpretation of geomorphology. Traditionally geomorphology has been interpreted by geologists with regard for the processes affecting the geomorphic features created, and there is a whole scientific sub-discipline of geomorphology within the terrestrial realm. However, in the marine realm we have not yet seen any real specialism in this direction and marine scientists, whilst having a background in one of the traditional sciences, tend to be more multi-disciplinary. Since the advent of desktop GIS and related technologies, shaded relief maps can easily be viewed and, to a certain extent at least, interpreted/classified by scientists from all disciplines who are interested in benthic habitat. Interpretation of geomorphology by non-specialists, without full understanding of geological/geomorphic processes, however, can have its drawbacks. The overgeneralization of geomorphic features is one such potential risk; another is the misapplication of terminology.

2.12.1. Comments on Morphology

In addition to bathymetry, the multibeam systems also commonly measure the backscatter intensity, which is related to the quantity of acoustic energy being returned from seafloor (Borgeld et al., 1999). Acoustic backscatter depends, at least in part, upon the physical properties of the seabed, including the density and grain size. A reliable method for estimating sediment density and grain size from acoustic backscatter values has not as yet been developed and remains one of the challenges to maximizing the usefulness of multibeam information.

Seismic methods are also being more and more integrated with the morphological data. In this sense, the development of 3D analysis of sediment architecture has recently been of growing interest and has been initiated by the oil industry. More recently, 2D and 3D seismic data have been integrated in the study of sediment deposition (Driscoll and Kramer, 1999). In parallel, the development of synthetic seismograms has provided a bridge between modellers and geophysicists. It is hoped that these techniques will also be integrated in the study of submarine mass movements.

2.12.2. Use of terrain variables derived from bathymetric data

There is a long term stream of literature related to terrain analysis of Digital Elevation Models (DEMs) in terrestrial applications, particularly in connection with soil science. Summaries focused on terrestrial terrain analysis and morphometric classification are available and all offer quite detailed insights into the computation methods involved and the key issues, including scale. Bathymetric data have more recently become widely available as raster data or digital terrain models (DTMs) which is equivalent to the terrestrial DEM. Bathymetric data, particularly full coverage multibeam data, offers tremendous potential for the generation of terrain variables that can be derived, and these data are now available at comparable resolutions to terrestrial DEMs, depending on the survey equipment used. Many desktop Geographic Information System (GIS) software packages offer tools to readily compute at least some quantitative terrain variables from bathymetry data (e.g. slope). These derived variables can be useful in describing, interpreting and classifying geomorphology in the marine environment, similar to practices for land data. They can also be of further use in geological interpretation and habitat mapping/modeling.

Calculation of terrain variables requires some method for mathematically representing the topographic surface and then using this to calculate the required terrain parameter. Surface representation is typically achieved by either using neighborhood analysis of raster pixels, or by fitting a polynomial expression to describe the surface, or digital terrain model. Data integration and multi-focusing approach

2.13.Crowd source bathymetry

The hydrographic community is discussing right now about the use of crowded sourced bathymetric data to empower marine knowledge and give an answer to the constant need of data especially in those areas not frequently surveyed. It is clear that in order to ensure data usability it is necessary to define standards and best practices to be comprehended inside the methodological approach previously described. This is the main aim of the International Hydrographic Organization (IHO) Crowded Sourced Bathymetry Working Group (CSBWG).

Crowdsourced bathymetry (CSB) data may be collected by any type of vessel, using a variety of sonar systems and for myriad reasons. Enlisting the resources of recreational boaters, pilot boats, tug boats, cruise ships, as well as fully equipped research ships in the "opportunistic" mode, this acquisition of bathymetric data may potentially open data streams of current observations to navigators, cartographers, scientists, engineers, and coastal zone planners. In fact, technology has reached the point where any boater can buy an echo sounder kit, add a GPS system, record depth measurements, and make their own geospatial observations in a common reference frame. The strengths and benefits of CSB data are the temporal frequency in repetitive and constant observations in heavily trafficked areas, access to an unlimited workforce, and availability of critical nautical data for the maritime community within a short timeframe, and engagement of the wider user community that will readily contribute to the mapping of our coastal zone.

For example, approximately 50% of the sounding data shown on US NOAA nautical charts is pre-1940, collected by antiquated lead-line soundings and wire drags. Even the 500,000 square nautical miles of the most navigationally significant EEZ waters would require 167 years to survey. Crowdsourced data can significantly augment authoritative geo-databases and provide answers to critical mapping deficiencies. The challenge in the marine geospatial sector is to ensure the reliability of crowdsourced data by managing and structuring the process to ensure that it can be confidently relied upon as useable and accurate.

However, navigation safety depends on data quality and accuracy. Hydrographic surveying is a rigorous, professional engineering discipline. There is general definite appeal to the concept of crowdsourced bathymetric data but the issues around using crowdsourced data are complex. Data quality, data processing and liability are at the top of this list. Looking into the future, it is necessary to take a measured approach to accepting third party data for use in nautical charting to help fill in the blanks.

Data processing is also an issue. Once collected, hydrographic survey data is processed using consistent and standard methods to arrive at a final answer and charted to help mariners to make sound navigation decisions. This is a labour-intensive process in which human judgment is intentionally applied. Experience has shown that feeding non-standard sources into this process explodes the labour required but accepting data into databases is costly and inefficient.

The aim to CSBWG is to provide guidance to empower a wide range of mariners to collect and contribute bathymetric data in a standard enough way to make the data as useful as possible to the broadest group of users. The important social engagement aspects of crowdsourcing such as gamification and recognition are also beyond the scope of the guidance document.

Although crowdsourced bathymetric data has the potential to improve global hydrographic charts by providing reconnaissance information for future systematic surveys and the identification of possible hazards to navigation, much of the data will not be suitable for direct incorporation into nautical charts. An analysis of data uncertainty will help users determine the feasibility of using the data for various applications, from creating DTMs to assessing offsite development sites.

Less than 5% of our oceans are mapped with in situ soundings, making it critical to preserve and share the data already collected and to identify and work together to fill high priority data gaps to support these important uses. The International Hydrographic Organization Data Centre for Digital Bathymetry (IHO DCDB), established in 1988 to steward worldwide bathymetric data on behalf of the IHO Member States, provides long term archive of and access to single and multibeam deep and shallow water ocean depths contributed by a range of mariners (Fig. 2-4). IHO DCDB welcomes bathymetric data and metadata, accepts descriptions and spatial footprints of data that is already online and of data that are not publicly available to provide easy search and discovery.

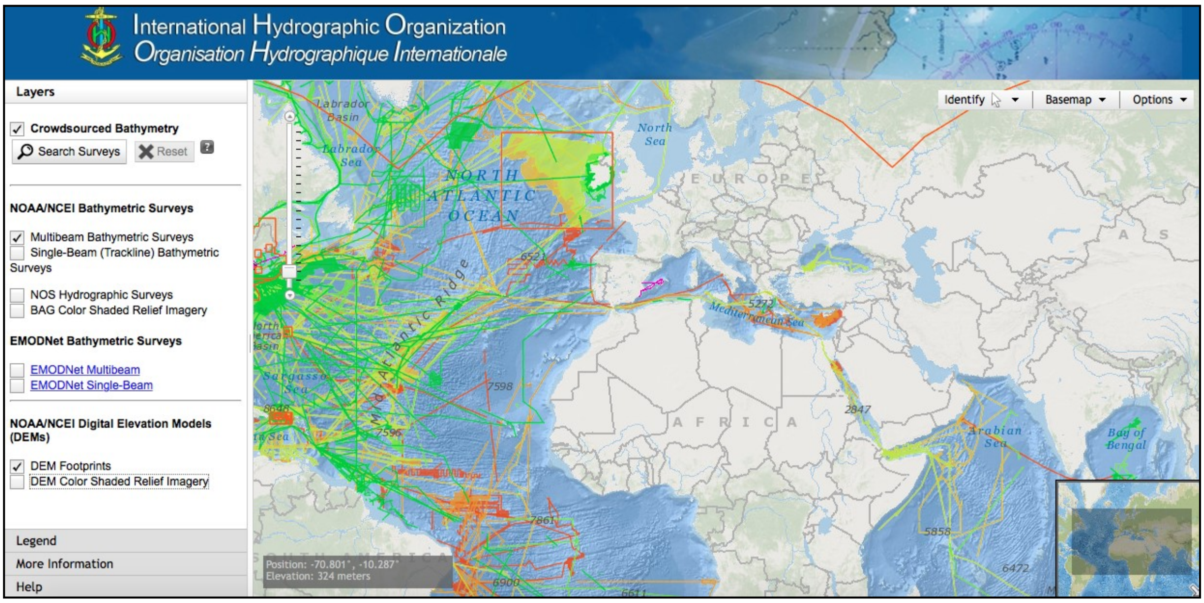


Fig. 2-4. Crowdedsourced bathymetry viewer (*https://maps.ngdc.noaa.gov/viewers/csb/index.html)*

3. Chapter 3: Seafloor Mapping along Continental Shelves

3.1. Introduction

Mapping the continental shelf seafloor topography has nowadays rich assets with varying techniques to accurately identify the submarine features and marine habitats. Acoustic mapping practices produce surprisingly realistic picture of the seafloor through the use of sound through sophisticated devices that were developed and used as sidescan sonar, single beam echo sounders, or multibeam reflection sounders. Also, other powerful ground-penetrating seismic techniques (low frequency devices) have also been used to not only map the surface layer of the seafloor, but to also visualize what lies below the seabed. However, aircraft and satellite-assisted techniques enabled researchers to recently make considerable advancements in the visualization of benthic environments. Historically used for military reconnaissance procedures for strategic planning, the advent of high-resolution aerial photography and ortho-imagery has proven to be among the most effective techniques for visualizing shallow, low turbid waters along continental shelves. Equally as effective for clear waters within the nearshore of the continental margin are airborne laser bathymetry (ALB) methods, which use pulses of light to acquire bathymetric and topographic configurations based on airborne laser reflectance. Lastly, hyperspectral and multispectral sensors onboard orbiting satellites (e.g., IKONOS, Landsat, MODIS, SPOT) provide a continuous stream of benthic environment visualization without the logistical inconveniences of deploying a vessel or aircraft every time images are to be acquired (Finkl and Makowski, 2016).

Therefore, and since the dawn of civilization, humans have been trying to draw the world's oceans maps and figuring out what is laying under the water surface. However, according to Finkl and Makowski (2016), the technology truly allow coastal marine scientists to visualize and interpret the topography of benthic environments on a wide scale during the twenties century (e.g., Blondel, 2003; Coco and Murray, 2007; Douvere, 2008; Finkl et al., 2014; Kenny et al., 2003; Klemas and Yan, 2014). With the advent of modern remote sensing techniques (e.g., seismic reflection profiling, aerial imagery, satellites), researchers have now gained the ability to effectively interpret and map large portions of coastal environments along continental shelf margins. Although these acoustic techniques have been used to detect seabed features and under seabed layers, they are also used to identify morphologies and sedimentary processes on continental shelves. This chapter aims to present acoustic instrumentations from which I used to complete this research, through environmental and physical surveys of the Lebanese continental shelf and seafloor.

3.2. Acoustic remote sensing instrumentations and techniques

The underwater environment (~70 % of the Earth's surface) does not allow for propagation of radio and radar waves because of the dissipation of sea water. Therefore, acoustic waves are the only way that permits of scientists to interpret the topography of the ocean bottom taking in consideration the combination of inhospitable underwater pressure conditions to humans. Seafloor topography on the continental shelf was traditionally determined using soundings that were contoured into isobaths and early bathymetric charts of shelf topography provided rudimentary insight into seafloor morphology due to the inability to provide detailed images, inaccurate positioning, and low-resolution interpretations of morphology.

Based on the result of Marie Tharp, who constructed a three-dimensional physiographic map of the world's ocean basins, according to Finkl and Makowski (2016), the first physiographic seafloor map of the North Atlantic was published in 1957 as an accompaniment to the Bell Telephone System's Technical Journal, with the Geological Society of America reprinting the map in 1959 (Doel et al., 2006). Following the previous efforts, The first map showing the entire ocean basin was published in 1977 as the *World Ocean Floor* (Barton, 2002; Heezen and Tharp, 1977), and is still a reference until today when describing the world's ocean basin in modern geographic software applications (e.g., Google™ Earth; URL: http://www.arcgis.com/home/webmap/viewer.html?webmap=5ae9e138a17842688b0b79283a4353f6) (Fig. 3-1).

Fig. 3-1. Image extracted from Google ™ Earth that clearly show how the modern-day geographic platform still uses the original Marie Tharp World Ocean Floor map.

3.2.1. Side-scan Sonar

Side-scan sonars emit conical or fan-shaped pulses across a wide angle perpendicular to the path of their towed sensors "towfish". The received signals (known as the backscatter effect) create a detailed image of the reflectivity of the sea floor "sonograph" and its anomalies within the swath (coverage width) of the beam. The reflectivity of the seafloor depends on its roughness and the nature of the topmost material: for example, coarse-grain sediments display higher reflectivity than fine-grain deposits, rocky outcrops reflect higher than sediments or objects that protrude from the seafloor create a light area (i.e. strong return) and shadows from these objects are dark areas (i.e. little or no return) (Able et al., 1987; Fish and Carr, 1991). Side-scan sonars are very useful for mapping archaeological features that are visible on or above the bottom (wrecks, exposed pole and rock structures, etc.) They are unable to penetrate the sediments and can therefore only provide information about the exposed surface of the sea floor. Normally frequencies between 100 and 1000 kHz are used. Higher frequencies yield better across track resolution (perpendicular to the direction of movement) but involve a narrower swath. Depending on the frequency of the emitting signal, a resolution of up to a few centimetres can be achieved. Along track resolution (parallel to the direction of movement) depends on the cruising speed and the triggering rate of the emitted signal. Therefore, slow cruising speed and high triggering rates enable higher resolution along track. Side-scan sonars can be operated from small vessels in water depths down to about 2m. The fish can either be towed behind the ship or fixated at the bow. The latter has the advantage that it is out of the bubbles of the propeller and the GPS antenna can be placed directly above it, which can provide better recordings with more precise positioning. Many hydrographic visualization surveys of the seafloor are primarily conducted acoustically with side-scan sonar to determine benthic topography. Figure 3-2 shows the three basic components: research vessel, towfish, and the transmission cable, while figure 3-3 highlights a ship wreck discovered using the side-scan sonar technique.

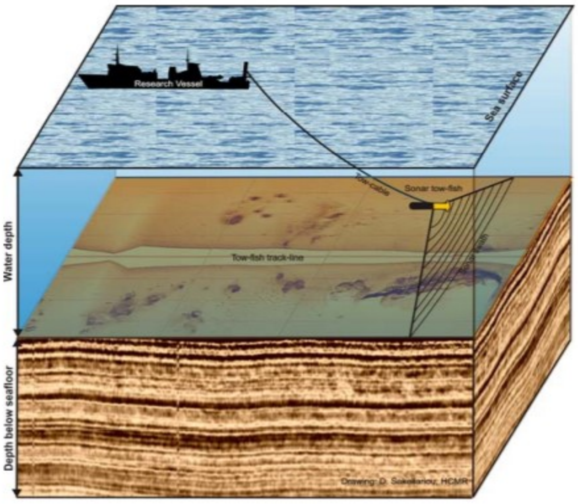


Fig. 3-2. Schematic showing side-scan sonar towed behind the survey vessel. Drawing by D. Sakellariou.

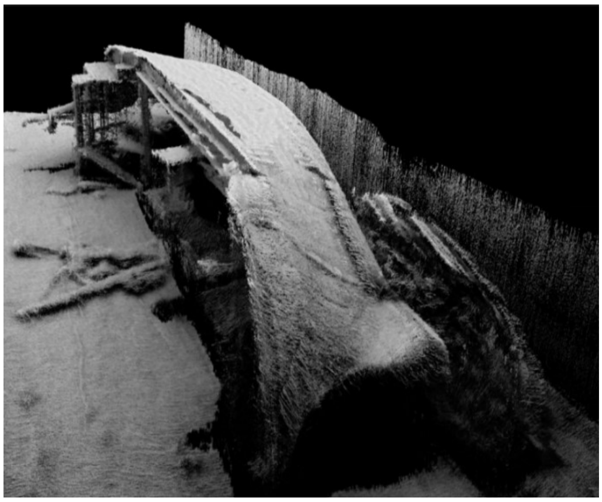


Fig. 3-3. Ship wreck discovered in Beirut harbour during training on side-scan sonar. Drawing by Lebanese Navy Hydrographic Service.

Talking about reflectors, in basic terms, strong ones create strong echoes, while weak ones create weaker echoes. Knowing this specific characteristic, we can use the strength of acoustic reflection from the side-scan sonar to determine the composition of the seabed (e.g., Finkl and Andrews, 2008; Lurton, 2002; Urick, 1983) (Figs. 3-4).

In order to get closer to the bottom in deep water, the side-scan sonars are placed in a "towfish" and pulled by a tow cable (Blondel, 2009; Fish and Carr, 1991).

3.2.2. Echo Sounder Reflection (Single and Multibeam) and Seismic Mapping Techniques

Echo sounder technology is an acoustic seafloor mapping technique and is one of the most active domains of modern underwater acoustics. Its principle is to transmit a pulse of sound directly downwards from the bottom of surveying vessel. The pulse of sound travels down through the water medium, bounces off the seabed, and then travels upwards until the reflection is heard and recorded by the echo sounder. The echo sounder recording device logs how much time the pulse of sound takes to travel to the seafloor and back up to the vessel. The depth of the water then can be calculated using the formula:

Water Depth = (Speed of sound in water) x (Time/2)

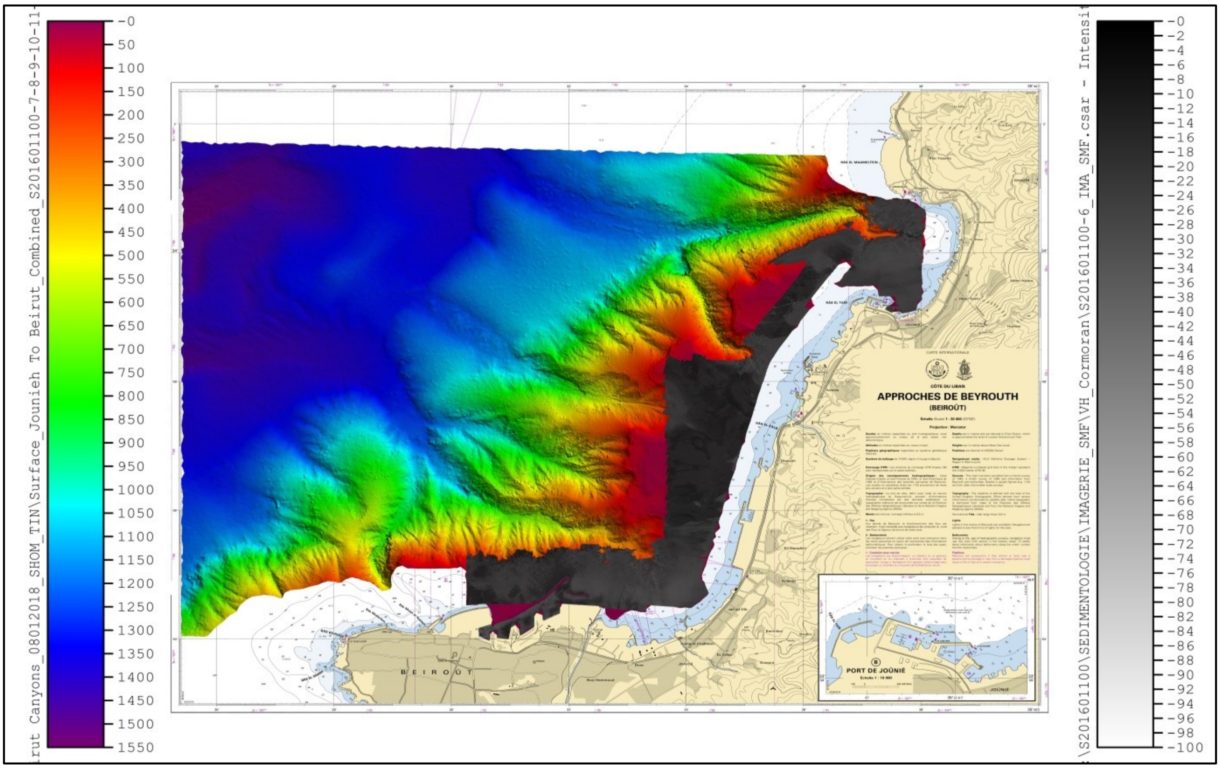


Fig. 3-4. A combined image of multibeam data (coloured) and side-scan sonar data (grey level) with the respective scales is produced and presented by the Lebanese Navy Hydrographic Service. Light grey colours, according to the scale, represent areas with higher reflectivity (coarser sediment).

The speed of sound in water is sometimes assumed to be approximately 1.5 km s^{-1} (kilometres per second) [Time ÷ 2 × (1.5 km per second)], however, a more accurate value is obtained from the Hydrographic Office's Carter Tables or by deploying a sound velocity probe into the water (Massa, 1989; Verbeek and McGee, 1995). According to Finkl and Makowski (2016) and as shown in multiple studies, acoustic echo soundings reflected by the seafloor contain more information than just the water depth (Diachok, 1995; Flood, 1980; Scanlon, 1989). The intensity and shape of a returning acoustic signal is affected by a number of factors, including primarily sediment grain size and sorting, seabed roughness, bedforms, and presence, concentration and type of benthic fauna and flora (Flood, 1980; Taylor Smith and Li, 1966). Therefore, echo sounder based classification systems are utilized to reveal geomorphological structures of the sea bottom, which are composed of various types of soft sediments and rigid structures (Flood, 1980; Scanlon, 1989). To correlate each acoustic echo class with seafloor characteristics, ground truthing is typically conducted by sampling bottom sediments in the surveyed area (Verbeek and McGee, 1995). The result of this analysis is a georeferenced track plot classified by ground truthed sediment types. A Digital Terrain Model (DTM) of the seafloor can then be built and isocontoured bathymetrical charts are computed and overlain on top of it.

<u>Single Beam Reflection</u>: Although the analysis of the echo can provide information on the type of seabed, but a single beam echo sounder is primarily used for bathymetric determinations. A single-beam sounder transmits, vertically below the ship, a short signal in a beam of small/medium angular aperture. As the craft travels forward along a track line, a profile of the seafloor is obtained from the returning acoustic pulses that are being emitted over time. The sounder measures the two-way travel time of the signal which allows deriving the local water depth with typical frequencies ranging between 10 and 500 kHz, depending on the water depth to explore. In addition, the system can detect echoes from targets in the water column, especially useful for fishing. The reliability of the depth calculation is dependent on accurately knowing the sound velocity in seawater, which is usually around

1500 ms−1 depending on water temperature, salinity, and other factors (Verbeek and McGee, 1995). While this gives researchers the water depth in a particular area, the single beam reflection provides only a profile of the seafloor in each recording. To gain a more detailed picture multibeam reflection, or swath bathymetry, is used.

<u>MultiBeam Reflection</u>: A MultiBeam Echo Sounder (MBES) consists in an extension of the single-beam sounder; Instead of a single vertical beam, a fan of beams (on a vertical plane perpendicular to the ship axis) with small individual widths (1°-3°) is used. Typically, 100 to 200 simultaneous depth measurements are performed, sweeping a large strip (a total width of 150° covers up to 7.5 times the water depth). Like in sidescan systems, the signal backscattered by the seabed is recorded overtime, and its intensity represents irregularities of the seafloor strip swept by the signal. In this way, the real topography of the seabed is considered in building the image and also the local slope between 2 adjacent beams can be taken into account. Therefore, rapid and accurate survey of very large areas is possible noting that most recent systems record both the bathymetric profile and the acoustic image of the seafloor (through reflectivity measurements) and considering that the imaging performance is poorer than that of a towed sidescaner due to the following reasons:

- The incidence angles are not sufficiently grazing.
- The movements of the ship are heavier than those of the towfish.

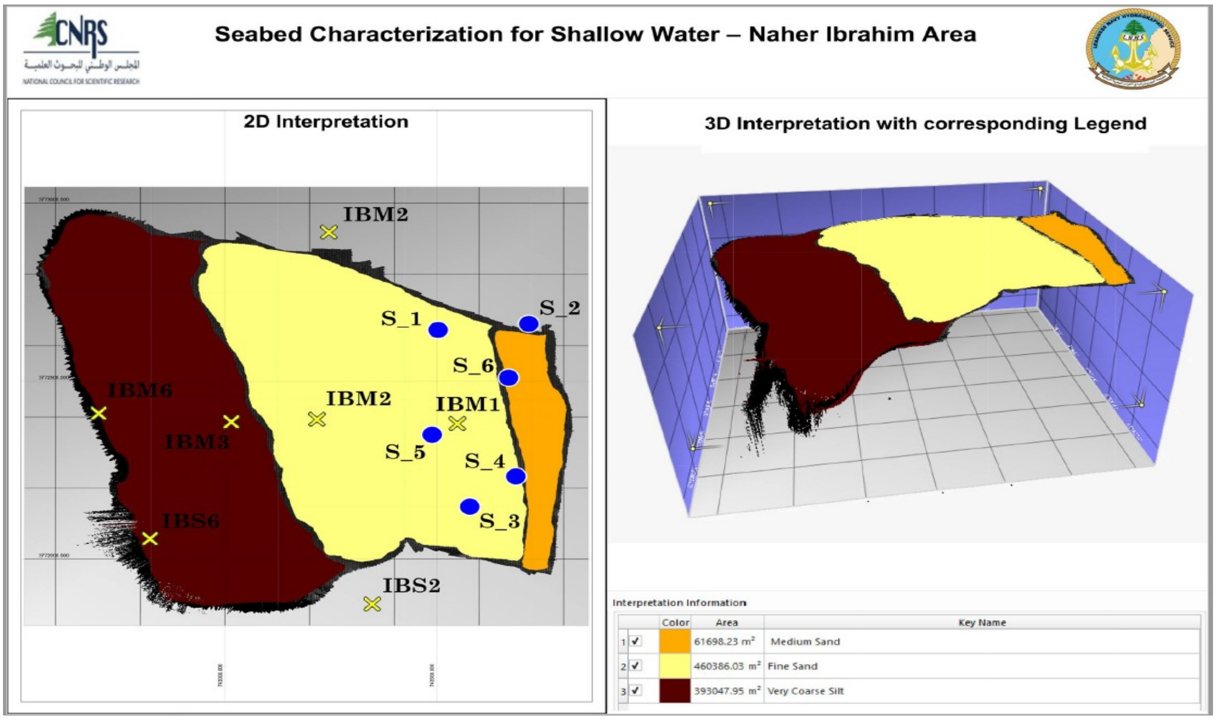


Fig. 3-5. Seabed characterization for Nahr Ibrahim area (2D and 3D) using the backscatter analysis technique of the seabed acoustic reflection. Blue dots and yellow crosses represent position of samples (ground truthing) to calibrate results of the software analysis.

The integrated measurement of bathymetry and reflectivity by a MBES, complemented by the information gathered by a sediment profiler, represent a very complete pool of data for geological purposes. Acoustic data from sounders and sonars can be used to assess some physical properties of the seabed (its reflectivity being linked to its impedance and roughness), and hence to get indications about its nature (Fig. 3-5). However, the nature of sediments is very complex, and they are only partially investigated by acoustic systems. Furthermore, the ground-truth operations to "calibrate" the identification system are very difficult to achieve, mainly in deep water. Ultimately, acoustics can just contribute to geological interpretation of the seabed, taking into account that it cannot directly access parameters such as granulometry or mineralogical composition, which are essential in geological analysis of sediments. Deep-water systems are designed for regional mapping; 12 kHz for deep ocean, 30 kHz for continental shelves taking into consideration that large array sizes require deep-sea vessels. Shallow-water systems frequencies range between 100 to 200 kHz and are the best suited to hydrography, while high-resolution systems frequencies are between 300 and 500 kHz and are used to local studies: hydrography, shipwreck location and object inspection (see Table 3-1).

Table 3-1

Some of MBES types with respective characterisitcs

Sounder type	Frequency (kHz)	Water depth (m)	Maximum width (m)	Total aperture (°)	Number of beams	Beam widths	Signal resolution (m)
Simrad EM120	12	50 → 11,000	20,000	144	191	1° * 2°	1.5–7.5
Simrad EM300	32	5 → 5,000	10,000	140	135	1° * 2°	0.5–3.75
Simrad EM1002	95	2 → 1,000	1,500	150	111	2.3° * 2.3°	0.15–1.5
Reson Seabat 8111	100	3 → 1,000	1,000	150	101	1.5° * 1.5°	0.05–0.25
Reson Seabat 8101	240	0.5 → 500	400	150	101	1.5° * 1.5°	0.015–0.15
Reson Seabat 8125	455	0.2 → 120	/	120	240	0.5° * 1°	0.01–0.2

During recent years, MBES have greatly evolved and are a broadly accepted tool for seafloor mapping, especially when used in tandem with Digital Bathymetric Model (DBM) rendering (Xu, 2010). Figure 3-6 represents the DBM of Nhar Ibrahim canyon head and its shallower part surveyed ($1500x1000m^2$) in less than 5 hours. This technology not only allows for the interpretation of geomorphological features, but also the presence of peculiar anomalies and artifacts as a result of human activity (e.g., ship wrecks) (Savini et al., 2011).

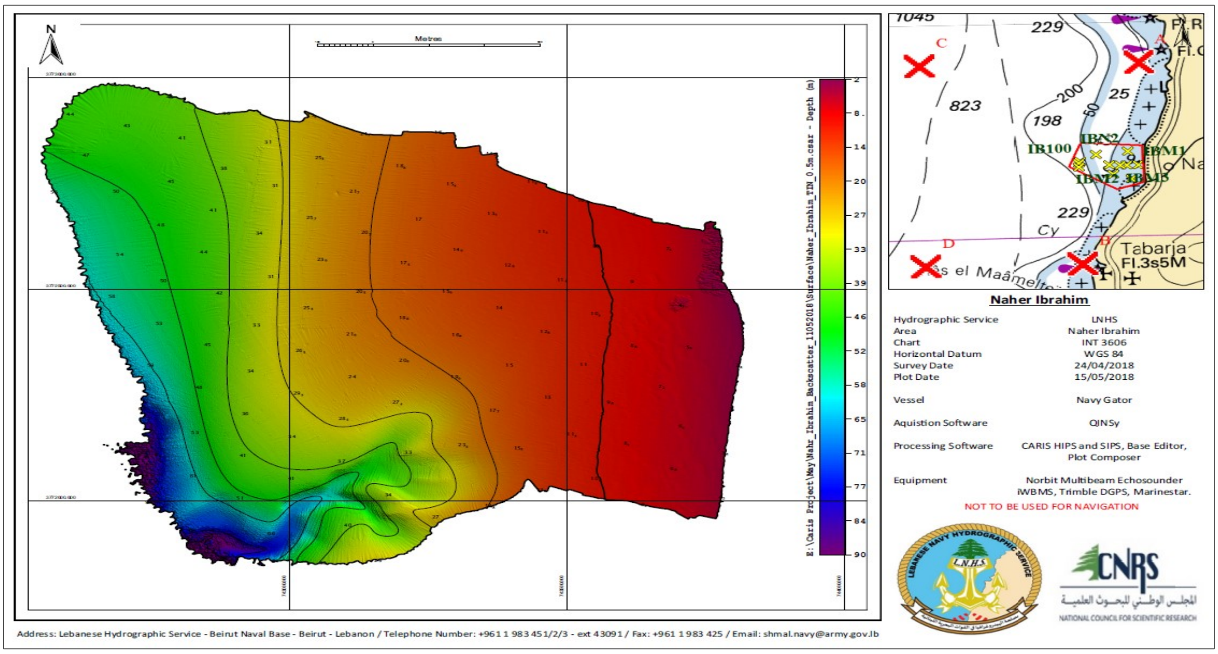


Fig. 3-6. Digital Bathymetric Map of Nahr Ibrahim area achieved with MBES techniques (270 kHz), depth ranging between 2 and 90m.

Sub-bottom profiler: Sub-bottom profiler is structurally similar to a single-beam sounder but working at lower frequency. Its goal is to gather vertical cross-sections of the inner sedimentary seabed by recording echoes from the interfaces between sediment layers (Fig. 3-7). They use reflections of the transmitted signal due to jumps in the acoustic impedance; backscattering is not involved. Also, the movement of the platform makes it possible to build a vertical cross-section image. The sediment penetration along the vertical direction is often expressed in seconds; it can be translated into a distance scale, making assumptions about the sound velocities within sediments layers. Latest systems adopt chirp signals and modern pulse-compression processing, enabling the following two crucial improvements:

- The processing gains (*PG*, i.e., improvements of the signal to noise ratio) due to the coherent processing that allows getting larger penetration depths.
- The absolute level of the echoes from the bottom is maintained and imaged, allowing estimating physical characteristics of the layers, like impedance and attenuation.

The working frequency range of sediment profilers is a few kHz, being 3.5 kHz the most used value, it is necessary to select a good compromise between penetration depth and antenna dimensions. Roughly speaking, the absorption in sediments is proportional to frequency. The strength of the reflected signal depends on the degree of contrast among the acoustic impedance. The first useful signal received represents the seafloor-water interface, and shows the geomorphology of the seabed in a manner similar to a single beam echo sounder reflection. The time of arrival and intensity of subsequent impulses provides information about layers that exist below the seafloor itself (Edelmann, 1968). Increased output power and lower emitted frequencies generally allow for greater vertical penetration into the marine substrate. However, according to Finkl and Makowski (2016), when attempting to survey harder substrate seabed (e.g., gravels or highly compacted sands) or those benthic areas in very shallow water, higher output power will most likely result in multiple reflections and more background scattered noise, or potential error, in the data (Grant and Schreiber, 1990). The depth of penetration also depends on the hardness of the upper layer sand and can be significantly limited by the presence of gas deposits (Hardage, 1985). Overall, the interpretation of seismic data has aided researchers in obtaining a complete benthic visualization, including the current tectonic state of the benthos, underneath specific areas of the seafloor.

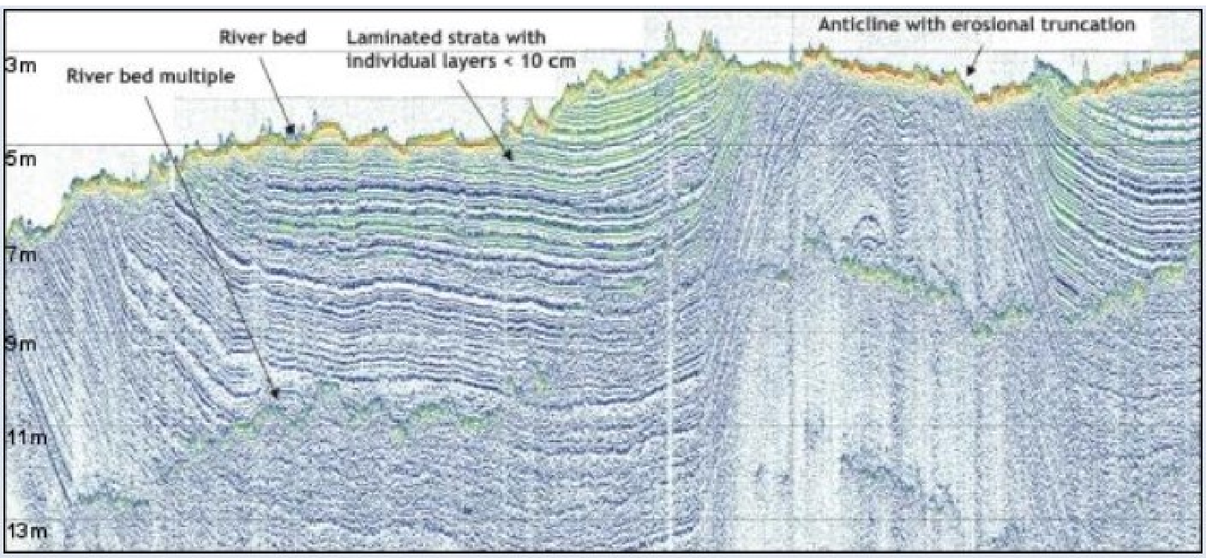


Fig. 3-7. SES-2000 standard shows parametric sub-bottom profiler echoprint data example from a river cable route survey (water depth 3-7m, penetration ranges between 2 and 14m, frequency 8 kHz).

3.3. Environmental and physical surveys of coastal and shelf environment

According to Finkl and Makowski (2016), Continental shelves cover an area of over 32 million km^2, which are equal to about 8.9 % of the total area of the ocean (Harris et al., 2014); From an economic perspective, continental shelves are the most important part of the world ocean, providing approximately 95 % of marine fish catches (Roberts and Hawkins, 1999) and 30 % of all petroleum extracted from both land and sea (Harris et al., 2015) not to mention other human uses such as shipping, tourism, mining and aquaculture. The continental shelf is defined by the IHO (2008) as "a zone adjacent to a continent (or around an island) and extending from the low water line to a depth at which there is usually a marked increase of slope towards oceanic depths".

Therefore, Coastal and shelf areas are among the most environmentally affected regions of the world and therefore particular vulnerable to the impacts of storms and tsunamis and the impacts of climate change such as sea level rise and associated coastal erosion. Researchers all around the world seeking answers to the hotly debated million dollar question of how rapidly and to what extent sea level will rise as a consequence of climate change. The evidence that the Earth's surface is warming rapidly is now exceptionally strong and beyond doubt. Sea level rise is one of the most series consequences of climate change.

Another important environmental topic is related to ocean basin evolution and plate tectonic revolution. Although, most geologists are familiar with the concepts of plate tectonics, only a few know the evidence supporting the theory, in which geophysics played the major role (seismology, including seismic refraction and reflection, gravity, magnetism and palaeomagnetism, heat flow and radiometric dating). Resolution of the sixty-year debate over continental drift, culminating in the triumph of plate tectonics, changed the very fabric of Earth science. Plate tectonics can be considered alongside the theories of evolution in the life sciences and of quantum mechanics in physics in terms of its fundamental importance to our scientific understanding of the world. Magnetometers towed behind ships, and accurate depth soundings provided data that led to the formulation of the hypothesis of seafloor spreading, adding the oceanic counterpart to the idea of continental drift. Together these two theories became united as the plate tectonic revolution.

Moreover, with the technological development, seafloor environments at most depths on the continental shelf are being surveyed and analysed at higher resolutions with the evolution of Remotely Operated Vehicles (ROVs) as stable survey platforms. This chapter provides an overview of the use of this technology for applications on the continental shelf. It explores applications of ROVs operation in mapping for different purposes, ranging from exploring benthic habitats to marine geology. According to Lucieer and Forrest (2016), ROVs are highly effective tools for sampling in continental shelf marine environments because: (1) they are untethered and can conduct non-destructive sampling in remote habitats (e.g. under ice shelves and over complex terrain) and in depths > 1000 m; (2) they can repeat spatial surveys with a high degree of precision over time; and (3) they can be equipped with a wide range of tools and sensors to sample both physical, chemical and biological data.

3.3.1. Applications of ROVs to Mapping for Benthic Habitats

ROVs are a great tool for scientists and researchers in discovering continental margins around the world. During October 2016, in the Lebanese submarine canyons, an underwater mission conducted by Sea Patron research ship (OCEANA mission), where a ROV reached 1000m depth and collected a full suite of data on the seabed (e.g., sediment samples, photos and videos for fauna and flora), which is important descriptor of biological patterns in correlation with the seafloor - the foundation of benthic habitat mapping (Harris and Baker, 2011). We can consider that generally underwater vehicles close the distance between the sea surface and the seafloor, and unlike mounted acoustic devices, they are able to collect data at much higher resolution with greater degrees of accuracy (Nicholson and Healey, 2008). During ROV transects, Sea Patron sailed at an average speed of 0.1-0.2 knots, filming both in high and low-definition, and simultaneously recording position, depth, course and time. Videos were viewed in real time, to carry out preliminary species identification and select species, habitats, and seabed features of interest for more detailed investigation (Fig. 3-8). In total, 51 ROV dives were carried out, ranging in depth from 36 to 1050m. These surveys yielded 71h 15min of video of the seabed, and 4601 still images. Samples of key habitat-forming species were also collected (by means of the robotic arm of the ROV) for detailed analyses to confirm preliminary species identifications based on the live video feed. The mission mentioned above was an effective example about capabilities of ROVs and their technical and water conditions limitations.

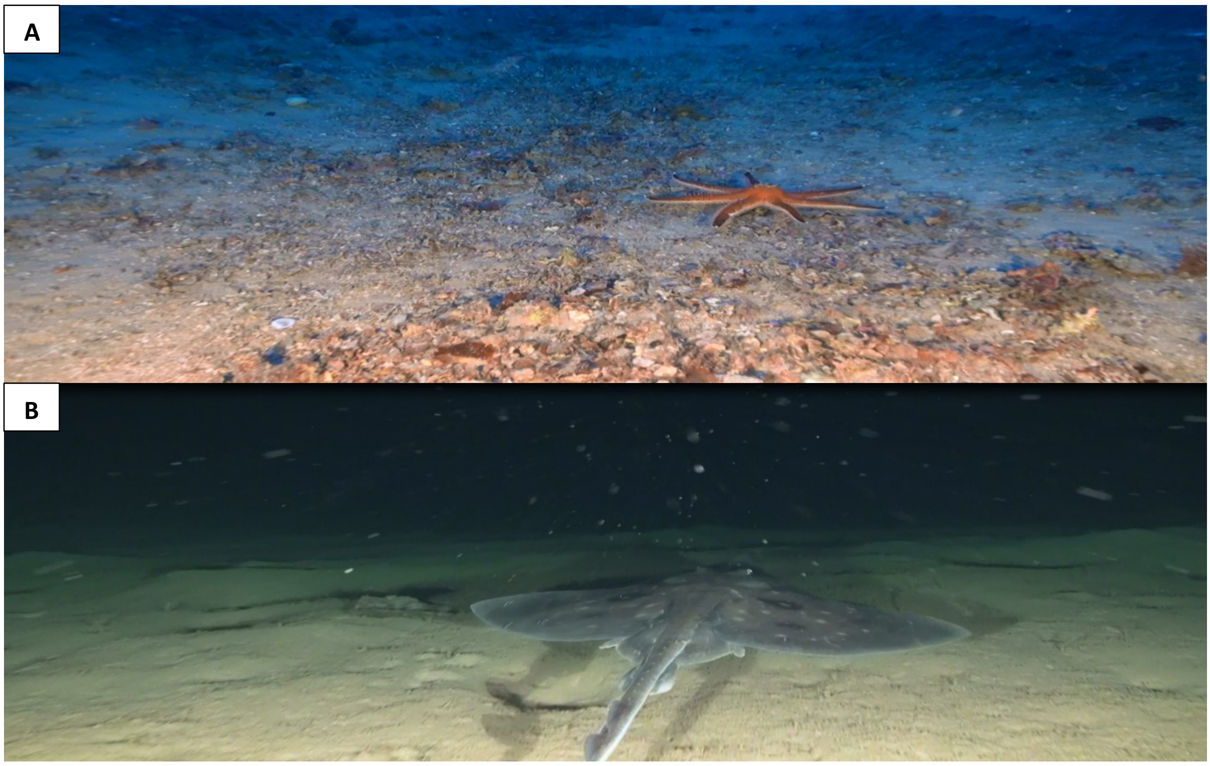


Fig. 3-8. ROV (remotely operated vehicle) images from a OCEANA environmental mission demonstrate the shells deposit on the continental shelf (sandy-gravel) in (A) and the importance biological diversity of the deep sea muddy bottom in (B).

Generally, following Finkl and Makowski (2016), benthic habitat mapping and monitoring provide marine stakeholders with useful data for the effective management of marine parks, marine resources and fisheries where the benthos provides a food source, plays a key role in the lifecycle of target species or may present indications of seafloor resources for marine geological applications (Roberts et al., 2015). As ROVs become cheaper and the advance in temporal observations for revisiting sites increases, the potential of ROVs for mapping benthic habitats will fundamentally change our view of continental shelf dynamics.

3.3.2. Marine Geology for hydrography

Marine geology for hydrography is concerned with the character and history of that part of the earth covered by seawater. The importance of Marine geology is evident when we consider that three-fourths of the earth's surface is covered by water. These areas consist of concern range from the beach to marine marshes and lagoons, across the continental shelf, and down to the deepest parts of the ocean. Marine geologist and geophysicists rarely restrict their research to areas below sea level because a considerable body of important information about history of the earth and the oceans is gained from rocks exposed above sea level. Marine stratigraphers and paleontologists often examine the uplifted marine sediments. Likewise, those interested in the evolution of the oceanic crust often visit oceanic island to understand better the processes of formation of the oceanic crust. Philip Kuener in 1958 described the importance of marine geology in his paper: "No Geology without Marine Geology".

The bathymetric data is used basically to derive information on morphology and habitat dimension, while collocated with the backscatter settings provides useful information on seabed characterization with high georeferencing precision which allows for marine geology science to grow and develop. Hydrographic ships and ROVs are able to carry a variety of sensor payloads relevant to marine geological studies, where the competition for marine mineral exploration is increasing. Most relevant to marine geological applications is the ability of ROVs for instance to acquire data ranging from the water column through to the subsurface of the seafloor. Hydrographic ship equipped with advanced sensor technologies such as laser scanners, chemical sensors, gravity gradiometers and sub bottom profilers can be used in conjunction with more 'traditional' multibeam bathymetric and sidescan sonars to create highly detailed georeferenced 3D models of what lies both above and below the seabed. Underwater laser scanners are used for precise mapping and monitoring of seafloor mining assets (Gordon, 1992), while chemical sensors are used for plume detection in the water column, tracking and localisation of constant emissions (Camilli et al., 2009).

3.3.3. Marine geomorphometry

According to Lecours et al. (2016), the science of geomorphometry has roots in morphography, hypsometry, cartometric, geophysics, and geomorphology (Pike et al., 2009; Evans and Minár, 2011; Evans, 2013). This science simply linked between the shape (e.g., geometry of seafloor) and the most common physical processes that could occur at the seabed and therefore influence the marine habitats. Our project is based on bathymetric data, particularly full coverage multibeam. These data are well suited for the generation of quantitative terrain variables such as terrain attributes and terrain features. These attributes and feature classifications can be very practical when describing, interpreting, and classifying geomorphology in our marine environment. Terrain variables can be grouped into four main types describing different properties of the seabed: slope, orientation, curvature/relative position, and terrain variability (Fig. 3-9).

For all researchers who have worked in this field, geomorphometric techniques have generally performed well in submarine environments. They have been amongst the most successful techniques, particularly with regard to the study of submarine mass movements, and canyons. Following the work of Lecours et al. (2016), mainly in the study of submarine mass movements, the general approach has been the prior identification of the boundaries of the landslides, the measurements of a series of morphometric parameters and their spatial and statistical analyses. This kind of approach has been applied to high resolution bathymetric data of Jounieh-Beirut basin, e.g., slope and rugosity, which has important implications for shelf and slope modelling in order to localise possible hazard assessment (Chap. 7, Fig. 7-4 and Fig. 7-5).

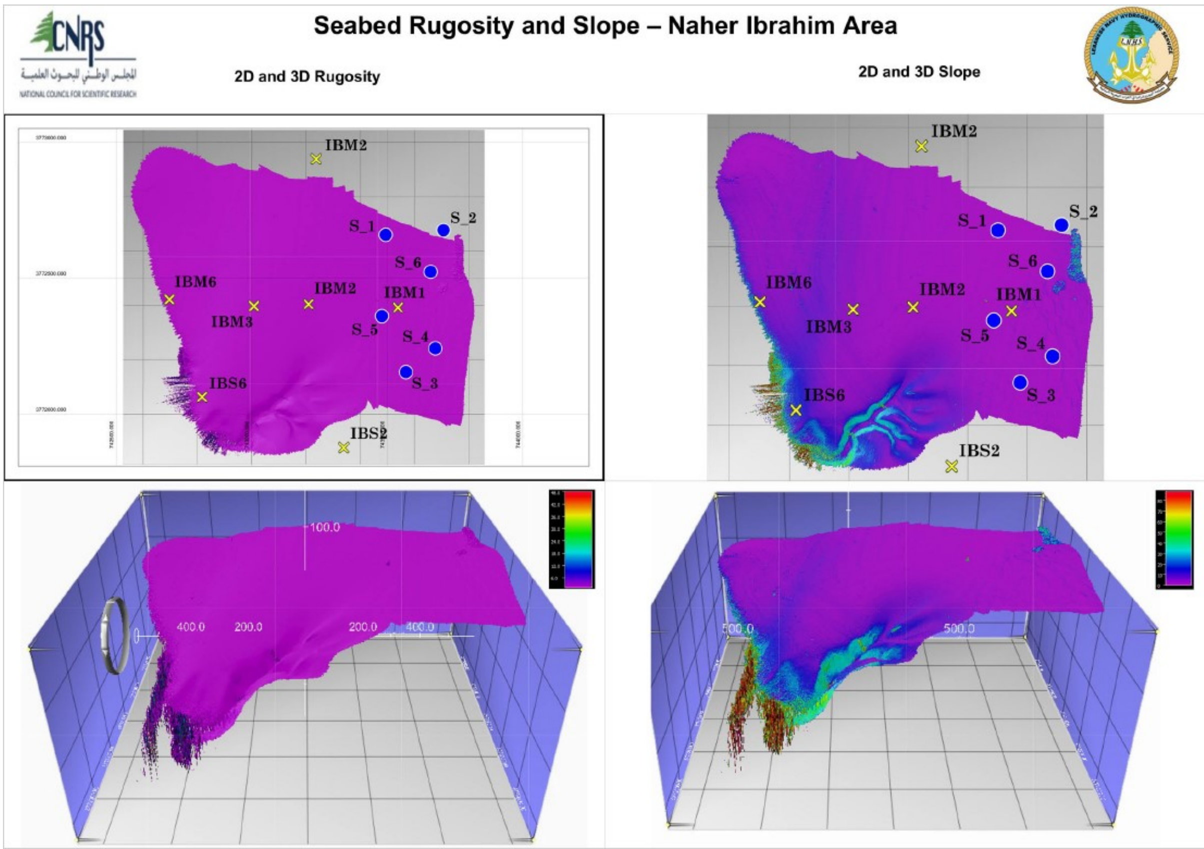


Fig. 3-9. Geomorphometric techniques (e.g., rugosity and slope) applied on Nahr Ibrahim area featuring respectively its seabed roughness and possible channels of sediment.

The geomorphometric technique is implemented in five steps: Sampling the depth of seafloor by acoustic remote sensing, generating a digital bathymetric model by interpolation means, post-processing by correction of errors and artefacts, analysing the digital bathymetric model by studying general and specific geomorphometry, and finally the application of results in marine geomorphology and geo-hazards (Pike et al., 2009).

Marine scientists are more familiar nowadays with geomorphometric techniques and practices. This will ensure that this science will be used to its full potential for studying the topography and morphology of the whole earth.

3.4. Sediment and Sedimentary processes on continental shelves

The term sediment refers to material composed of particles that have settled to bottom of a liquid. Sediments are classified by the processes involved in determining the physical and chemical character. The application of multibeam systems, sediment transport measurement technologies and the adoption of integrated techniques in the approach to research have greatly advanced our understanding of sediments, morphology and sedimentary processes on continental shelves in the last decade. The multibeam provides wide area coverage of seafloor variations in bathymetry and backscatter at typical horizontal resolutions as small as 2% of the water depth, therefore the routine application of multibeam sonar has revolutionized our understanding of continental shelf morphodynamics, e.g., the surficial sediment distribution over continental shelf areas.

3.4.1. Continental shelf sediment transport

The sedimentary cycle is responsible for the sediment supply of the coastline and continental shelf; the weathering and the erosion are the first factors, then the transportation of the sediment to the shoreline where it flows to the continental shelf. According to wright, advances in the sediment transport at the continental shelf have been made in five general, but overlapping areas: (1) bottom boundary layer hydrodynamics; (2) sediment suspension and vertical flux; (3) along-shelf flux; (4) flow-driven across-shelf flux; and (5) gravity-driven across-shelf flux and deposition. Within suspended load the materials are those that make up the continents, particularly those that are resistant to weathering or dissolve incongruently. Major sources of sediment particles (aeolian, riverine, volcanic, biologic activity, etc.) and processes (settling, mud flows, transport by currents, etc.) had been identified. Also, the distribution of the major types of sediments had been recognized, but not explained yet in that period because the technology was also poor developed.

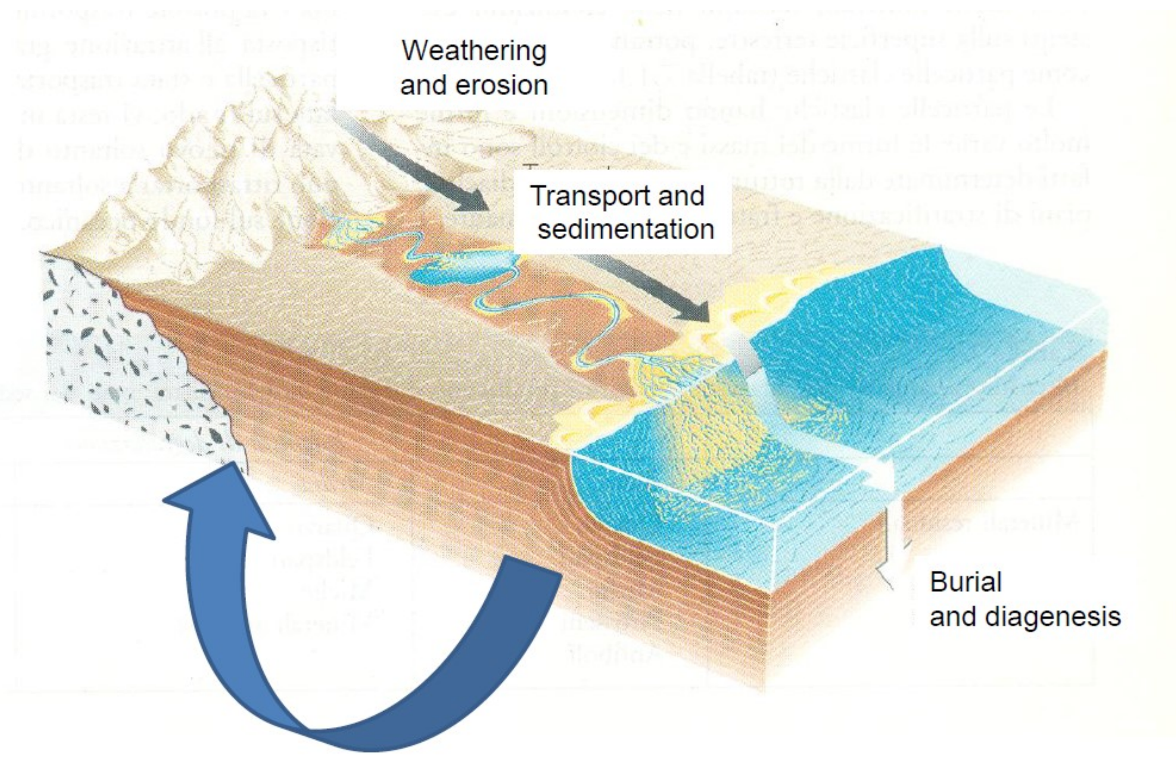


Fig. 3-10. The sedimentary cycle is described above from weathering and erosion to transport and sedimentation until burial and diagenesis.

Sand is deposited near the coast whereas the smaller silt and clay particles are transported farther distances offshore before they settle to the bottom. Terrigenous sediments are dominant in coastal areas near river mouths. When the terrigenous load of the river is important a delta develops, progressively creating a coastal plain and expanding the shelf. These piles of sediment can slide down the continental slope into the deeper ocean and produce debris flow and turbidity current (mixed sediment and water) that moves along the ocean floor and then deposited when the energy of the current decreases (Fig. 3-10).

3.4.2. Recent advances in instrumentation used to study sediment transport

Although our present understanding of sediment processes is still incomplete, technological advances continue to unveil the complexities of sediment dynamics deposit and grant the development of improved predictive tools. Technologies nowadays are producing new instruments capable of measuring simultaneously water columns components, e.g., suspended sediment concentrations, and bed location. These recent advances combined with new technologies to measure complex three-dimensional bed morphology are providing new insights into sediment dynamics deposit. According to Williams (2012), the most significant advances have been made in four interrelated areas: (a) boundary layer hydrodynamics (e.g. Lacy and Sherwood, 2004); (b) bedload transport, including sheet flow (e.g. Hassan and Ribberink, 2005); (c) sediment suspension and vertical sediment flux (e.g. Thorne and Hanes, 2002); and (d) bed morphodynamics (e.g. Trayovski, 2007).

According to Williams (2012), from the recent advances in studying and characterizing the distribution of sediment, one should merges bathymetry maps, sidescan sonar and sub-bottom profiler data and sediment samples. This takes in consideration the sediment perturbation; therefore the strong correlation between seabed disturbance magnitude and bedforms formation and movement. Numerical model predictions demonstrate that hydrodynamic forcing and sediment mobilization are strongly controlled by waves and wave-current interaction during winter storms (Fig. 3-11).

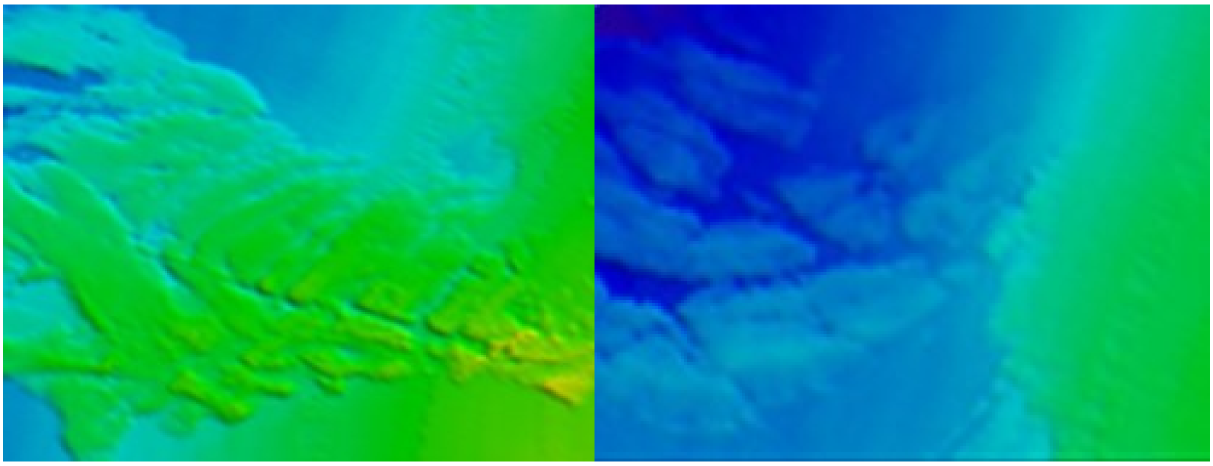


Fig. 3-11. Bedforms formation in Nahr El kalb's region; the Nahr El Kalb river is responsible of the disturbance magnitude in this case.

3.4.3. Measurement of bedload transport in a coastal sea using repeat swath bathymetry surveys

Throughout our study at Jounieh-Beirut basin, a recent bathymetric survey data is used for the creation of digital bathymetric model where the morphologies play the biggest role in identifying bedloads formation. A repeated bathymetric survey at the same area should be achieved in the near future to estimate the bedload transport and movement. Processing of two serial multibeam surveys of the shelf and coastal area of Jounieh-Beirut basin will result in an estimation of the rate of sediment transported. Bedload can be estimated using measurements of migration rate and bedform height by differentiating the two digital bathymetric models. According to Duffy et al. (2005), the morphology of the sand dunes changes noticeably across the sand bank. These visual changes suggest that the bedforms change in response to decreasing cohesion, noting that the increased mapping resolution of multibeam technology nowadays allows the gathering of highly detailed, quantitative information regarding bedforms and therefore forward understanding of coastal and shelf physical sediment transport processes, which can provide valuable information to coastal managers for more efficient sediment resource management. The frequency of disturbance or sediment movement affect also, according to Connell (1978), the biodiversity, where the period of ecological succession in shelf environment range from 1 to over 10 years. Research by physical sedimentologists has shown that the results of such disturbances may include bed stresses that cause widespread erosion, deposition of bedloads over 1m in thickness and destruction of seagrass beds as well as bioherms such as coral reefs.

3.5. Conclusion

With the accumulation of population on coastal areas and their demands on marine resources, the development of remote sensing techniques are more than required to investigate this effect extended to shelf domain. Visualization of seafloor environments has gone through a big development during the past decades. Thus, remote sensing of the seafloor is a developing technology that has facilitated evidence on morphology, marine geology, and marine habitats environment. Due to this development, it is now possible to map a wide range of shelf environments using airborne, shipboard, and other assets. Since our research is related to possible mass movement inside submarine canyons, it was primordial that our investigation of the seafloor and subfloor geological structures includes the continental shelf parts and zones and not only the canyon by itself and its adjacent slope zone. Between all developed sonars visualization, one is the multibeam echosounder techniques that embrace both of bathymetric and acoustic reflection data, which provide much valuable information when combining to the morphology with the nature of seabed information. Multibeam bathymetric and backscatter data are providing a new view of bottom morphology and surficial sediment distribution over continental shelf areas. Attention is now being given to the scattering properties of cohesive sediments where few instruments are available to measure concentrations and physical properties. A proper interpretation of the possibility of artefacts is needed for a good interpretation of continental shelf morphodynamics. Scientific applications of the same data revolve around geomorphological interpretation of bathymetric patterns. Every method of seafloor visualization has its advantages and disadvantages. No method is perfect for all applications and consequently, it exists today a wide variety of survey techniques that depend on the goal or purpose of what is attempting to be detected, in relation with the scale of the survey. Knowing accurately the tidal and water height reduction is a principal concern for bathymetric accuracy, especially for repeatable bathymetric surveys. Studying the continental shelf and nearshore environments have provided to this project a wide range of scientific data which was essential for the understanding of the sediment dynamics along and across shore, and therefore the sediment movement inside canyons heads before it moves downslope to the deep waters. Quantifying bedforms movement and sediment behaviour prediction remain a challenge to researchers, even if the technological instrumental advances identify the sediment dynamics and seabed morphology. A problem arises also when so much data acquired from the shelf areas could be available in so many different formats, but its management and analysis are still poor.

4. Chapter 4: Aspects of Submarine Mass Movement

4.1. Introduction

With the Development of integrated surveying technologies such as multibeam echosounder that permits a full coverage seafloor data, significant improvements were achieved in mapping and describing the morphology of submarine mass movements. Submarine mass movements however, can have run out distances in excess of 100 km, so that their impact on any offshore activity needs to be integrated over a wide area (Locat and Lee, 2000). However, the phenomena of submarine mass movements is still not very well dissected due to the authenticity of each case from one side and difficulties in studying in general submarine dynamics and behaviour from the other side. A major challenge ahead is the integration of mass movement mechanics in a valuable risk assessment to create methods and actions to permit safe and proper human activities offshore and along coastlines.

A special attention related to the continuing development of natural resources such as oil and gas in particular, either closer to the continental slope or in deeper water, should be given to study the growing need for seafloor transport, communication routes, the pressure on coastal development (cities, harbours), the protection of the marine environment and the impact of global changes.

This chapter will firstly revise types and causes of submarine mass movements. Then it will briefly investigate the geotechnical aspect of submarine mass movements, noting that the rapid development of the geomorphological analysis of submarine mass movements using multibeam techniques, proposed by Leroueil et al. (1996), has permitted to examine the pre-failure and failure stages and the final post-failure stage. Also, it is important to reveal of the economic significance of submarine mass movements, by analysing the role of submarine landslides in the law of the sea and to highlight the relation between tectonics and mass movement. This chapter will end by discussing some elements of hazard and risk assessment related to submarine mass movements. The conclusion will underline achievements and remaining challenges.

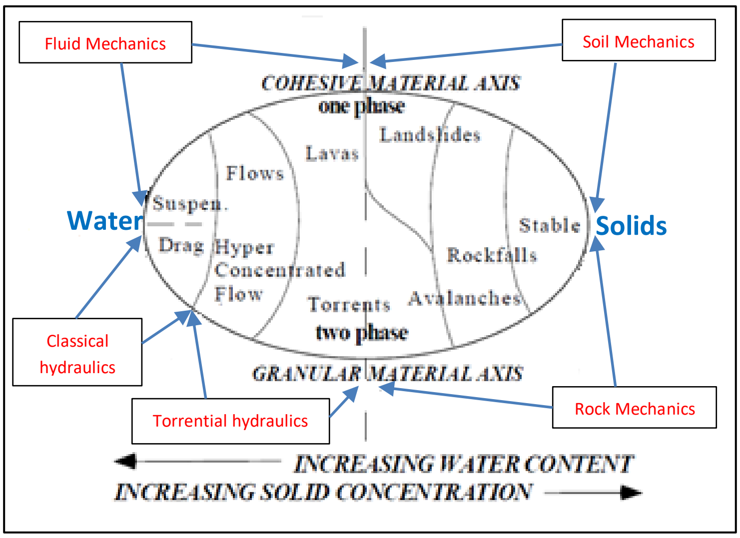


Fig. 4-1. A schematic view of mass movements made of mixtures of solid and water at various stage of mixing and as a function of solid characteristics (one or two phase flow) with indication of the physics involved in the phenomena (modified after Meunier 1993).

4.2. Causes and dynamics of submarine mass movements

Researchers have specified many possible triggers for the initiation of submarine landslides including: 1) over steepening, 2) seismic loading, 3) storm-wave loading, 4) rapid accumulation and under consolidation, 5) gas charging, 6) gas hydrate disassociation, 7) low tides, 8) seepage, 9) glacial loading and 10) volcanic island processes. Gas charging and wave action are particular causes to the marine environment (Locat and Lee, 2000). Materials involved in submarine mass movements are as diverse as those on land, *i.e.* rock, soils, mud and mixtures of both. A submarine mass movement can also be analysed from a geotechnical characterization standpoint (Leroueil et al., 1996), considering the various stages from pre-failure conditions to the run out and depositional phase.

The complexity of submarine mass movements can be great and we must now consider their possible various phases which are: initiation, transition into debris flow (Norem et al., 1990), the subsequent formation of a turbidity current (Normark and Piper, 1991) and its movement on the sea floor until final deposition. Here, we must distinguish the cases where turbidity currents can be directly generated by hyperpicnal flows originating at mouths of major rivers entering the ocean, as often seen in fjords (Syvitski et al., 1987, Mulder and Syvitski, 1995), from those originating from mass movements or debris flows. To illustrate the continuity of the mass movement phenomena, we modified a diagram proposed by Meunier (1993) (Fig. 4-1). This diagram has two axes: granular and cohesive. It also takes into account the relative proportion of solid and water. Therefore, depending on the type of mixture (one or two phases), its behaviour will be best analysed by soil/rock mechanics principles, fluid mechanics or torrential hydraulics.

This means, for example, that for mud flows, where the rate of movement is fast enough so that there is no time for excess pore water dissipation, the mechanics of the movement cannot be adequately explained by soil mechanics but rather we must apply fluid mechanics principles. For a comprehensive review of debris mechanics, the reader is referred to the work of Iverson (1997). A first observation based on the above presentation is that if we wish to carry out a risk assessment related to submarine landslides, we must take into account the various components of the phenomenon, *i.e.*, from failure initiation to the final deposition, which will require scientific consideration covering all the physics involved.

Another way of representing the physics involved in a submarine mass movement is to present the classification of mass movements proposed by the ISSMGE (International Society for Soil Mechanics and Geotechnical Engineering) Technical committee on Landslides (TC-11) and adjust it to the submarine environment (Fig. 4-2). In this case, the main difference is the development of turbidity currents from mobile types of mass movements such as avalanches, debris and mud flows. Clearly, one could introduce subdivisions (*e.g.* Prior 1984, Mulder and Cochonat, 1996) but the terms presented in Figure 4-2 can cover most of the observed phenomena. The widespread use of multibeam surveys shows us that mass movements are occurring in various environments and involve all types of earth material from mud to hard rocks.

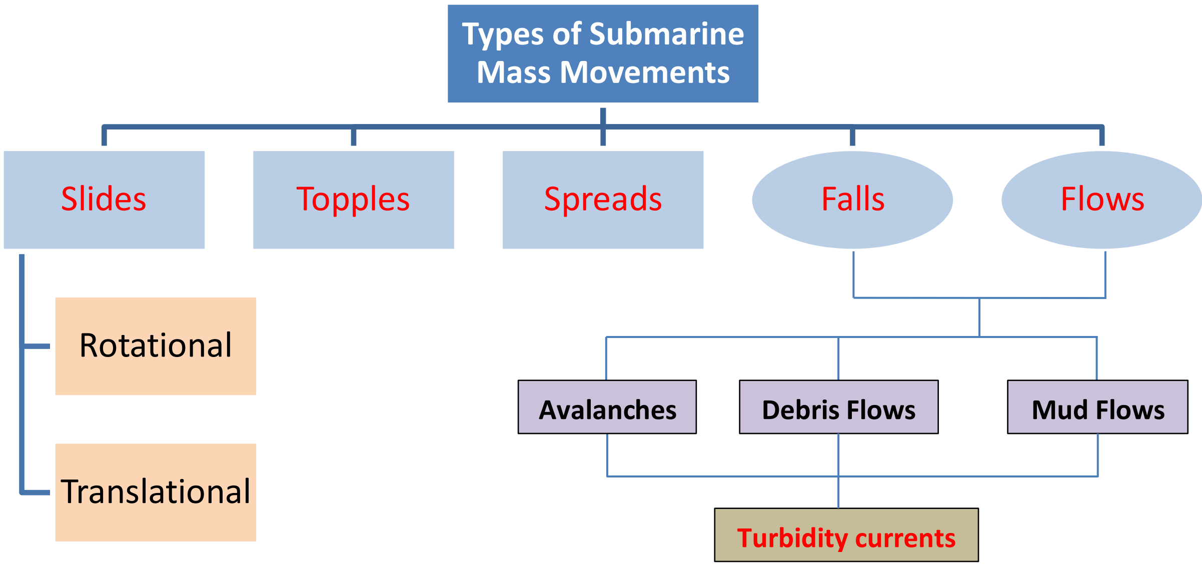


Fig. 4-2. Classification of submarine mass movements adapted from sub-aerial classification (modified after the ISSMGE Technical Committee on Landslides) (TC-11).

4.3. Geotechnical investigations of submarine landslides

Advances in geotechnical technology have been driven by the need for quality data required to quantify slope sensitivity response to deformation. Such progress in the recent past is being driven by engineering concerns around seafloor stability with respect to infrastructure hazard (Forsberg et al., 2016). Unprecedented insights into mass movement are now being offered by recent technological advances, in the laboratory (Torbahn et al., 2016), through the comparison between laboratory to in-situ observations (Kluger et al., 2016), and by correlating geophysical and in-situ geotechnical experiments (Stegmann et al., 2016). The confines offered by fjords and estuaries make perfect natural laboratories to study detailed geotechnical aspects of mass movements that can then provide insight into less accessible submarine processes (Forsberg et al., 2016; Kluger et al., 2016; Mastbergen et al., 2016; Turmel et al., 2016).

According to Locat and Lee (2000), submarine landslides occur in various environments, like on land mass movements. While seismic and multibeam surveys can be carried out on a cost effective manner, sampling and *in situ* testing, on the other hand, are not as easy and often much more costly for the same level of quality. Except for cases involving offshore resources such as oil and gas, in most situations sampling is done by means of gravity methods: Calypso (up to 60 meters, mounted aboard the Marion Dufresnes II, IFREMER), Long Coring Facility (up to 30, meters, Geoscience Atlantic, Canada), Lehigh (up to 3 metres), Kastin corer (up to 3 meters), box corer (0.6 meter) and surface sampler (Shipek, VanVeen). The best coring method is the box corer but it has a very limited penetration. All other methods have their intrinsic difficulties mainly related to the partial remolding of the soil during the penetration in the sediment.

As stated by Locat and Lee (2000), Ongoing research efforts are being directed toward developing remotely operated drilling equipment, called the PROD. This coring tool is designed to sample to 100 meters below the seabed in any kind of material (soil or rock). Such depth ranges would be satisfactory for most of the submarine mass movement investigations.

In situ techniques have been developed for general purposes but can be used in submarine landslide investigations. The Lancelot and Excalibur probes were designed as piezocone, which can also collect gas samples (limited to about 10 meter in soft sediments, Christian et al., 1993, 1994).

4.4. Mechanics of submarine landslide initiation: pre-failure and failure stages

Seismic loading and over steepening were considered in the early work of Morgenstern (1967), and many submarine landslide initiation prediction procedures have focused on these triggers ever since (*e.g.*, Lee et al., 2000). However, a recent work (Boulanger et al., 1998; Boulanger, 2000) has shown that repeated, non-failure, seismic events can actually strengthen the sediment column through development of excess pore water pressures during earthquakes and subsequent drainage and densification during intervening periods. By carrying out a series of cyclic-loading tests on normally consolidated specimens, we observed (Fig. 4-3B) that the sediment begins to exhibit over-consolidation and a significant strength increase if a period of drainage is allowed between repeated earthquake simulations.

This figure illustrates the dynamic response (Fig. 4-3A) of a soil sample from Eel River margin tested under cyclic loading under a cyclic stress ratio of 0.242 and an effective stress of 50 kPa. Figure 4-3A shows the three ways used to define the failure criteria: (1) pore pressure, (2) deformation and (3) failure envelope, while the figure 4-3B presents the test results on a normally consolidated specimen which has been taken through repeated cyclic loading (below the failure point) and drainage periods. The specimen clearly exhibits a decrease in the void ratio and an increasing shearing resistance to liquefaction after each cycle. We propose to call this build-up of shearing resistance, seismic strengthening, and suggest that this mechanism partly explains the paucity of shallow submarine landslides on the Eel River Margin, the most seismically active margin in the continental U.S., and possibly in other areas with similar sediment and tectonic settings.

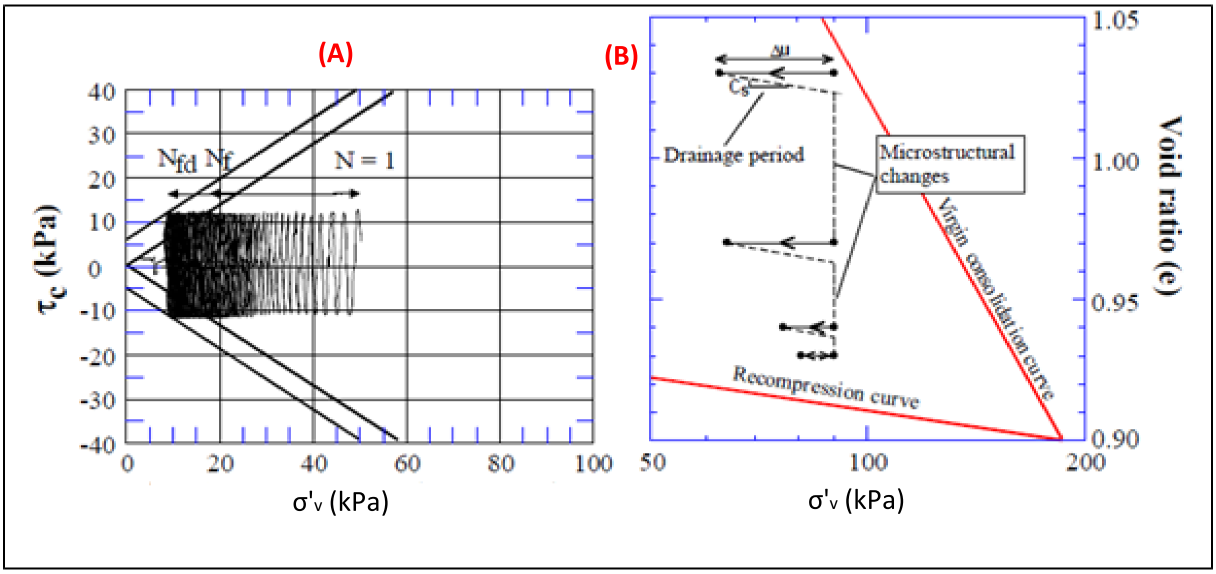


Fig. 4-3. (A): Dynamic response of a natural sample from Eel river Margin (California) showing the number of cycles to failure in an undrained case using different methods. (B): effects on void ratio of only few cycles of cyclic loading and drainage (modified after Boulanger et al. 1998). Symbols specific to this figure are as follows: τc: horizontal shear stress; N: number of cycles; Nf: number of cycles to failure; σ'v: Vertical effective Stress.

Storm-wave loading and under-consolidation became recognized as major factors in causing submarine landslides following the failure of or damage to several offshore drilling platforms when Hurricane Camille struck the Mississippi Delta in 1969 (Bea et al., 1983). Further work (*e.g.*, Whelan et al., 1977; Hampton et al., 1982) showed that bubble-phase gas charging can degrade sediment shear strength and contribute to slope failure. Other studies (*e.g.* Kvenvolden and McMenamin, 1980) have shown the existence of gas hydrates underlying many submarine slopes. Such hydrates are ice like substances, consisting of natural gas and water, which are stable under certain pressure and temperature conditions that are common on the seafloor. When temperatures increase or pressures decreases, the stability field changes and some of the hydrate may disassociate and release bubble-phase natural gas. Unless pore water flow can occur readily, this gas charging leads to excess pore pressures and degraded slope stability. Kayen and Lee (1991) suggested that worldwide lowering of sea level during glacial cycles could lead to numerous slope failures because of gas hydrate disassociation. Of more immediate interest, warming of the seafloor through changes in current patterns or global warming could potentially cause a similar effect (Fig. 4-4). The impact of oil and gas offshore production in areas where gas hydrates are present poses difficult questions regarding the effect of these activities on the gas hydrate stability and its link to slope instability or the potential re-activation of older mass movements.

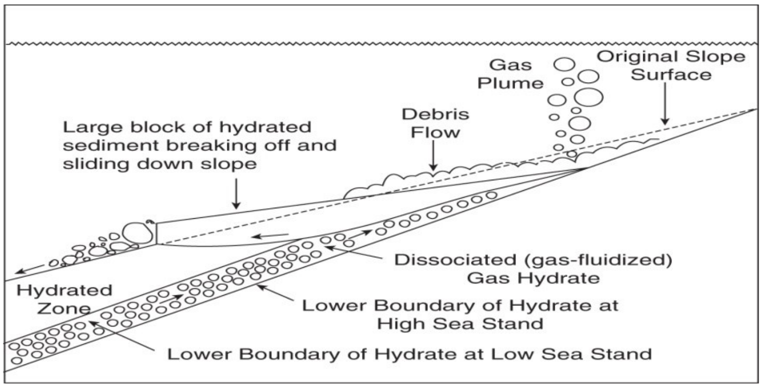


Fig. 4-4. The role of gas hydrates on slope instability development as a results of sea level lowering.

4.5. Tectonics and Mass Movement Processes

The hazard and risk associated with submarine mass movement remains a fundamentally important focus of the scientific community. Hard efforts to clarify the relation between tectonics and mass movement occurrence have been achieved (Katz et al., 2016; Locat et al., 2016; Moore and Strasser, 2016). The effect of tectonic activity on seismic strengthening is a hypothesis that is being supported by a comparison of shear strength in cores from active and passive margin settings (DeVore and Sawyer, 2016). Chapron et al. (2016) and Gracia et al. (2013) deduced some beneficial outcomes for improving seismic hazard assessment through the study of submarine mass movements to identify the ancient seismic activities at local or regional scale.

4.6. Economic significance of submarine mass movements

4.6.1. The role of submarine landslide in the law of the sea

Based on Mosher et al. (2016), using scientific arguments in reclaiming economic zones is a debatable subject. The responsible body reviewing this matter is the Commission on the Limits of the Continental Shelf (CLCS); this commission encouraged coastal states under the UN convention on the Law of the Sea to define the extended continental shelves and the delimitation of the outer edges. The submarine landslides by their nature spreading define the so called "Foot of the continental Slope" (FoS), that help in the limitation of the outer edges.

Following Mosher et al. (2016), the outer edge of the legal continental shelf is defined in article 76 of the United Nations Convention on the Law of the Sea as the submerged prolongation of the land mass of the coastal State, consisting of the seabed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor. The outer edge of the legal continental shelf is determined by either 60 nautical miles (M) from the foot of the continental slope (known as the Hedberg formula (Hedberg, 1981)), or not more than the distance in which the thickness of sedimentary rocks is 1% of the shortest distance from the foot of the continental slope (the Gardner formula) (Fig. 4-5). The foot of the continental slope is defined within article 76 as 'the point of maximum change in the gradient at its base'; the key requirements for identifying the point of maximum change in the gradient at the base of the continental slope are: the identification of the region defined as the base of the continental slope and the determination of the location of the point of maximum change in gradient within this region.

According to Mosher et al. (2016), in some areas the morphology of the continental margin can be clearly subdivided into shelf, slope, rise and abyssal plain. In these areas it is relatively straight forward to identify the region where the lower continental slope meets the rise, or where it meets the abyssal plain in cases where a rise is absent. Along many margins around the world, however, there is substantial geographic variation in the morphology of the continental slope. The continental slope typically has a gradient of a few degrees, but can vary locally from steep escarpments to horizontal surfaces across terraces and ponded mid-slope basins. The morphology of the seabed where the continental slope merges with the deep ocean floor may be an abrupt boundary where the smooth and near-horizontal surface of the abyssal plain borders the continental slope, or it may be a complex transition where local relief on the ocean floor meets an irregular lower slope.

As a result of this and other ambiguities, the CLCS adopted a set of scientific and technical guidelines (CLCS/11 and Add.1) to assist State's in the preparation of their submission (CLCS, 1999). These guidelines provide that identification of the foot of the continental slope first requires identification of the region defined as the base of the continental slope; and then the determination of the location of the point of maximum change in gradient within the base of the continental slope (Fig. 4-5). In order to identify the base of the continental slope, one must first distinguish the various elements of the margin.

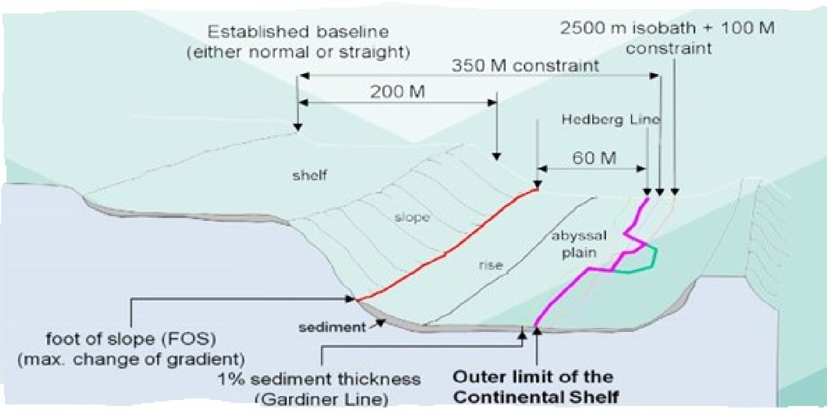


Fig. 4-5. Elements prescribed in article 76 for defining the outer edge of the legal continental shelf.

4.6.2. Hazard and risk assessment

Submarine mass movements hide a big potential of hazard along coastal zones, continental shelves and deep water. The challenge remains in discovering, predicting and evaluating the future danger at regional scale. Many questions, asked by Locat and Lee (2000), could rise about the hazard by itself: (1) where did mass movement occur and where will it occur, (2) how frequently, (3) what are the triggering mechanism(s), (4) what is their area of influence and (5) can previous failures be re-activated?

Creating a DTM, using multibeam echosounder, and by analysing its morphology, the size and extent of submarine mass movement can be identified and documented to have the ability later to estimate the probability of landsliding's occurrence. Various examples, from around the world, can be given to understand the possible extent of submarine movements; the 1929 Grand Banks earthquake triggered a major submarine slide which transformed into a debris flow travelling over a distance of not more than 80 km (Locat et al., 1990). The debris flow initiated a turbidity current which covered a distance of at least 1000 km. Cable breaks data were used to indicate that the initial velocity was as high as 25 m/s and that it was still about 5 m/s at a distance of more than 500 km from the starting zone (Locat and Lee, 2000).

4.7. Conclusions: achievements and challenges

This was a brief presentation explaining aspects of submarine mass movements and achievements made since the early 1990s. It also presents some of the major challenges still facing us. We therefore took this opportunity to look in greater details on the geomorphological and engineering aspects. When considering the intense research activities initiated over the last 5 years, a lot more could be said. As a summary, following Locat and Lee (2000), many main conclusions on achievements and challenges are adopted and presented hereafter.

The major achievements were:

- Development of surveying techniques providing aerial photograph-like quality images of the sea-floor.
- Physics of rapid mass movements with a description of post-failure behaviour, in particular for debris and mud flows.
- Determination of the rheological parameters and the use of the liquidity index.
- Recognize the role of gas hydrates in the development of slope instability.
- The introduction of the concept of hydroplaning to explain some of the large run-out distances achieved by debris or mudflows.

The major challenges facing us are:

- Improving sampling and in situ measurement techniques.
- Integrating 3D seismic methods into slope stability analysis.
- Use of long cores to provide estimates of the frequency of catastrophic events in the aquatic environment.
- Modification of mass properties to provide mobility to the flowing mass: the transitions from failure to post-failure behaviour and from debris flow to turbidity current.
- Generation of tsunami from submarine mass movements.
- Hazard assessment: frequency and extent in particular.
- Monitoring the movement and mobilization of actual landslides.
- Determining the role of subsurface water flow in initiating submarine landslides.

- Integrate the role of gas hydrates in the analysis and prediction of submarine slope stability.
- Evaluating the mechanics of giant landslides and improving our understanding of the causes of their great run out distances.
- Developing criteria to determine the cause of seafloor deposits that have been described as either landslides or migrating sediment waves.

5. Chapter 5: Environmental status of the Bay of Jounieh through the evaluation of its marine sediments' characteristics

5.1. Introduction

The continental margin of the central Levant, offshore northern Palestine and Lebanon is characterized by a sharp continental-oceanic crustal transition, exhibited on the bathymetry as a steep continental slope. The western Lebanese continental margin, in the eastern Mediterranean Sea, extends from the Lebanese coastal belt up to 10 km west.

Jounieh Bay area is poorly explored, its offshore coastal strip is characterized by a very narrow continental shelf, crossed by a deep canyon that, from a short distance from the coast, goes down to the depth of one thousand meters. Offshore Jounieh Bay, a high resolution bathymetric data with full multi-beam coverage have revealed a dense network of submarine canyons within the depth range from 80 to 1400m, across a wide range of morphological settings. The Jounieh Bay canyon (Eastern Mediterranean Sea) where sediments are transported across the slope is aligned with a prominent land valley near the center of Jounieh Bay and has a northern tributary which is roughly in line with an important fault and shear zone near Ras-el-Maameltein (Goedick and Sagebiel, 1976). Its seabed topography is the continuation of an inland geomorphology with its almost absent coastal plain on which agglomerations have developed, and steep hills belt exceeding 500m in elevation, in less than 1 km from the coast.

The coastline of Jounieh Bay is stretched in a semicircle, surrounded by several cities: Kaslik, Jounieh, Maameltein and Tabarja and is considered as one of the most frequented touristic coastal region of Lebanon. The northern part of the Bay contains the "Casino of Lebanon", a famous place that contributes to the prosperity of that area.

The Bay of Jounieh is facing the threats of uncontrolled urbanization with illegal construction expansion along the sea side altering the natural landscape and promoting the release of high inputs of untreated sewage water. The Bay is under the influence of a wide range of anthropogenic impacts due to its port of pleasance and the numerous marinas projects including fishing, diving activities, leisure boats, restaurants, night clubs. The Bay of Jounieh might be also affected by the discharges of the power plants lying at its northern side (Hamdan, 1998).

The evaluation of sediment is considered an important tool for pollution monitoring more than the water evaluation. Marine sediment is an indicator of the environment history with all its human activities that affected the sediment characteristic, status and composition. It is a final destination and an efficient natural trap for natural and anthropogenic contaminants. It is also a natural regulator of the biological processes that occur inside the sea floor. Sediment can store large amounts of organic matter and affect the oxygen content of bottom water (Burone et al., 2003). It also constitutes a source of nutrients for the water column above them leading to benthic-pelagic coupling and influencing primary productivity (Jørgensen and Richardson, 1996).

This investigation aims to evaluate the state of environment of Jounieh Bay, to reveal the impact of anthropogenic activities, to get a better understanding of the sources and distribution of multiple contaminants, and to have a reference for future investigation by studying the variation of geochemical, chemical and biochemical characteristics of marine sediment.

5.2. Material and Methods

With the help of the Lebanese scientific vessel CANA-CNRS, the samples of sediment were collected from the Bay of Jounieh at 3 designated depths (15, 30 and 60m) along 3 horizontal transects located to the north (NJ), to the middle (MJ) and to the south (SJ) of the bay (Table 5-1, Fig. 5-1) during spring season of 2013. A stainless steel Van Veen grab was used to sample the first 5cm of surface sediments. All samples were freeze-dried for further analysis. The grain size composition is determined by sieving the sediments on a series of variable mesh size sieves (ranging between 2000 and 63 µm) on a Retsch AS200 siever. The organic matter is determined using the simple titration method approved by the Expertise Centre in Environmental Analysis of Québec (MA., 2010). Chlorophyll-*a* and pheopigments are extracted by acetone (90%) and calculated by spectrophotometry according to Lorenzen (1967) method modified by Magni et al. (2000). Calcium carbonate is measured according to UNEP (1995) manual by the loss of weight after addition of hydrochloric acid. The analysis of phosphate in sediment is processed by the adoption of the semi-automated method of Aspila et al. (1976). The 3 major biochemical components of the labile fraction are analysed according to the method of Lowry et al. (1951) for proteins, that of Dubois et al. (1956) for total carbohydrates and the method of Marsh and Weinstein (1966) for lipids. The statistical analysis is performed with the "R Project" for statistical computing. Two-way ANOVA without repetition is adopted to highlight the significant differences of mean values of variables between the depth and stations. Matrix of correlation was performed to estimate the strength of correlation between the different set of parameters, while Principal Component Analysis "PCA" was applied to identify the group of stations that were supposed to have similar properties relying on the measured variables.

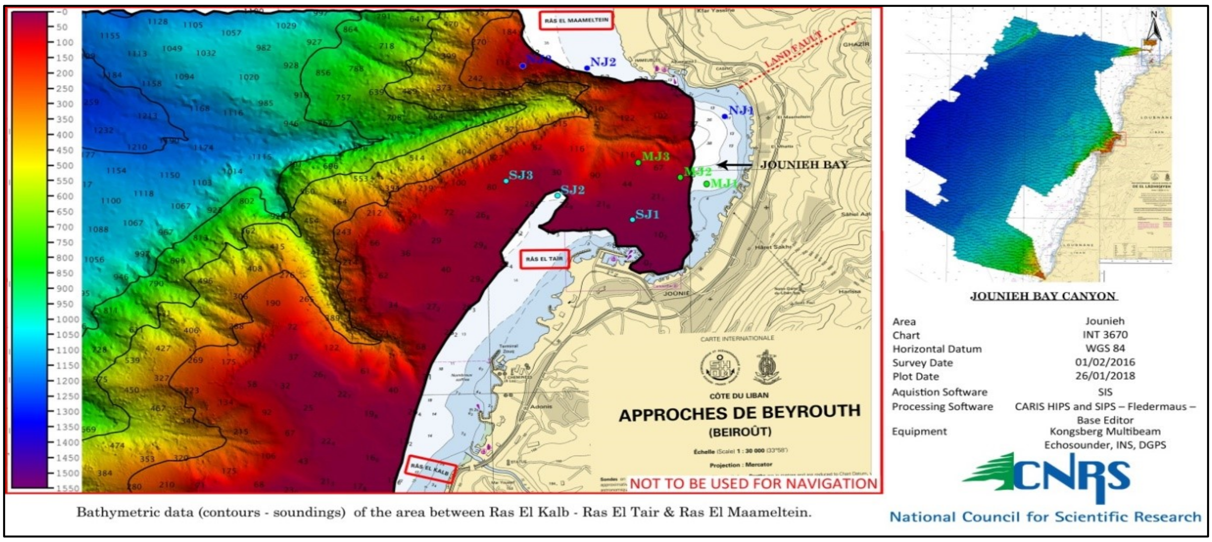


Fig. 5-1. The bathymetry of Jounieh Bay including the sampling sites at the 3 transects.

Table 5-1

Coordinates, depth and redox status of the sampling points in the Bay of Jounieh

Station	Latitude N	Longitude E	Depth (m)	Sediment Eh(mV)
NJ1	34º00.501’	35º38.399’	15m	103
NJ2	34º00.976’	35º37.050’	30m	31
NJ3	34º01.017’	35º36.407’	60m	-100
MJ1	33º59.895’	35º38.199’	15m	80
MJ2	33º59.958’	35º37.946’	30m	-188
MJ3	34º00.105’	35º37.531’	60m	-126
SJ1	33º59.576’	35º37.456’	15m	-72
SJ2	33º59.815’	35º36.719’	30m	-65
SJ3	33º59.955’	35º36.212’	60m	-127

5.3. Results

5.3.1. Grain size composition

At the northern transect the sediments of NJ1 sampling point (15m depth) were mainly made up of medium sand and fine sand fractions (42% and 46% respectively). At NJ2 (30m depth) the sediments were dominated by fine sand (75.3%) with only 8.9% of fine fractions. The deepest sampling point, NJ3 (60m depth), was exclusively composed of fine fractions (100%).

Through the middle transect, the sediment grain size composition at MJ1 was distributed between fine sand (55.9%), medium sand (23%) and coarse sand (20.7%). Similar to the northern section, MJ2 was dominated by fine sand (88.3%) with only 1.2% of fine fractions and MJ3 was totally composed of fine fractions. In the southern transect, the two shallower sampling points SJ1 and SJ2 were mainly composed of fine sand, 94.7% and 83.3% respectively, while fine fractions totally dominated SJ3 (Fig. 5-2).

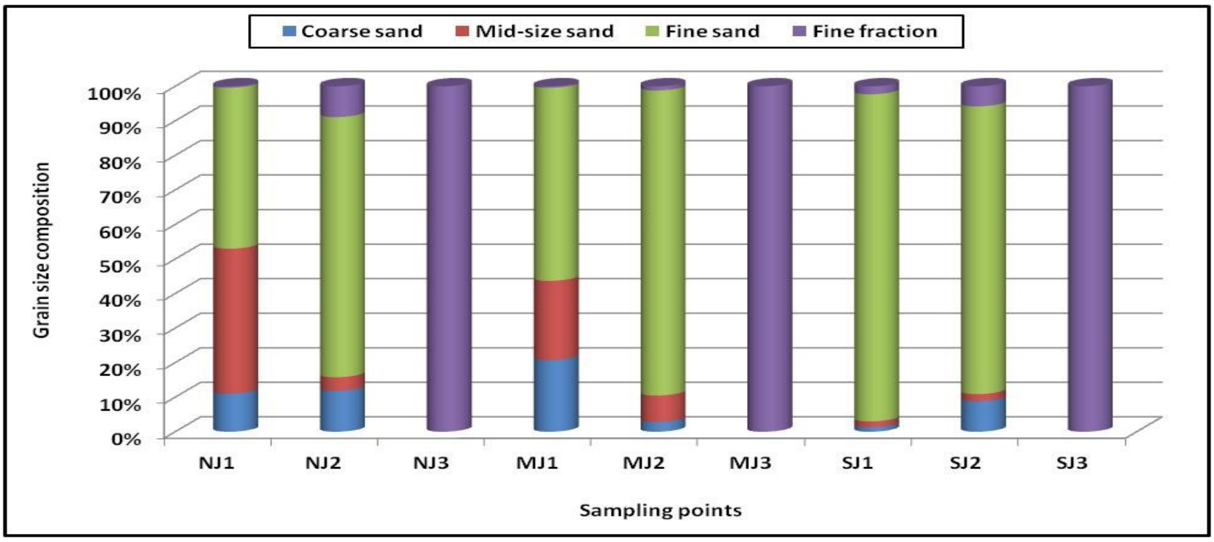


Fig. 5-2. Grain size composition of sediments of Jounieh Bay.

5.3.2. Organic Matter

The distribution of organic matter in sediment followed the same trend along the 3 transacts and its percentage increased with depth, the lowest value (0.22 ± 0.05) was recorded at MJ1 and the highest 2.97 ± 0.12% at SJ3 (Fig. 5-3).

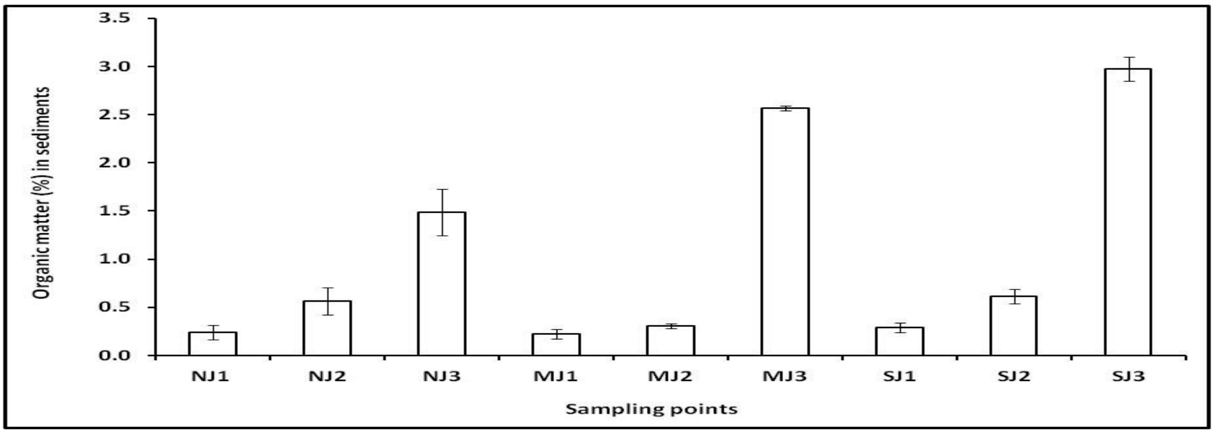


Fig. 5-3. The percentage of organic matter (± SD) in the sediments of Jounieh Bay.

Chlorophyll-*a*, pheopigments & chl-*a* /pheo Ratio:

At the northern transect, the concentration of chlorophyll-a decreased from 1.17 µg/g in the sediment of NJ1 to 0.57 µg/g at NJ3. The concentration at the southern transect decreased also with depth from 2.44 µg/g at SJ1 to 0.7 µg/g at SJ3. At the middle transect the concentration increased from 1.44 at MJ1 to 2 µg/g at MJ2 then decreased again at MJ3 (1.34 µg/g).

Through the 3 transects the concentrations of pheopigments showed a constant increase with depth. The lowest value (0.33 µg/g) was measured at NJ1 and the highest (7 µg/g) at MJ3. The chl-*a*/pheo ratio decreased with depth through all transects. At 15m depth it was >1 with maximum value of 11 at MJ1 while at 30 and 60m the ratio was < 1 (Fig. 5-4)

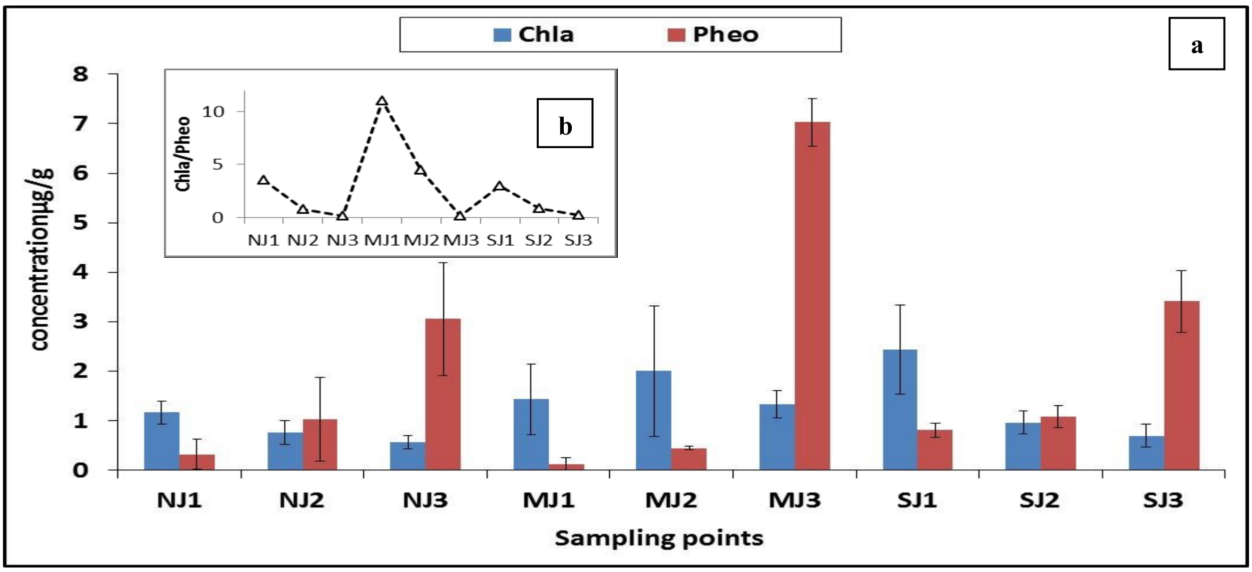


Fig. 5-4. (a)The concentrations of Chlorophyll-*a* and pheopigments (± SD) and (b)The Chla/Pheo ratio in the sediments of Jounieh Bay.

Calcium carbonate:

The percentage of calcium carbonate increased with depth in all transects, the lowest percentage of calcium carbonate 12.5 ± 0.2% was recorded in the sediment of MJ2 and the highest value of 48 ± 8% at NJ3. The northern transect seems to contain more $CaCO_3$ than the 2 others (Fig. 5-5).

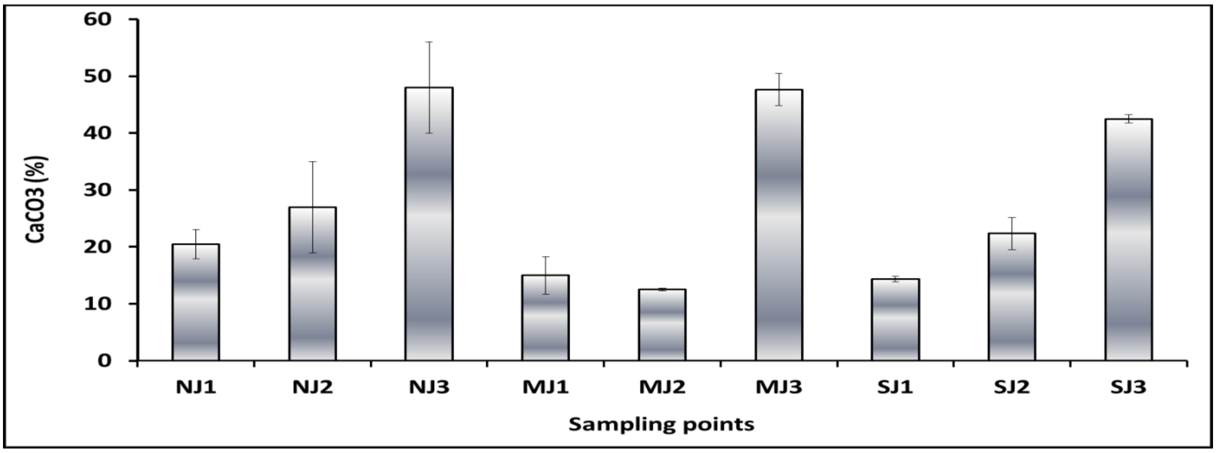


Fig. 5-5. The percentage of calcium carbonate (± SD) in the sediments of Jounieh Bay.

Total phosphates:

The concentrations of total phosphate followed the same trend through the 3 studied transect by increasing with depth. They ranged between a minimum value of 39 ± 1 µg/g at NJ1 to a maximum value of 264 ± 28 µg/g at MJ3 (Fig. 5-6).

The inorganic fraction seems to dominate the total phosphate in the sediment of Jounieh Bay, except at MJ3 with a dominance of organic phosphate of 52% (Fig. 5-7).

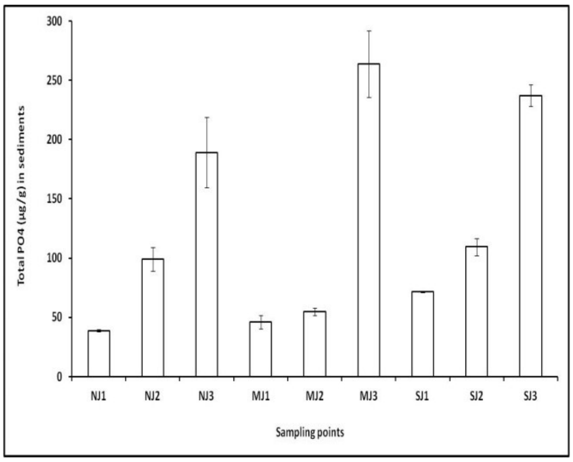


Fig. 5-6. Total phosphate (± SD) in the sediments of Jounieh Bay.

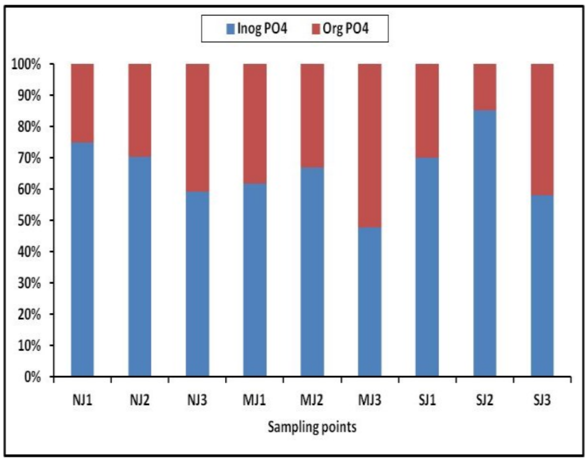


Fig. 5-7. Distribution of the percentages of inorganic and organic phosphate in the sediments of Jounieh Bay.

Labile fraction: Proteins, Carbohydrates & Lipids

The concentrations of proteins were low in the sediments of the whole Bay of Jounieh. The comparison among transects showed that the northern one contained the least of proteins concentrations (0.009 to 0.025 mg/g) and the southern transect contained the most (0.016 to 0.053 mg/g) (Fig. 5-8a). Like for the proteins, the sediments of Jounieh Bay were found to be poor in carbohydrates.

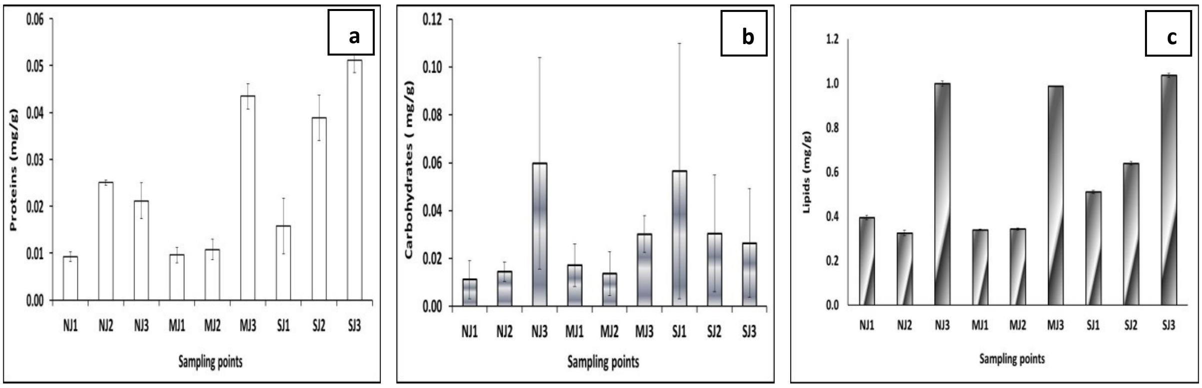


Fig. 5-8. The concentrations (± SD) of: (a) proteins, (b) carbohydrates, (c) lipid in the sediments of Jounieh Bay

Through the northern transect, the concentrations of carbohydrates increased from 0.011 mg/g at NJ1 to a maximum of 0.06 mg/g at NJ3. On the contrary, through the southern transect, carbohydrates concentrations followed a descending trend while proceeding offshore (0.057 mg/g at SJ1 to 0.026 mg/g at SJ3). The middle transect contained the least of carbohydrates (Fig. 5-8b). The labile fraction was well represented by lipids in the sediment of Jounieh Bay. The 3 transects showed almost similar distribution of lipids with depth with a small advantage for the southern transect, which showed the highest concentrations (from 0.510 mg/g at SJ1 to 1.036 mg/g at SJ3 (Fig. 5-8c).

Proteins/Carbohydrates (PRT/CHO) & Lipids/Carbohydrates (LPD/CHO) Ratios:

Table 5-2

Proteins/Carbohydrates & Lipids/Carbohydrates ratios in the sediments of Jounieh Bay

Stations	PRT/CHO	LPD/CHO
NJ1	0.82	35.25
NJ2	1.72	22.36
NJ3	0.35	16.71
MJ1	0.56	19.69
MJ2	0.79	24.95
MJ3	1.44	32.70
SJ1	0.28	9.02
SJ2	1.27	20.97
SJ3	1.94	39.20

The proteins/carbohydrates ratio varied between 0.28 and 1.94, while the ratio lipids/carbohydrates ratio fluctuated between 9.02 and 39.20 (Table 5-2).

Application of principal component analysis

The Principle Component Analysis (PCA) revealed the presence of two main components: the first component (Dim1) explains 69% of the total variance while the second component (Dim2) represents only 14%. The principal plan of the stations (Individuals' graph) represents the gathering of sampling points with similar properties according to the first two principal components (Fig. 5-9). The second plot represents the variables factor map (circle of correlation) and shows the distribution of all the variables according to the two components (Fig. 5-10).

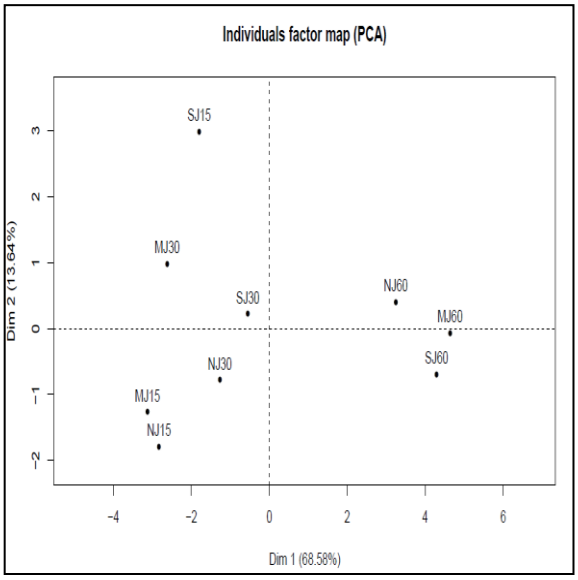


Fig. 5-9. The principle plan of the stations (Individuals) in Jounieh Bay.

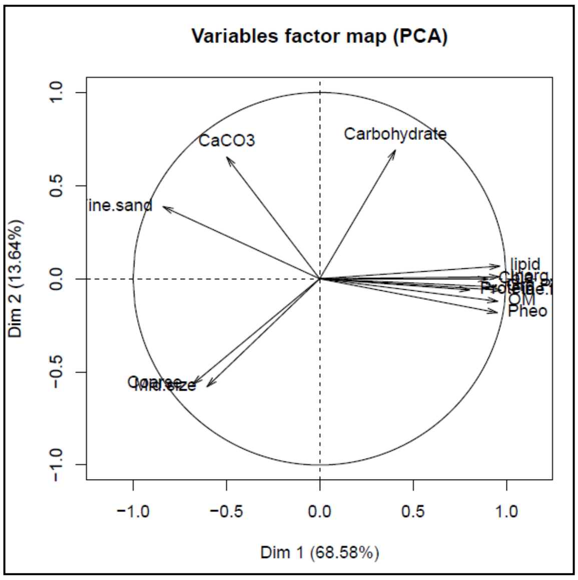


Fig. 5-10. Variable factor map of the parameters in the marine sediments of Jounieh Bay.

5.4. Discussion

As expected, while moving deeper the size of particles decreases and the percentage of fine fraction increases to be 100% at 60m. The hydrodynamic factors seem to play a major role in the distribution and deposition of particles, carrying the lighter particles away from the coast. The accumulation of fine particles is accompanied with negative low redox potentials (Table 5-1). This reduced state of sediments shows the presence of anoxic environment, translated by the black colour and hydrogen sulphide smell (Fakhri et al., 2008).

The values of organic matter detected in the Jounieh Bay were within the normal range usually measured in coastal marine areas. The increase of organic matter gradient with depth might be related to the dominance of the fine sedimentary fractions at the deepest sites and its capacity in creating more anoxic environment by preventing the oxidation of organic matter leading to its preservation (Lazar et al., 2012). A strong correlation appeared to exist between the concentrations of organic matter and the percentage of fine fraction ($r=0.94$, $p<0.001$, $k=16$).

The effects of hydrodynamic factors combined to the narrowness of the continental shelf inside the bay might be responsible for the redistribution of the suspended particles deriving from the sources of pollution extending along Jounieh coast and the transfer of fine particles containing organic matter from shallower into deeper depth levels (MoE/UNDP, 2011). It is known that the wave action is a principal hydrodynamic phenomenon responsible for the bottom sedimentary processes (Furtado and Mahiques, 1989) and turbidity currents redistribute the trapped organic matter into deeper levels (Buscail et al., 1995).

The low concentrations of chlorophyll-*a* in the sediments of the Bay of Jounieh might be related to their degradation into pheopigments. The predominance of pheopigments mainly in deep sediments might be attributed to strong anthropogenic stresses that impact the photosynthetic potential of the primary producers (Renjith et al., 2013). When referring to chlorophyll-a/pheopigments ratio as an indicator used for assessing the quality and freshness of organic matter (Misic and Harriague, 2013), it shows that the highest ratio at MJ1 indicates that this site is less perturbated and contains fresh organic material while the lowest ratios at NJ3, MJ3 and SJ3 showed the presence of stressed cells and accumulated old organic matter proved by the strong correlation that was established between fine fraction and pheopigments ($r=0.85$, $p<0.001$, $k=16$) and organic matter and pheopigments ($r=0.86$, $p<0.001$, $k=16$).

Calcium carbonate and phosphate were found to accumulate in the sediment of deepest sampling points. The fine fraction that is dominating the line of 60m is strongly correlated with calcium carbonate ($r=0.94$, $p<0.001$, $k=16$) and total phosphate ($r=0.90$, $p<0.001$, $k=16$). The increase in calcium carbonates concentrations may be attributed to the decomposition and the sinking of the shells and some aquatic organism such as Coccolithophores, foraminifers, gastropods and bivalves (Karageorgis et al., 2004) while the accumulation of total phosphate may be related to the discharge of domestic, agricultural and industrial waste water. But it is necessary to mention that high concentrations of phosphate do not always lead to eutrophication (Correll, 1998) but may, till certain limits, influence positively the living organisms by providing a fertilizing agent for their proliferation (Fakhri et al., 2013).

The labile fraction represented by proteins, carbohydrates and lipids, was used to determine the nutrition values of the sediments of the Bay of Jounieh. The low concentrations of proteins showed that the bay might be considered a productive marine area. Low concentrations of proteins at 15 and 30m depth may indicate either their rapid utilization by benthic organisms or the low input of organic matter (Sane et al., 2012). Since the 60m depth contained additional proteins, it could be related to recently deposited organic matter or to partially degraded organic matter derived from both primary production and anthropogenic source (Garcia-Rodriguez et al., 2011).

The low concentrations of total carbohydrates may indicate the high nutritive aspect of organic matter in the Bay of Jounieh and their freshness since carbohydrates show aged and refractory nature (Renjith et al., 2013).

In comparison with proteins and carbohydrates, the high concentrations of lipid might be linked to the presence of leisure ports, boats, human wastes (Fichez, 1991a) or due to the association with hydrophobic organic micropollutants (Silva, 2011). Actually, the lipids bulk may also include non-autochthonous compounds, such as hydrocarbons, because the methods used to extract lipids from sediments may also recover significant quantities of organic contaminants (Galois et al., 2000) thus, overestimating the real trophic quality. This fraction may be responsible for the significant increase in the lipids concentrations (Misic et al., 2013).

The high concentrations of lipids may also show the presence of an energetic source in nutrition for heterotrophic metabolism in sediments (Fichez, 1991b). The decomposition of this high energetic compound is delayed in an oxygen–restrictive condition (Carreira et al., 2002) (Pinturier-Geiss et al., 2002) as in almost all sampling points except NJ1, NJ2 and MJ1. This may be an additive factor for the high concentrations of lipids leading to its preservation under highly anoxic conditions. Moreover, there was an important effect of the depth on lipids, since the p-values of lipids 0.042 was smaller than the significance level ($\alpha = 0.05$) in a two-way ANOVA without repetition analysis, while all the other variables showed no significant difference with depth. In addition, there were no correlation recorded in the matrix of correlation between biochemical labile compounds and chlorophyll-*a* and this may indicate a higher contribution of allochthonous materials of anthropogenic origin and a lower contribution of phytobenthic population (Cotano and Villate, 2006).

High PRT/CHO ratios might be related to the arrival of anthropogenic wastes. They showed the contribution of fresh organic matter since protein is usually mineralized faster than carbohydrates by bacteria. For that only, fresh compounds show high index of PRT/CHO (Cotano and Villate, 2006) especially when the PRT/CHO ratio ranges from 0.2 to 1.94 indicating that the sediments were characterized by fresh organic matter (Kumar et al., 2013).

The low protein/carbohydrate ratios that are below 1 suggest the presence of aged organic matter. This ratio ranges from lower than 0.1 in oligotrophic Eastern Mediterranean Sea sediments (Danovaro et al., 1993) to higher than 10 in coastal Antarctic sediments (Pusceddu et al., 1997). Hence the values in Jounieh Bay are higher than the case of an oligotrophic state. Values of the proteins/carbohydrates ratio>1 are associated with recently produced organic matter from different non-source points.

The LPD/CHO ratio is a useful index of energetic (food) quality of the organic matter. High LPD/CHO ratio indicates high quality of labile organic matter to support benthic fauna. Higher PRT/CHO and LPD/CHO ratios provided evidence of high nutritional value as well as the freshness of labile organic matter (Renjith et al., 2013).

Dell´Anno et al. (2002) defined meso-oligotrophy for protein concentrations<1.5 mg/g and carbohydrate concentrations<5 mg/g. In Jounieh Bay, the concentrations of protein and carbohydrate ranged from 0.009 mg/g to 0.051 mg/g and from 0.011 mg/g to 0.06 mg/g, respectively. According to this classification, the trophic condition of Jounieh Bay is considered meso-oligotrophic. In spite of the continuous exposure of different sources of contaminants, nutrient loads from sewage outfall, industrial installations, leachates from fertilizers and leisure boats, the Bay of Jounieh is still able to adapt and provide nutritive values that are acceptable for primary production and benthic organisms within it.

The circle of correlation shows that the first principal component, which contributes with 69% of the total variance, gives significant loadings on fine fraction, organic matter, chlorophyll-*a*, pheopigments, inorganic phosphate, organic phosphate, proteins, lipids and depth. All the latter parameters are clustered on the positive side of this component, while coarse, mid-size and fine sand are distributed around its negative side. Hence the first principal component shows that the texture and anthropogenic perturbations allowed for the accumulation of all these parameters together. The position on the individuals factor map of the first group of sites (NJ3, MJ3 and SJ3) that have the highest concentrations for almost all parameters, confirmed that the 60m depth (rich with fine fraction in all transects) is mostly affected by the anthropogenic activity. The shallower points, at 15 and 30m, are less contaminated and are found on the negative side of the first component. The sampling points at 30m in the northern, middle and southern transact (NJ2, MJ2 and SJ2) constitute a group with probably similar properties. For the shallow depth, 15m, is split into 2 groups, one contains NJ1 and MJ1 and located on the negative side of the second component and another contains SJ15 alone located on the positive side of it. This SJ1 sampling point, which contains the second highest concentrations of carbohydrates in the whole bay, seems not to be affected by the potential sources of runoff, but varied according to the sediments mineralogy since it is affected by calcium carbonate (Youssef et al., 2014) as presented in the circle of correlation. Carbohydrates can serve in the composition of the component storage in marine and terrestrial organisms as well as in the transport of organic matter from the surface to greater depths. According to Bohm (1973), polysaccharides are accompanied by carbonate skeleton sediments.

5.5. Conclusion

Sediment is a memory recorder to all interactions that occur in an aquatic environment. In this study, the evaluation of the geochemical, physical, chemical and biochemical characteristics of sediments from 3 different depths defined the trophic level of Jounieh Bay by being a meso-oligotrophic system, a moderate environment helpful for benthic organisms. The deepest sampling points at 60m were found to be more contaminated than the shallower ones at 15 and 30m in all the studied transects and they behaved as a sink for the fine fraction on which organic and mineral compounds are usually adsorbed.

The labile fraction of organic matter was exclusively dominated by total lipids and the low concentrations of organic matter, chlorophyll-*a*, pheopigments, total phosphate and the highest percentages of calcium carbonate in the northern transect revealed that this transect is the least stressed part of the Bay where shell animals may be able to grow. The middle and the southern transects are considered perturbed areas, more affected by terrestrial sources of contamination with particularly high values of lipids.

More samples are to be collected in order to follow-up the concentrations of all studied parameters because this case has a tendency to develop into an eutrophic if no treatments are implemented. As well, it is crucial to determine the levels of some toxic pollutants in the sediment matrix of the whole Bay such as trace metal elements, polycyclic aromatic hydrocarbons and microplastics.

6. Chapter 6: Sediment deposit dynamics along and across the Lebanese continental shelf and slope

6.1. Introduction

Submarine canyons are widespread complex features along continental margins and are pathways for sediment transport to the deep basins (Piper and Savoye, 1993) (Wynn et al., 2007) (Palanques et al., 2012). They play a key role in hydrography, biogeochemistry and carbon cycle dynamics (Epping et al., 2002) (Canals et al., 2000) (Huvenne et al., 2011).

This paper is devoted to a morphological characterization of the Lebanese seafloor in Jounieh area North Beirut following a hydrographic approach. This area is poorly explored; the offshore coastal strip is characterized by a very narrow continental shelf, crossed by deep canyons that, after a short distance from the coast, go down to depths of 1000 meters. The seabed topography is a continuation of inland geomorphology marked by a nearly absence of the coastal plain on which the main Lebanese cities have developed, and by a steep mountain belt exceeding in elevation 3000 meters away 20 km from the coast. The submarine canyons are nothing else than the continuation of steep inland valleys which correspond to active tectonic faults. Although being an important subject, the processes of creation, evolution and maintenance of canyons remain unsatisfactorily understood.

Offshore western Lebanon (Eastern Mediterranean Sea), high resolution bathymetric data deriving from full multi-beam coverage have revealed a dense network of submarine canyons with depths ranging from 80 to 1400m, across a wide range of morphological settings. The main aims of this work are: (1) to describe the morphologies of submarine canyons mapped in the Gulf of Jounieh, (2) understand the sediment deposit dynamics along and across the Lebanese continental shelf and slope through a morphological characterization and terrain attribute generation (slope and rugosity) following a hydrographic approach, integrated with a sediment map classification (Backscatter calibrated with ground truthing), (3) unveil the steepness of slope and canyon walls which are known as an important factor controlling the location and volume of submarine failures.

6.2. Project Settings

The Western Lebanese continental margin, in the eastern Mediterranean Sea, extends from the Lebanese coastal belt up to 12.5 km west. The Jounieh Bay canyon is aligned with a prominent land valley near the center of Jounieh Bay and has a northern tributary which is roughly in line with an important fault and shear zone near Ras El Maameltein (Goeddicke and Sagebiel, 1973) (Fig. 6-1). The red rectangle (A, Fig. 6-1) shows the location of study area between Beirut and Jounieh, detailed in (B, Fig. 6-1), where high resolution full coverage multibeam data are represented in the area north of Beirut to Jounieh bay with depths range from tens to thousands of meters; it demonstrates also the complex morphology of the area varying from gullies to canyons. The cyan rectangle (C, Fig. 6-1) highlights: Jounieh and Nahr El Kalb canyons signalled by two blue navy rectangles, which share (red circle) the same mouth at 1000 m depth, the inshore red line representing the active normal fault mapped in the area of Ras El Maameltein (Goeddicke and Sagebiel, 1976), and a black line which represents the direction of the morpho-structural section in crossing: (1) Middle Jounieh canyon from N-NW to S-SE, (2) between canyons continental shelf part from NE to SW, (3) Head Nahr El Kalb canyon from NE to SW. The Metadata of the survey project (D, Fig. 6-1) illustrates specially the 2 agencies' Logos; SHOM (Service d'Hydrography et Oceanography de la Marine Française) and LNHS (Lebanese Navy Hydrographic Service).

The study area corresponds to a micro-tidal setting, with maximum tidal height of 0.25m above sea level (a.s.l.) (Lebanese Navy Hydrographic Service, LNHS, 2017), mainly dominated by sporadic winter storms coming from the W-SW and N sectors (Astraldi et al., 2002). High energy events have a low recurrence period, occurring during 3% of the year, with maximum wave heights of 4–5m and periods of 6s. The surface salinity varies from 37.6‰ to 38.2‰ between winter and summer. The surface currents follow an anticyclonic regime parallel to the coastline from west to east with maximum velocities of 0.9 knots.

Hydrological data indicate that over 2,525 × 10^6 m^3 of surface-water runoff annually discharge into the sea through the perennial streams of western Lebanon. Preliminary work suggests that these contribute in appreciable loads into the Mediterranean. Overall, marine net sediment transport is directed northwards by the alongshore current and predominant WSW waves, but investigations in progress indicate that the submarine valleys provide avenues for across-the-shelf and down-slope movement of this sediment.

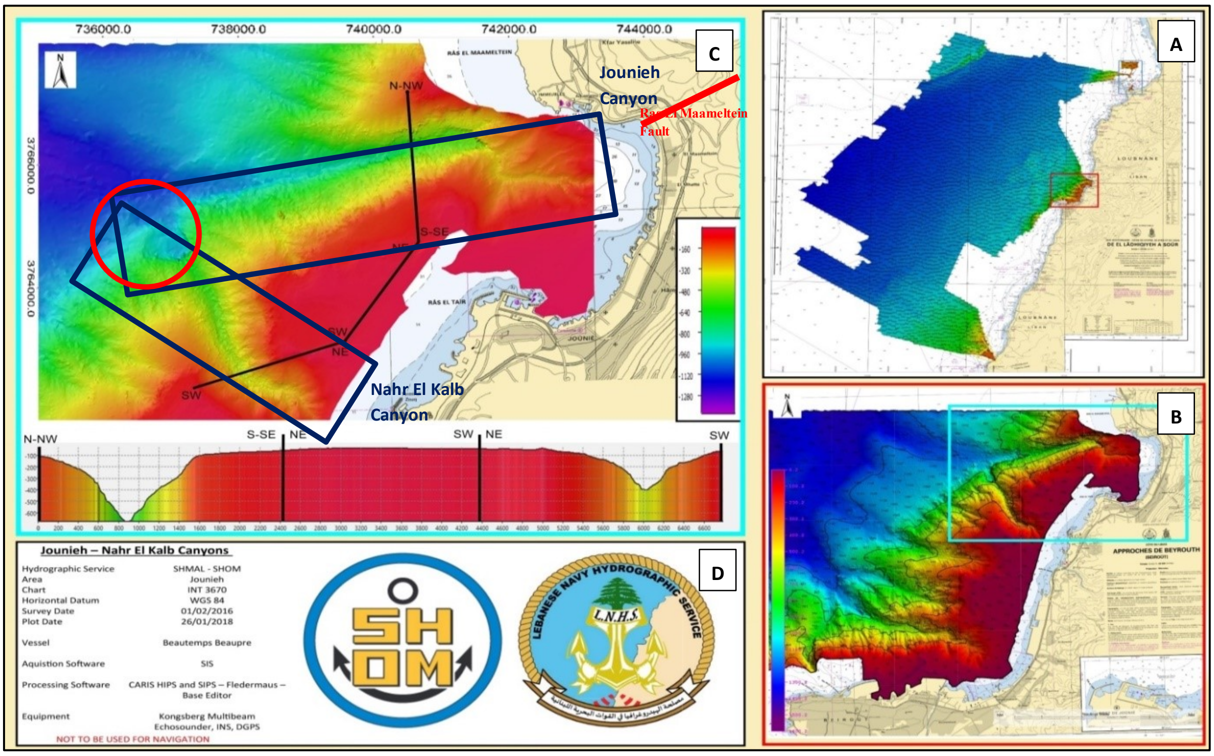


Fig. 6-1. Bathymetric data available at western Lebanese Coast at different scales (A, B & C) showing the location of study area between Beirut and Jounieh.

6.3. Materials and methods

Swath-bathymetry MultiBeam EchoSounder (MBES) data were acquired during a combined hydrographic cruise in February 2016 (Fig. 6-1), between SHOM and LNHS. The bathymetric survey in Lebanon was conducted using EM122 and EM1002 multibeam sounders on the BHO Beautemps-Beaupré covering depth range between 100-12000m and using the EM2040C multibeam sounder on the HV Cormoran and Pelican covering depth range between 0-200m. The adopted configurations are detailed in table 6-1. The data is corrected in real time from the installation parameters (lever arm and relative orientations between sonar transducer, GNSS antennas and inertial unit) and sonar calibration.

The bathymetry data were processed using the CARIS HIPS & SIPS 7.1 software. Echo sounds were examined by a hydrographer for manual invalidation of the errors and artefacts in the CARIS HIPS & SIPS Subset Editor. A performance check of multibeam echo-sounders was conducted in December 2015 and January 2016. At the date of this last check, the conformity of the systems with the orders of the IHO Standard for Hydrographic Surveys (S-44) (5th Edition), has been verified on a reference area for EM122, EM1002 and EM2040C. Post-processing steps included the removal of erroneous beams, noise filtering, processing of navigation data and correction for sound velocity. Digital Bathymetric Models (DTMs) were produced with a foot print resolution of 3m. Base Editor Software from CARIS and Fledermaus software from QPS were used to obtain 3D maps of the bathymetric data, shaded relief maps, slope maps and bathymetric profiles.

Table 6-1

The adopted configurations for different sensors used for the mission.

Instrument	Survey asset	Profil type	Method and frequencies	Swath angle	Speed of survey
MBES EM122	BHO	Winglines & Crosslines	Auto-Equidistant	$2*45^{o}$ to $2*65^{o}$	Between 6 & 12 knots
MBES EM1002	BHO	Winglines	Auto-Equidistant	$2*60^{o}$ to $2*65^{o}$	Between 6 & 12 knots
MBES EM1002	BHO	Crosslines	Auto-Equidistant	$2*45^{o}$	8 knots
MBES EM2040C	HV	Winglines	Auto-HD-Equidistant-300 kHz	$2*60^{o}$	Between 5 & 6 knots
MBES EM2040C	HV	Crosslines	Auto-HD-Equidistant-300 kHz	$2*45^{o}$	Between 5 & 6 knots
MBES EM2040C	HV	Research	Auto-HD-Equidistant-300 kHz	$2*30^{o}$	Between 5 & 6 knots

6.4. Morphology

Throughout the study area, we describe two canyons systems with same morphologies but of different sizes: the canyon of the Gulf of Jounieh or Jounieh canyon which shares the same mouth with canyon of Nahr El Kalb (C, Fig. 6-1). Both canyons are characterized by a variable extension of the continental shelf, different gradients of the continental slope and different river networks discharging sediments in the shelf. Bathymetric transects from the Jounieh and Nahr El Kalb canyons outline a difference in the extension and morphology of the shelf-upper slope systems (Fig. 6-2). Across the Jounieh and Nahr El Kalb canyons, an abrupt change of slope due to tectonics, at a depth of 400m and 600m respectively, (Fig. 6-2) separates graduate shallow sector to steep slope at different depths.

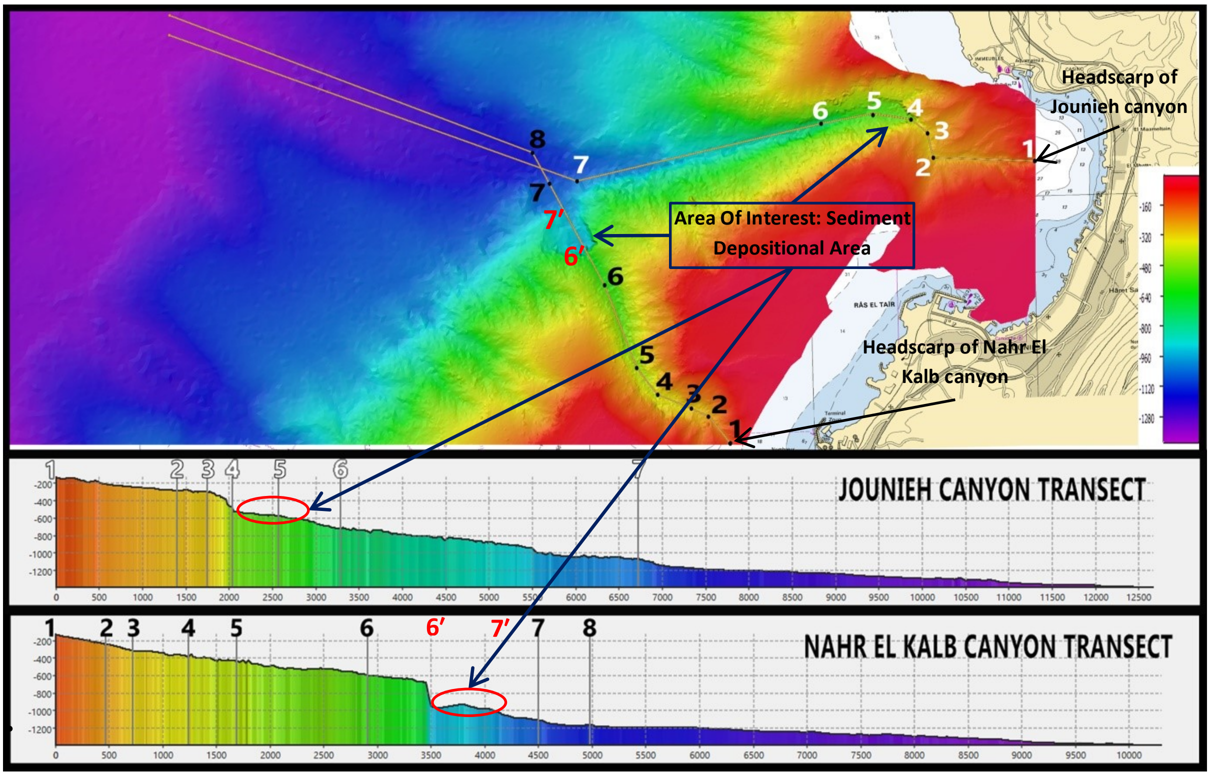


Fig. 6-2. High resolution full coverage multibeam data covering the area of study, reaching 1400 m depth; Jounieh and Nahr El Kalb canyons morphologies are represented and sharing the same mouth at (7).

6.4.1. Jounieh canyon morphology

The present-day, Jounieh Submarine Canyon (Fig. 6-2) is composed of: (1-2-3) a narrow (up to 1.2 km) and steep head (up to 12%) incised in the continental shelf, with the edge between -60m and -70m; (3-4) a very steep (up to 40%) upper Middle canyon (Area of Interest: sediment depositional area) ranging in water depth from 300 to 500m, in less than 250m distance; (4-5-6-7) a steep (up to 11%) lower middle canyon in water depth from 500 to 1100m extended to 4.75km; (7-…) an upper distal canyon, wider and gentler (up to 5%) than the upper slope, in water depth from 1100 to 1400m extended over 5.75km.

6.4.2. Nahr El Kalb canyon morphology

The present-day, Nahr El Kalb Submarine Canyon (Fig. 6-2) is composed of: (1-2-3) a narrow (up to 1.5 km) and very steep head (up to 26%) incised in the continental shelf, with the edge between -75m and -100m; (3-4-5-6) a steep (up to 18%) upper Middle canyon ranging in water depth from 300 to 700m, extended over 2.75km; (6') a very steep (up to 80%) lower middle canyon (Area of Interest) in water depth from 700 to 1000m, in less than 50 m distance; (7') a deposit of "Slumping" sediment to be analysed (Area of Interest); (7'-7-8-…) an upper distal canyon, wide and gentle (up to 6%), in water depth from 1000 to 1400m extended over 6km.

6.5. Marine geo-morphometric analysis

Geo-morphometric techniques were applied at Jounieh and Nahr El Kalb submarine environments (Lecours et al., 2016). In the study of submarine mass movements, the general approach is the prior identification of the landslides′ boundaries, the measurements of a series of morphometric parameters and their spatial and statistical analyses. The use of specific geo-morphometric techniques such as Slope and Rugosity, where features of interest are identified prior to analysis, has involved examining how different morphological parameters would change spatially and in function of each other.

6.5.1. Slope

The Slope scalar allowed us to compute a surface that represents the maximum slope at each grid centre of the currently loaded SD File. The generated surface has the same dimensions as the original surface file and represents the maximum slope from each cell to any of its neighbouring cells. Figure 6-3 shows the high slope percentage at middle Jounieh and distal Nahr El Kalb canyons (yellow circles) reaching 70 to 80%, putting in evidence the role of these features in sediment transportation and accumulation along canyons.

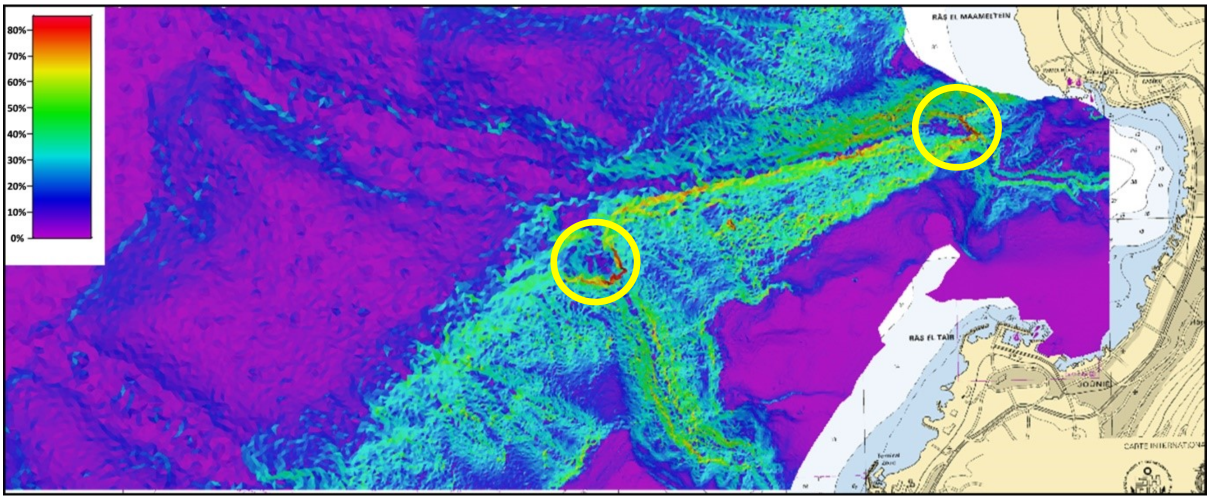


Fig. 6-3. Slope scalar calculation between Ras El Maalmetein north and Nahr El Kalb south.

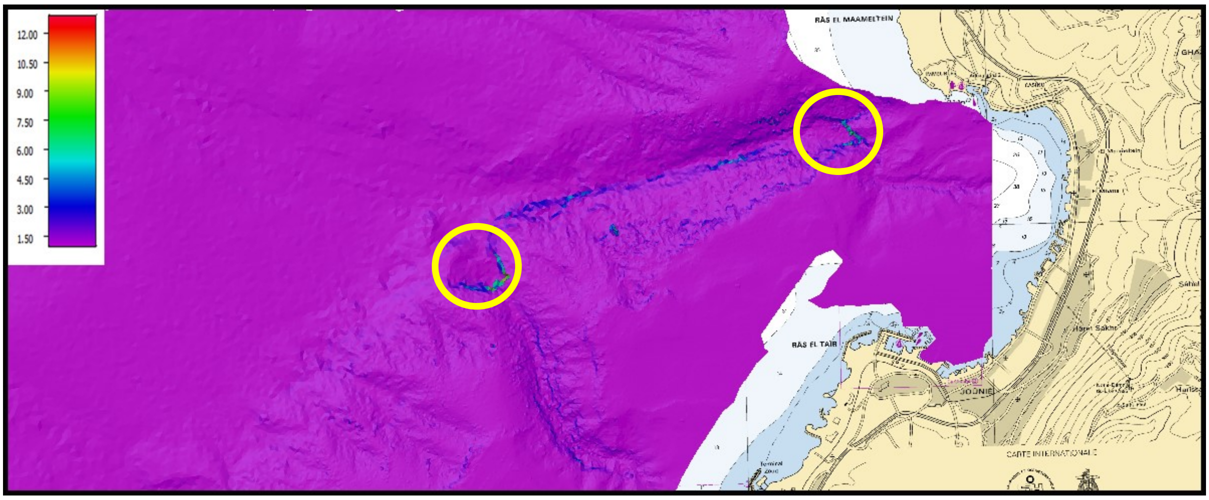


Fig. 6-4. Rugosity scalar calculation between Ras El Maalmetein north and Nahr El Kalb south.

6.5.2. Rugosity

The Rugosity scalar is the measurement of the seabed surface roughness and can be calculated and saved either attached to the SD File or as a Scalar. A value equal to 1 represents smooth seabed whereas values > 1 imply an increasing surface roughness. Areas of high Rugosity allow corals to attach and grow on higher substrata not influenced by sand and sediment movement along the bottom. Figure 6-4 demonstrates: (1) the high Rugosity at middle Jounieh and distal Nahr El Kalb canyons (yellow circles), putting in evidence the increase of seabed roughness and sediment accumulation, (2) the low Rugosity elsewhere reaching values of 1, showing the low seabed roughness and the high sediment movement in these areas.

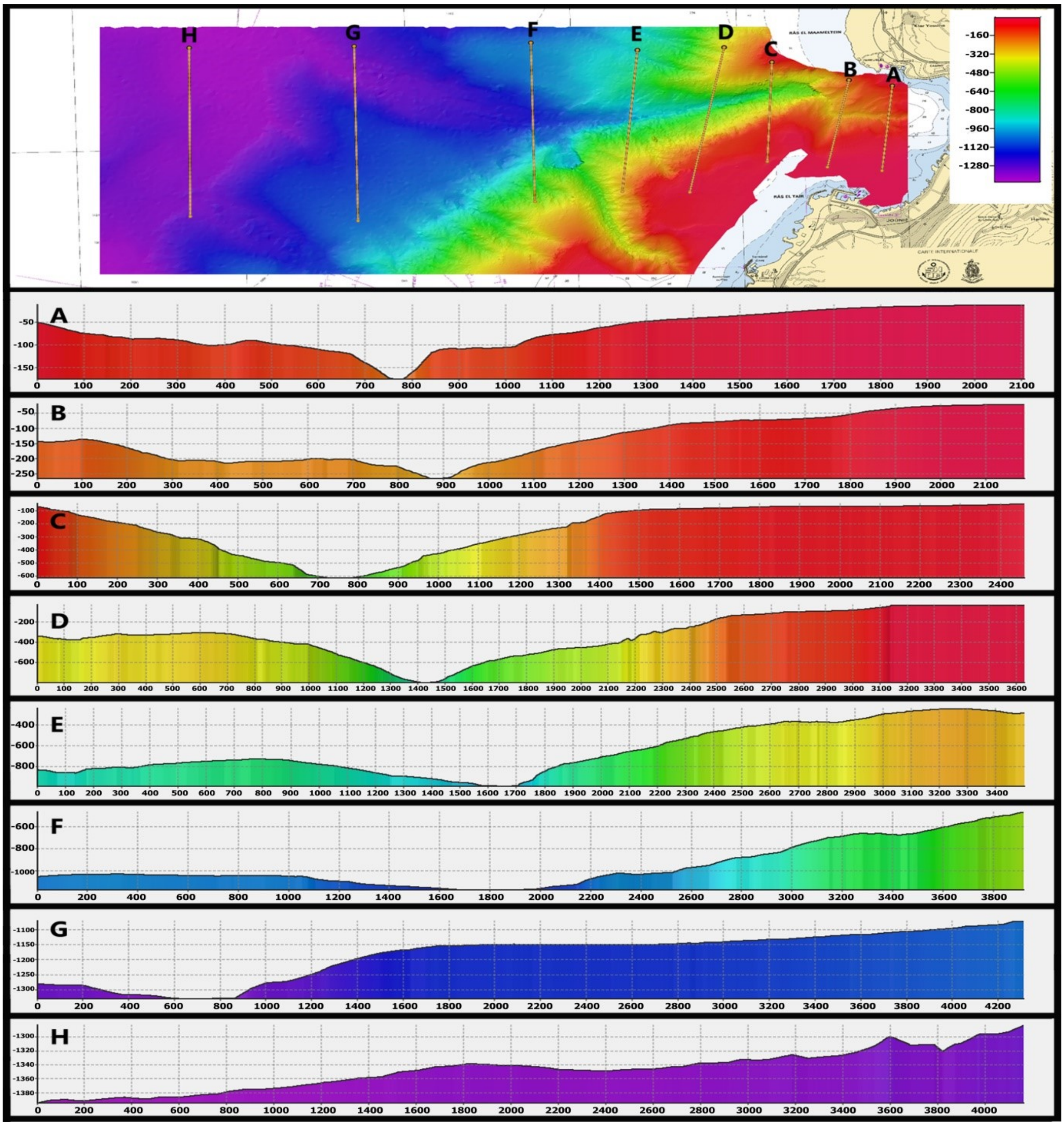


Fig. 6-5. A series of profiles from Jounieh canyon are achieved from shallower to deeper part of the canyon, putting in evidence the Thalweg and sinuosity of the canyon.

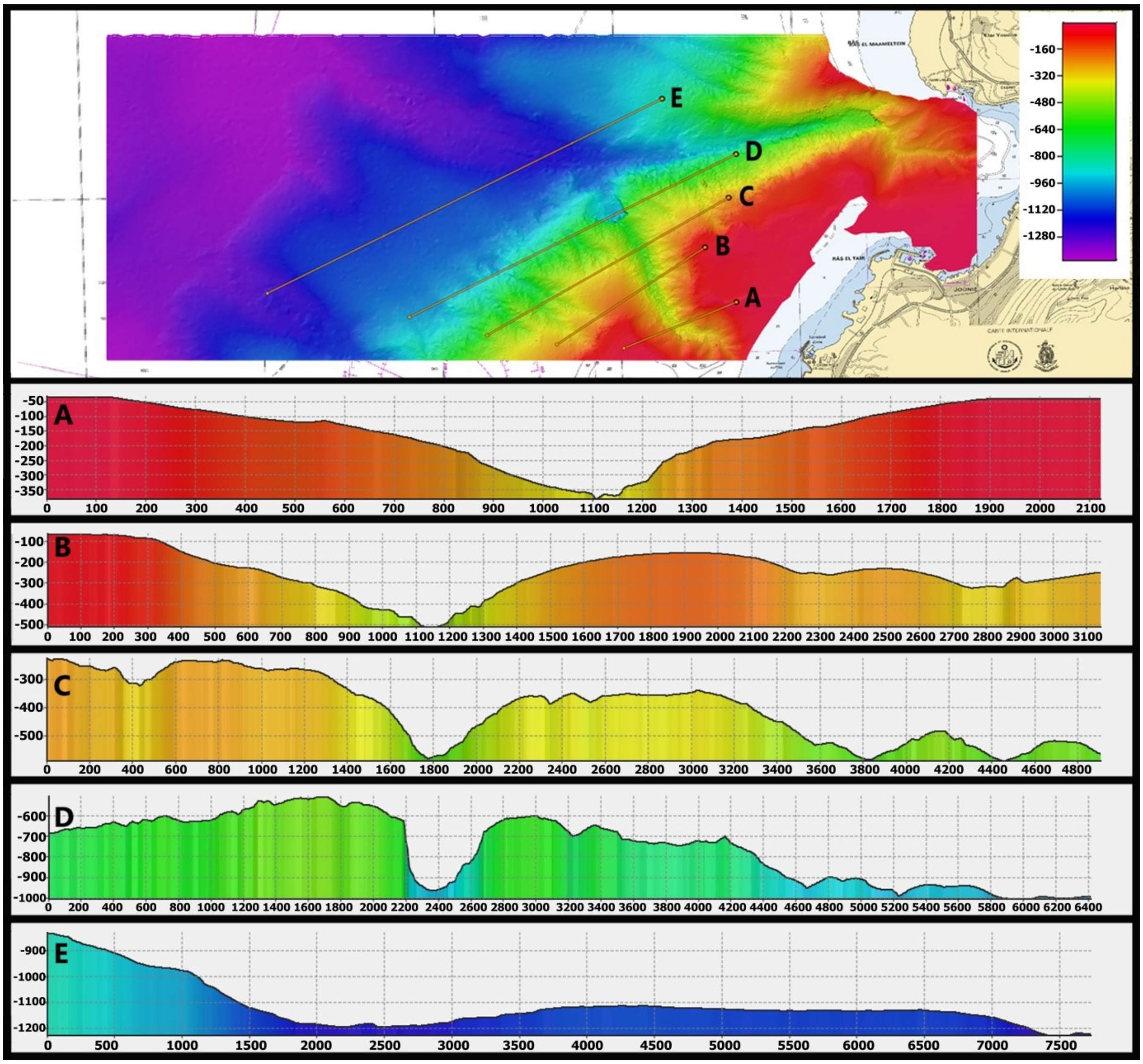


Fig. 6-6. A series of profiles from Nahr El Kalb canyon are achieved from shallower to deeper part of the canyon, putting in evidence the Thalweg and sinuosity of the canyon.

6.5.3. Morphology discussion

Three main submarine canyons have been observed along the upper slope of Beirut – Jounieh basin (Fig. 6-7). Canyons are, from the north to the south: Jounieh canyon, Nahr El Kalb canyon and Saint George canyon. The research area includes only the two first canyons, related to each other by sharing the same mouth at 1000m depth. All the canyons indent the shelf and show a more or less straight path, connecting to the sub-horizontal Beirut - Jounieh intra slope Basin (1400m depth). Canyons range in depth from 60m to 1400m and 10–12.5km in length. All the canyons display an incised Thalweg along the proximal reach, which flattens from a depth of 800m. The main morphometric parameters of the area of research are summarized in Tables 6-2 and 6-3. Both Jounieh and Nahr El Kalb canyons do not display any obstructions at all depths, probably due to the steepness of both canyons, however they mark a roughly change (will be detailed in the chapter 7, at smaller scale) between a V transversal canyon profile upslope to a U transversal canyon profile downslope at a common depth of 600m (Fig. 6-5 and Fig. 6-6). The yellow lines (Fig. 6-2) represent the direction of transects of the two canyons simultaneously. Area of interest at Jounieh (4-6) and Nahr El Kalb (6′-7′) canyons shows a sediment depositional area extending over 1km length and growing after two submarine cliffs: Jounieh submarine cliff ranging from 300 to 500 m depth and Nahr El Kalb cliff ranging from 700 to 1000 m. A drop of about hundreds of meters occurs in the AOI (Area Of Interest, Fig. 6-2), leads to an important sediment dynamics in both canyons at different depths. Profile "D" (Fig. 6-6) in Nahr El Kalb canyon illustrates the steepness of canyon walls between 700 and 1000m depth.

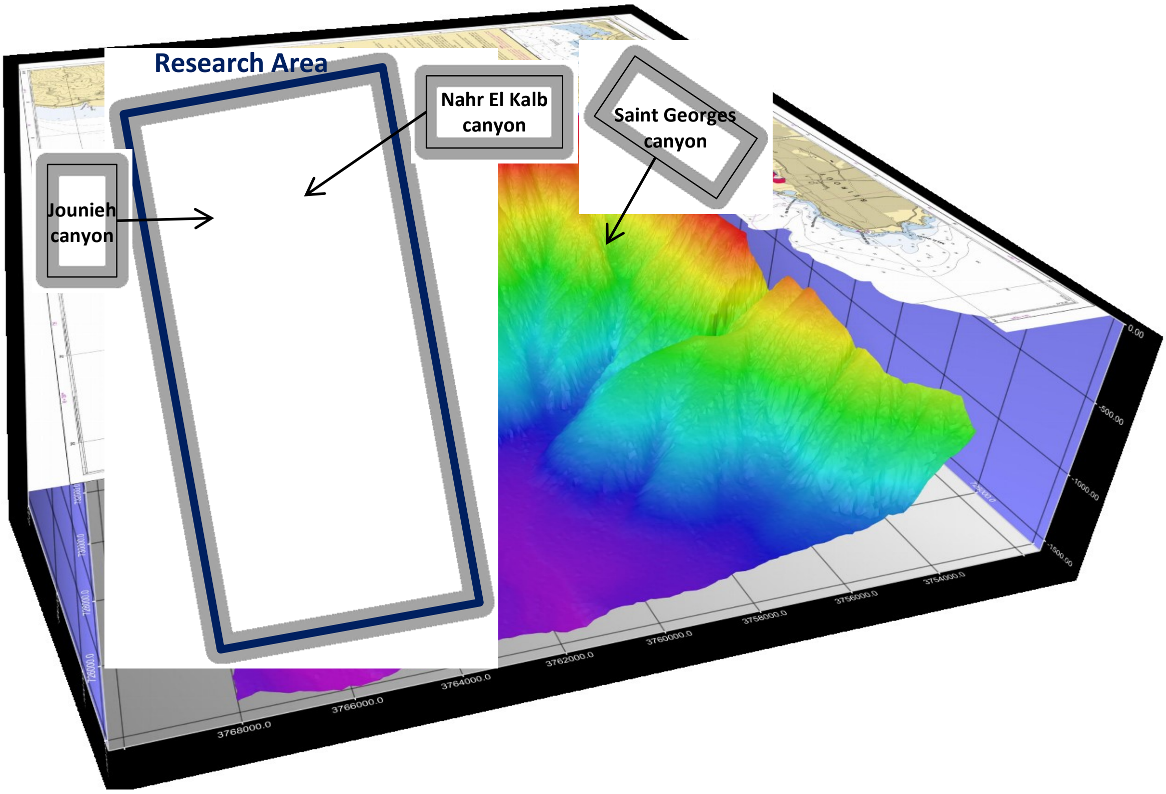


Fig. 6-7. 3D bathymetric map showing: (1) Jounieh, Nahr El Kalb and Saint Georges submarine canyons, (2) the main morpho-structures of the area extending from north of Beirut to Jounieh Bay, (3) the research area marked by a blue rectangle and (4) the red circle putting in evidence the common mouth of Jounieh and Nahr El Kalb canyons.

Morphologies within the area of research mostly indicate sedimentary processes (Tubau et al., 2015) and, in particular, longitudinal slope (Transect) can be used to determine sediment transport through the canyon. Area of Interest in both canyons demonstrates the strong correlation between slope intensity and sediment movement, and it harmonizes well (see yellow circles in Fig. 6-3 and Fig. 6-4) with the Geo-Morphometric analysis (Slope and Rugosity attributes). The high sinuosity, illustrated by a series of profiles from both canyons (Fig. 6-5 and Fig. 6-6), reveals the activity of downstream sediment flows, however more information must be known on the identity of the substrate to classify the energy flow through the canyons (Tubau et al., 2015). Slumps, scours and scarps seen in the tributaries and gullies between the 2 canyons suggest movement and flow that effect the seafloor morphology (Espinosa et al., 2016).

Table 6-2

Main morphometric values of the studied area.

Main morphometric values	Jounieh canyon	Nahr El Kalb canyon
Depth range (m)	90 – 1200	70 – 1200
Difference in water depth (m)	1110	1130
Total length (km)	12.5	10
Straight length (km)	10.5	8.75
Average slope gradient (%)	17	32
Max right flank height (m)	30	50
Max left flank height (m)	50	50
Right flank gradient range (%)	50	40
Left flank gradient range (%)	45	30
Maximum width (m)	1500	800
Distance of the headscarp from the coast (km)	1.2	1.4

Table 6-3

Calculated slopes of the north and south sides of the Main and Tributary canyons (Fig. 6-5 and Fig. 6-6).

Jounieh Canyon			
Profile	**Profile length (m)**	**South Slope (%)**	**North Slope (%)**
A	2100	45	40
B	2100	30	20
C	2400	30	35
D	3600	30	45
E	3400	30	15
F	3800	20	10
G	4200	40	5
H	4000	20	3

Nahr El Kalb Canyon			
Profile	**Profile length (m)**	**South Slope (%)**	**North Slope (%)**
A	2100	45	40
B	3100	45	40
C	4800	55	60
D	6400	70	95
E	7500	15	45

6.6. Sedimentology

6.6.1. Backscatter analysis – Sediment Map

In addition to the bathymetry, the bottom reflectivity (Acoustic Reflection) measurements were recorded by the multi-beam echo-sounders EM1002, EM122 and EM2040C (Fig. 6-8). The treatment was carried out in accordance with procedure PS2015-023. The following sediment characterization images were defined using FMGT (FlederMaus Geocoder Tool) application. FMGT (QPS, 2018) adjusts the backscatter data by performing backscatter extraction then radiometric corrections based on sonar type and bottom topography. Finally, FMGT deduces the ARA (Angle vs. Range Analysis); it is the method of seafloor characterization which compares the actual backscatter response to expected acoustic response curves based on a mathematical model (the Jackson Model). Due to the nature of the process, it is preferable to use the term characterization rather than classification. For this process, the Jackson Model generates an expected acoustic response curve as a function of grazing angle vs. returned backscatter intensity. This is a complex model where acoustic frequency and many sediment properties contribute to the overall modelled curve. As the parameters are adjusted the resulting modelled curve changes accordingly. The goal of the ARA is an attempt to characterize the measured response curve from the survey data using a best fit to the modelled curve. If a good match is found, it is expected that tells something about the sediment properties. However, many things can affect the veracity of the results starting with the quality of the system calibration and the appropriateness of the radiometric corrections applied. Many systems that had been well calibrated have shown good correlation between the characterized sediment types and measured sediment types. However, the ARA process is still in its infancy and much more ground truthing work needs to be done.

As stated above, good calibration was the key to reasonable results from the ARA. The survey environment affected also the results, as using ARA required a wide coverage of grazing angles. In deeper water we have limited grazing angles, so the process didn't work or didn't work very well.

Finally, different interpretations of seabed characterization are deduced from the different sensors: EM2040C, EM1002 and EM122, on board of hydrographic vessels (Cormoran, Pelican and Beautemps-Beaupré) as following:

(Top left, Fig. 6-8), which shows specially two important results: (1) the presence of mud (silt and clay) inside Jounieh canyon from head at about 50m depth through the thalweg, (2) the presence of sand inside Nahr El Kalb canyon. (Top right, Fig. 6-8), which confirms roughly the previous results. (Bottom, Fig. 6-8), which represents results that correlate mostly with previous interpretations done by EM2040 (Top, Fig. 6-8) more dedicated to shallow water interpretation.

6.6.2. Ground Truthing

The following sample analysis results are presented in Table 6-4 and plotted in figure 6-9.

6.6.3. SHOM Sampling

The sediment samples taken from Beautemps-Beaupré BHO (February 2016) were made with the shipeck tipper of the ship: 4 samples were taken in between Jounieh & Nahr El Kalb Canyons. Sediment sampling from the Pelican hydrographic vessel were made using Van Veen tippers. 9 samples were taken in shallower part of Jounieh Bay: No manipulation or sediment analyses were done aboard BHO Beautemps-Beaupré. Samples were sent to SHOM / DOPS / HOM / SEDIM.

6.6.4. Oceana Sampling

The 6 samples taken by OCEANA mission (October 2016) were analysed at the sedimentological laboratory of the Physics and Earth Sciences Department – University of Ferrara, where they have been wet sieved due to the presence of many silty aggregates. After the sieving, sand and mud were dried into an oven at 105°C. Weights were recorded using a Mettler PJ3600 scale.

A small amount of the sandy fraction of each sample, obtained by the mean of a sediment splitter, was analysed using a Thalassia Settling Tube, recording data into the Sedimcol software. An analysis time of 20 min was chosen. About 5g of muddy fraction were rehydrated for at least 24 hours using a 0.5% solution of Sodium Hexametaphosphate and analysed using a Micromeritics Sedigraph 5100.

6.6.5. ROV Investigation

ROV (remotely operated vehicle) images from OCEANA mission (October 2016) demonstrate the shells deposit on the continental shelf (sandy-gravel) and the significant biological diversity of the deep sea (muddy bottom). ROV investigation track in the studied area is highlighted.

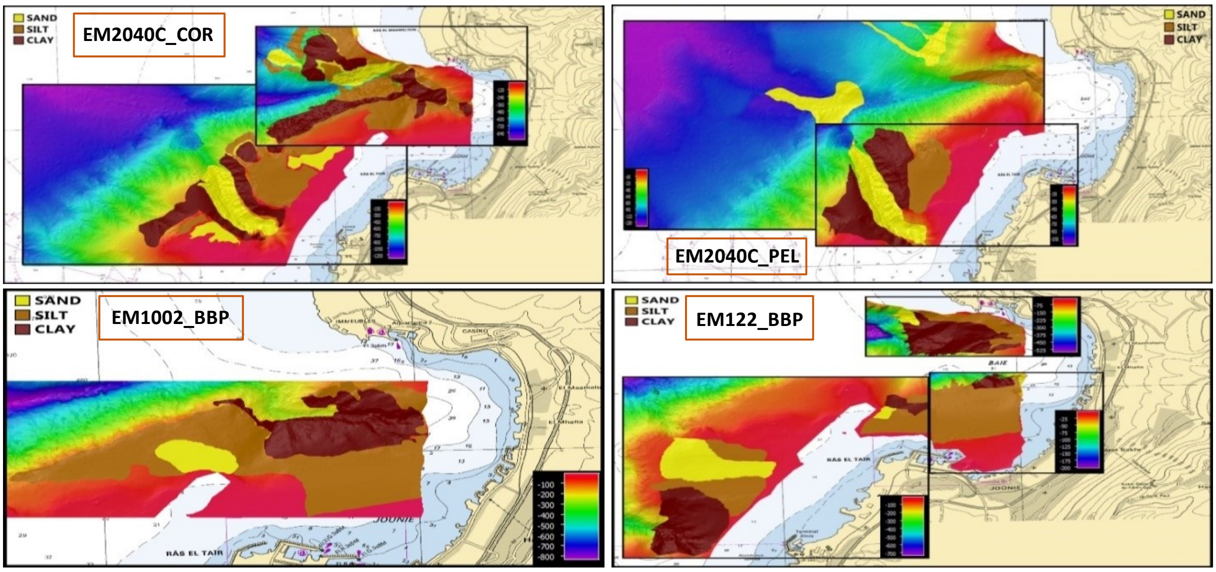


Fig. 6-8. Backscatter analysis from different sensors used to collect data: EM2040 on board of CORMORAN and PELICAN (frequency ranges from 200 to 400 KHz), EM1002 and EM122 on board of BEAUTEMPS-BEAUPRÉ (frequency ranges respectively 100 and 12 KHz).

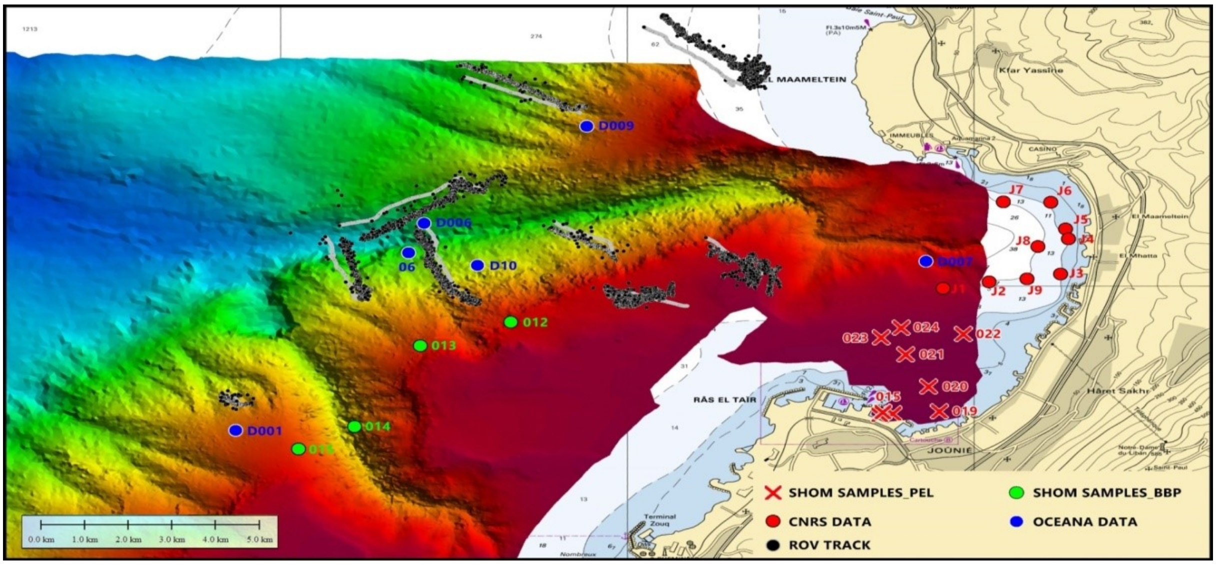


Fig. 6-9. Plotted samples positions in the bathymetric map of the research's area. Every packet of samples are indicated with the corresponding agency or boat and symbolized differently.

For each sample, data coming from the Settling Tube and from Sedigraph were processed within Sedimcol software prior to import them into Gradistat spreadsheet (Blott and Pye, 2001) in order to calculate the grain size distribution and the main statistical parameters.

6.6.6. CNRS Sampling

The 9 sediment samples taken by CANA (CNRS-L) in the shallower part of Jounieh bay and canyon head (February 2018) were analysed at the sedimentological laboratory of the Physics and Earth Sciences Department – University of Ferrara (same procedure as 6.2.2).

Table 6-4

Sample analysis results from October 2016 until April 2018.

Samples			Classification
	Samples names	Depth (m)	
SHOM Samples_BBP	012	142	Clay
	013	187	Clay
	014	392	Gravel
	015	211	Clay
SHOM Samples_PEL	015	6	Clay
	019	7	Clay, Sand
	020	10	Sand
	021	13	Clay, Sand
	022	11	Sand
	023	15	Sand
	024	20	Sand
OCEANA DATA	D006	800	Medium Silt
	D007	96	Medium Silt
	D009	220	Medium Silt
	D10	668	Medium Silt
	06	857	Medium Silt
CNRS DATA	J1	53	Coarse Silt
	J2	36	Very Fine Sandy Very Coarse Silt
	J3	16	Moderately Well Sorted Fine Sand
	J4	20	Slightly Fine Gravelly Medium Sand
	J5	15	Moderately Well Sorted Fine Sand
	J6	14	Moderately Well Sorted Fine Sand
	J7	38	Moderately Well Sorted Fine Sand
	J8	40	Very Coarse Silty Very Fine Sand
	J9	52	Very Coarse Silty Very Fine Sand
ROV TRACK			- Steepness of Jounieh Canyon. - 2 ROV dives from 70 to 400m & from 400 to 950m. - Sandy-muddy bottom at shelf break to muddy bottom at slope. - Walls of South Jounieh canyon are steeper than Northern part.

6.7. Observations and results

6.7.1. DBM Observations

The final DBM (Digital Bathymetric Model), although the original data was acquired from different assets and sensors, was generated using a TIN (triangulated Irregular Network) of 3m resolution to put in evidence shallower parts morphologies. DBM analysis shows evident tributaries and gullies, responsible for sediment discharge across shore; these tributaries and gullies are also evident south of Nahr El Kalb canyon all the way until Saint George canyon. The very shallow part of the continental shelf from canyons head to the coastline needs to be surveyed, analysed and exploited in order to link these canyons with equivalent coastline and understand how the sediment flows along shore or across canyon head.

6.7.2. Geo-Morphometric and Morphology Observations

Jounieh and Nahr El Kalb canyons were analysed together because of their similarity and since they share the same mouth at 1000m depth. Morphometric attributes and their statistical analyses at continental slope (by analysing the DBM) find their way in the application in Geomorphology and Geo-hazards. Future developments in the marine geomorphology are based on data availability and quality. Area of Interest in both canyons is an area of depositional sediment for about 1000m length and needs to be examined at larger scale.

6.7.3. Sediment Map Observations

Considering different backscatter sensors and Ground truthing analysis; results correlate with the fact of the abundance of fine sediment (Silt and Clay) inside Jounieh canyon and the presence of sand at the continental shelf and slope inside Nahr El Kalb canyon which is directly related to an active driver (Nahr El Kalb river). Backscatter results from EM122 show a big sand accumulation at the common mouth of both canyons, which prove the terrigenous origin of this sand.

6.8. Conclusion

The application of high resolution Multibeam bathymetry revealed the presence of several submarine canyons western Lebanon in the area between Jounieh and north of Beirut. Despite the fact that the two canyons in the Area of Research belong to the same continental margin, share the same morphology characteristics and are located few kilometres apart, they display relevant differences in sedimentary processes. The different interplay between tectonics and sedimentary processes is recognized as the main geologic fact for distinguishing the evolution of the two canyons (Lo Lacono et al., 2013). We deduce that present-day activity of Jounieh canyon is reduced. It is due to its isolation from the main sediment sources. Probably this canyon represents relict features, in contrast with its steep average slope and walls. The SW current is the main governing cause of sediment movement alongshore inside Jounieh bay. Contrarily, the Nahr El Kalb canyon, is still a living canyon due to its relation with an active driver (Nahr El Kalb river), which controls the sediment across shore movement from inshore through shoreline, head of canyon, down to middle and distal canyon. Future works need to focus on the shallower part of both canyons to unveil the link between coastal part and head of canyons.

7. Chapter 7: Sediment movements inside canyons heads of Jounieh-Beirut basin.

7.1. Introduction

Based on new high-resolution multibeam bathymetric data, a significant number of submarine canyons heads have been spotted in the area between Jounieh and North of Beirut. Despite the fact that Lebanese submarine canyons are features that have occurred on active continental margin and should play an important role in the transportation of sediment from shelf to deep basin, it has been proven also that Lebanese canyons are important reference of benthic biodiversity due to a recent study conducted in 2016 by the research vessel OCEANA (Aguilar et al., 2018). Three main submarine canyons are on the scene along the upper slope of Beirut-Jounieh common basin (Fig. 7-1), however not all of these canyons behave in the same manner due to their dimensions, shapes and connections with the coastline.

Morphologies within the mentioned area indicate mostly sedimentary processes (Tubau et al., 2015), and in particular, longitudinal and transversal sections through canyons heads are used to evaluate their evolution. Slumps, scars and scarps in the tributaries and gullies are all proof of mass movement and dynamics that affect the canyon head morphology, thus defining the amount of sediment supply participating in the sediment movement into canyon Thalweg toward the basin.

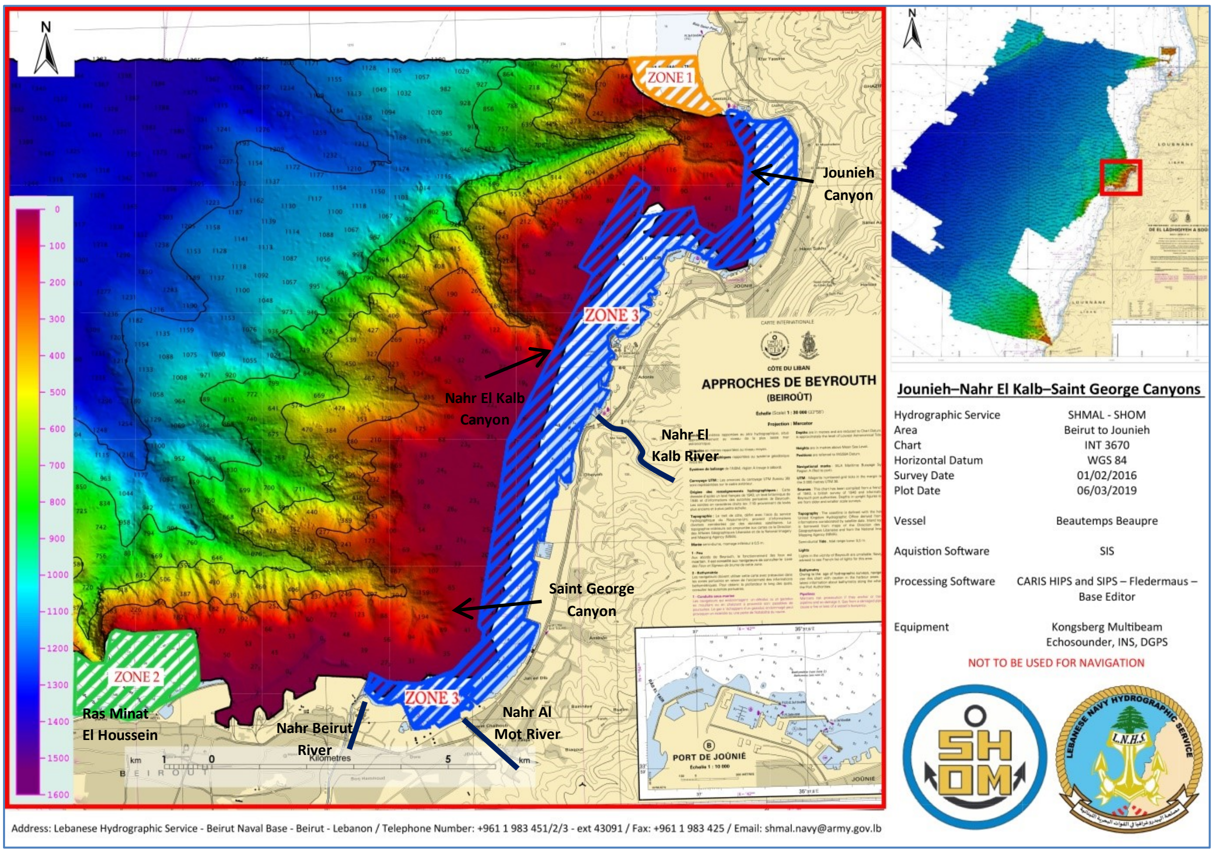


Fig. 7-1. 2D bathymetric map of the research area extending from North of Beirut to Jounieh putting in evidence morphologies of 3 main submarine canyons, from North to South: Jounieh, Nahr El Kalb and Saint George canyons.

Tectonics processes, by influencing the structural deformation of the margin, can control the shelf width, gradients and the associated distance from canyon heads to the coast (Puig et al., 2017). The different interplay between tectonics and sedimentary processes is recognized as the main geologic fact for distinguishing the evolution of the three canyons (Lo Lacono et al., 2013). We have deduced that present-day activity of Jounieh canyon is reduced. It is due to its isolation from the main sediment sources. Probably this canyon represents relict features, in contrast with its steep average slope and walls. The SW current is the main governing cause of sediment movement alongshore inside Jounieh Bay. Contrarily, the Nahr El Kalb and Saint George canyons, are still active canyons due to their relation with dynamic drivers (Nahr El Kalb, Nahr Al Mot and Nahr Beirut river), which control the sediment across shore movement from inshore through shoreline, head of canyons, down to the middle and distal canyons (Fig. 7-1).

This study aims to focus on the shallower part of canyons to unveil the link between coastal zone, continental shelf and head of canyons.

7.2. Subject field

7.2.1. General description

The Mediterranean Sea is a semi-enclosed water basin. It extends over an area of 2.5 million Km^2 and divided into a western and an eastern basin. The Levantine Sea situated in the Eastern basin of the Mediterranean is a water area situated between Antalya in Turkey and Port Said in Egypt. This area is generally considered oligotrophic due to a semi-arid climate with limited precipitation and low river input (Aguilar et al., 2018).

Diversely, Lebanon has a typical Mediterranean climate, with an average annual temperature of 20^{o}C and about 300 sunny days each year. It is also characterized by a relatively high average rainfall, ranging from 700 to 1000 mm along the coast to 1400 mm on Mount Lebanon. Surface water temperature shows high seasonal variation and range from 17^{o}C in winter to 30^{o}C in summer. The water in the upper 50m is well mixed in winter and becomes stratified during the rest of the year. Lebanon's continental shelf is relatively narrow with tight isobaths. The bottoms are very rugged and are intersected with a network of underwater canyons. The study area corresponds to a micro-tidal setting, with maximum tidal height of 0.25m above sea level (a.s.l) (Lebanese Navy Hydrographic Service, LNHS, 2017) (Greenpeace Mediterranean, 2010).

7.2.2. Geological settings

The continental margin of the central Levant, offshore northern Palestine and Lebanon is characterized by a sharp continental-oceanic crustal transition, exhibited on the bathymetry as a steep continental slope. The western Lebanese continental margin, in the eastern Mediterranean Sea, extends from the Lebanese coastal belt up to 10 km west (Fakhri et al., 2018). The Jounieh-Beirut system canyon and basin (Fig. 7-1), offshore western Lebanon, is a part of eastern Mediterranean Sea. Situated relatively in the middle of Lebanese elongated coastline, and according to Ben-Avraham et al. (2006), this offshore margin is affected by the complex tectonic evolution of the Carmel fault zone and Dead Sea fault, inducing strong convergence in Lebanon and causing transpressive mountain uplift (Fig. 7-2).

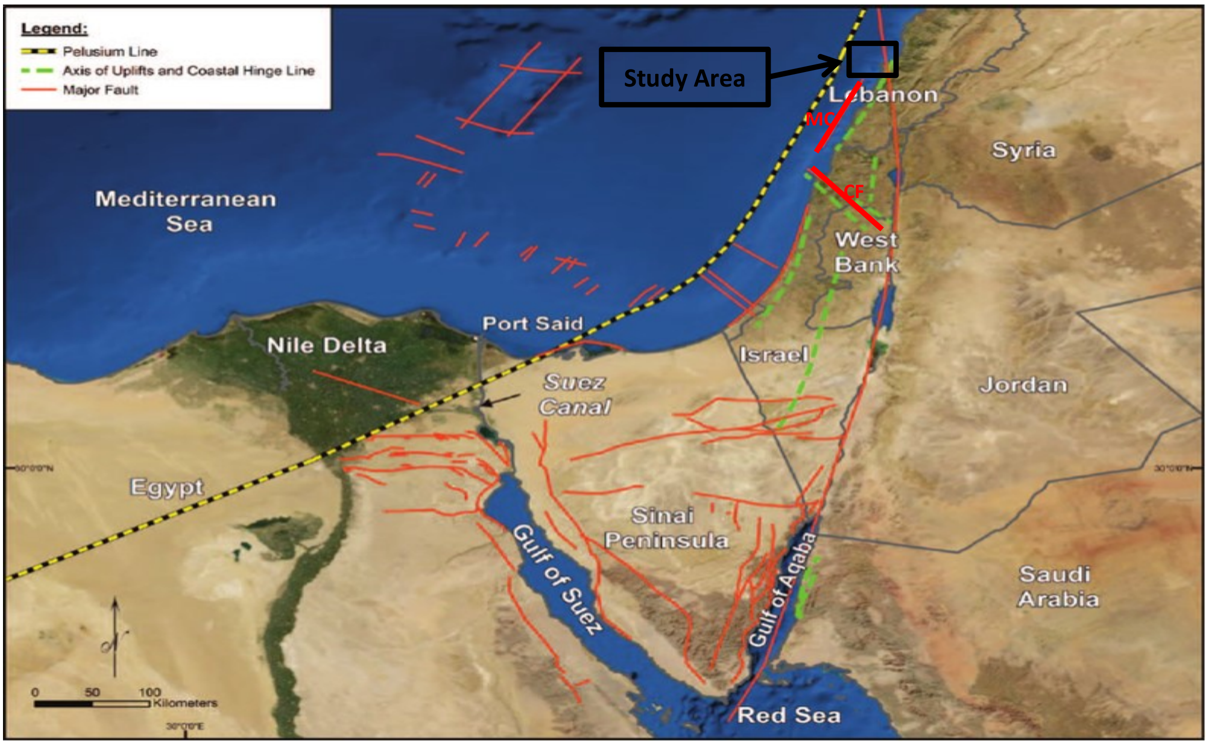


Fig. 7-2. Regional tectonics image, highlig0hting: (1) the marine continuation (MC) of the Carmel fault (CF) zone and its structural relations to other major tectonic features in the area, (2) the study area marked by a black rectangle offshore Lebanon.

7.3. Materials and methods: Bathymetric data

Swath-bathymetry MultiBeam EchoSounder (MBES) data were acquired in 2 periods; the first one during a combined hydrographic mission in February 2016 (Fig. 7-1), between SHOM and LNHS, covering depth range between 60-1000m, the second one during a combined hydrographic mission in October 2018 (ZONE 1-2-3, Fig. 7-1), between Italian hydrographic ship MANGNAGHI and LNHS, covering depth range between 10-200m. The bathymetric survey in Lebanon was conducted using EM122, EM1002 and EM2040C multibeam sounders on board of French and Italian assets, and Lebanese hydrographic boat Navy-Gator equipped by NORBIT iWBMSh Dual Head system capable of surveying depths from 2.5 until 100m.

The data is corrected in real time from the installation parameters (lever arm and relative orientations between sonar transducer, GNSS antennas and inertial unit) and sonar calibration. The bathymetry data were processed using the CARIS HIPS & SIPS 9.1 software and the processing tool inside QINSy software. Post-processing steps included the removal of erroneous beams, noise filtering, processing of navigation data and correction for sound velocity and tide. Digital Bathymetric Models (DBMs) were produced with a variable foot print resolution ranging from 1.5 to 25m, depending on depth and wanted morphology details. Base Editor Software from CARIS and Fledermaus software from QPS were used to obtain 3D maps of the bathymetric data, shaded relief maps, slope maps and bathymetric profiles.

7.4. Geo-Morphometric Results

7.4.1. Marine geo-morphometric analysis

Geo-morphometric techniques were applied at Jounieh, Nahr El Kalb and Saint George submarine and their heads environments (Lecours et al., 2016). In the overall study of submarine mass movements, the general approach is the prior identification of the landslides′ boundaries, the measurements of a series of morphometric parameters and their spatial and statistical analyses. The use of specific geo-morphometric techniques such as Slope and Rugosity, where features of interest are identified prior to analysis, has involved examining how different morphological parameters would change spatially and in function of each other.

7.4.2. Slope

The Slope scalar was applied on the bathymetric data of Beirut-Jounieh basin; it allowed us to compute a surface that represents the maximum slope at each grid centre of the currently loaded SD File. The generated surface has the same dimensions as the original surface file and represents the maximum slope from each cell to any of its neighbouring cells. Figure 7-3 shows the slope percentage calculation reaching 70 to 80% at some critical areas of interest, putting in evidence the role of these features in sediment transportation and accumulation along canyons. Looking more into details of the bathymetry at canyons heads, equivalent results of Slope scalar permit us to analyse the possible channels, that the sediment pursuits after a washing phase (Fig. 7-3, a, b and c).

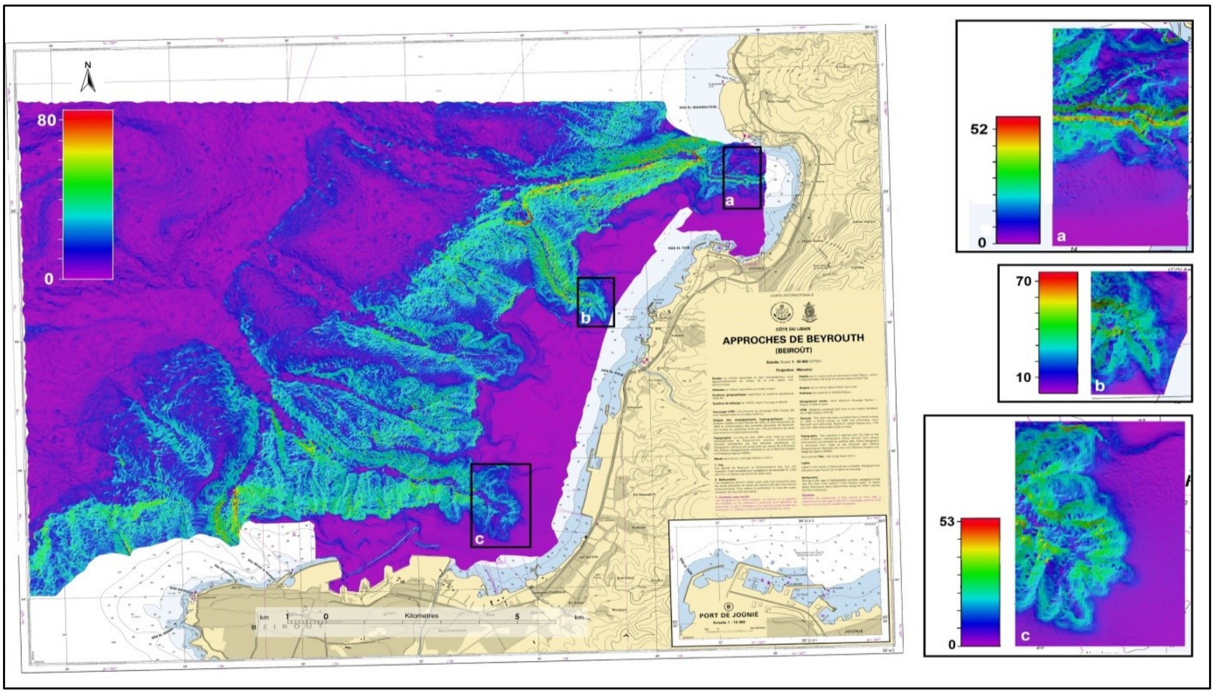


Fig. 7-3. Slope scalar calculation applied on bathymetric data between North of Beirut and Jounieh. a, b and c black rectangles are Slope scalar calculation at canyon heads.

7.4.3. Rugosity

The Rugosity scalar is the measurement of the seabed surface roughness. A value equal to 1 represents smooth seabed whereas values > 1 imply an increasing surface roughness. Rugosity scalar was registered from the bathymetric data of Beirut-Jounieh basin; areas of high rugosity allow corals to attach and grow on higher substrata not influenced by sand and sediment movement along the bottom. Figure 7-4 demonstrates: (1) the high rugosity at areas directly after high slopes, putting in evidence the increase of seabed roughness and sediment accumulation, (2) the low Rugosity elsewhere reaching values of 1, showing the low seabed roughness and the high sediment movement in these areas.

To better understand the rugosity characteristic, the rugosity scalar was applied on heads of canyons at big scale to analyse the seabed roughness of different channels, where the sediment or the corals have respectively the possibility to move or grow (Fig. 7-4, a, b and c).

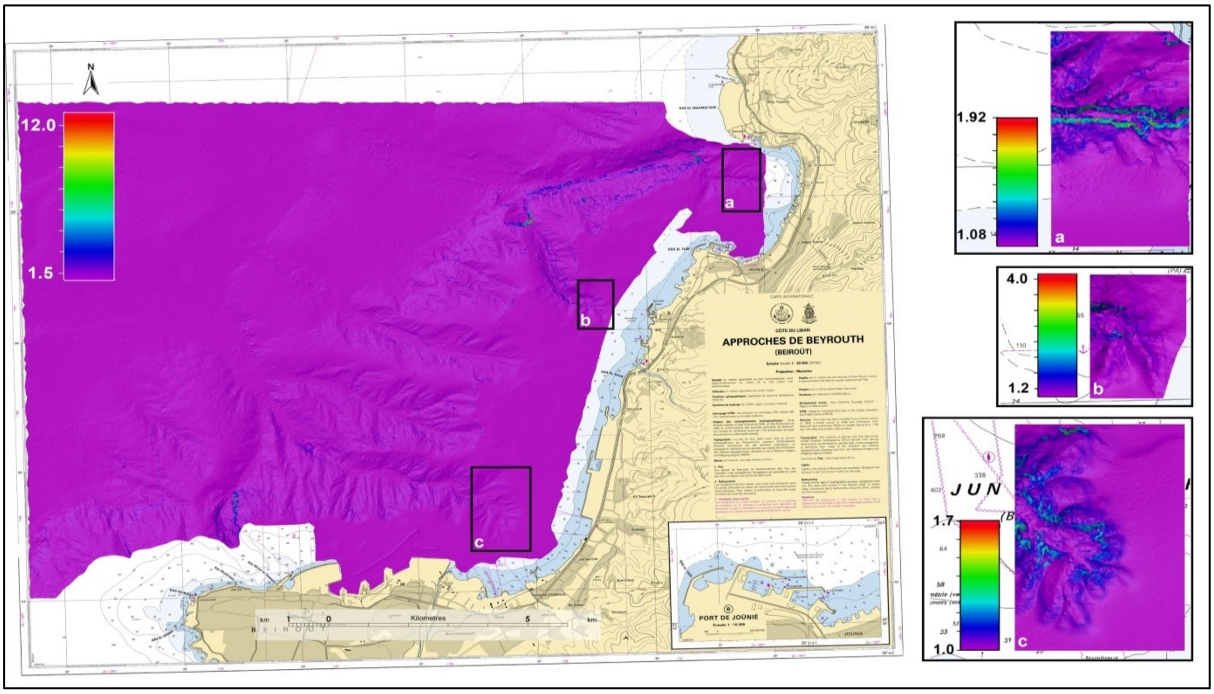


Fig. 7-4. Rugosity scalar calculation applied on bathymetric data between North of Beirut and Jounieh. a, b and c black rectangles are Rugosity scalar calculation at canyon heads.

7.5. Geo-Morphological Results

7.5.1. General morphology

Morphologies within the area of research are illustrated in (Fig. 7-1), and mostly indicate sedimentary processes. Three main submarine canyons have been observed along the upper slope of Beirut-Jounieh basin. Canyons are, from the north to the south: Jounieh canyon, Nahr El Kalb canyon and Saint George canyon. All the canyons indent the shelf and show a more or less straight path, connecting to the sub-horizontal Beirut-Jounieh intra slope Basin (1400m depth). The narrow continental shelf (max 2.5 km) extends down to 120m water depth. The seabed topography is a continuation of inland geomorphology marked by a nearly absence of the coastal plain, and by a steep hill belt exceeding in elevation 700 meters away 2 km from the coast. All canyons tributaries are marked by a complex network of gullies along their flanks. Even though, the three main canyons that define the study area have signalled differences in the orientation and extension of canyon heads, they share same morphological specifications (table 7-1).

Table 7-1

Main morphometric characteristics of studied canyons.

Submarine canyon	Length (km) **a**	Area (Km^2)	SI **b**	Gradient (°) **c**	Shelf depth incision (m) **d**	Width shelf edge (m) **e**	Incision shelf edge (m) **f**	Confluence depth (m)
Jounieh	12.5	18.75	1.25	8	20	1200	558	1200
Nahr El Kalb	10	7.5	1.11	10	40	1000	477	1115
Saint George	13	26	1.05	7.7	50	2000	600	1210

a Total length of the main canyon.
b SI: Sinuoisity index = channel axis length/length of the straight-line distance.
c Mean gradient along the canyon axis.
d Minimum depth of incision on the continental shelf.
e Canyon width at the shelf edge.
f Canyon axis incision at the shelf edge.

All the canyons display an incised Thalweg along the proximal reach, which flattens from a depth of 800m. Jounieh, Nahr El Kalb and Saint George canyons do not display any obstructions at all depths, probably due to their steepness, however they mark a change between a V transversal canyon profile upslope to a U transversal canyon profile downslope at a common depth of 600m, as described in chapter 6.

7.5.2. Canyons heads morphologies

Throughout the subject field, a finite numbers of young canyon heads (Pliocene-Quaternary) have been developing (CIESM Workshop Monographs No47, 2015); Jounieh, Nahr El Kalb and Saint George canyon heads are positioned close to the coast at 20-25m bathymetric depth and their widths at the shelf edge range between 1000-2000m. In this study, morphology of canyon head are described in two ways; first, by identifying the main Thalweg (middle to distal head) analysing 6 series of sections through the canyon head at depth range between 40-320m, second by analysing the shallower part of the canyon head where is depth range between 3-90m to put in evidence channels head morphologies and trying to link canyon head with adjacent coastline.

7.5.3. Jounieh canyon head

Many canyon head branches, at middle to distal head cutting the outer shelf of Jounieh Bay can be identified through the high resolution bathymetric data (Fig. 7-1). Two of these branches are well notified by their morphologies and intersect at depth of 160m to form the main Thalweg (Fig. 7-5). The northern branch follows an E-W orientation until reaching the main Thalweg, starting at a depth of 80m and incising the inner shelf at shallower depths (to be developed later). Contrarily, even though the southern branch is morphologically similar to northern one, following a SE-NW orientation and starting at a depth of 60m, it does not incise the inner shelf and stop in the middle of Jounieh Bay. The shallower part of both branches shows several small sinuous tributary channels that can be found at different depths.

When reaching the main Thalweg most of northern tributaries evolve downslope into gullies incised on the canyon head flanks (Fig. 7-5).

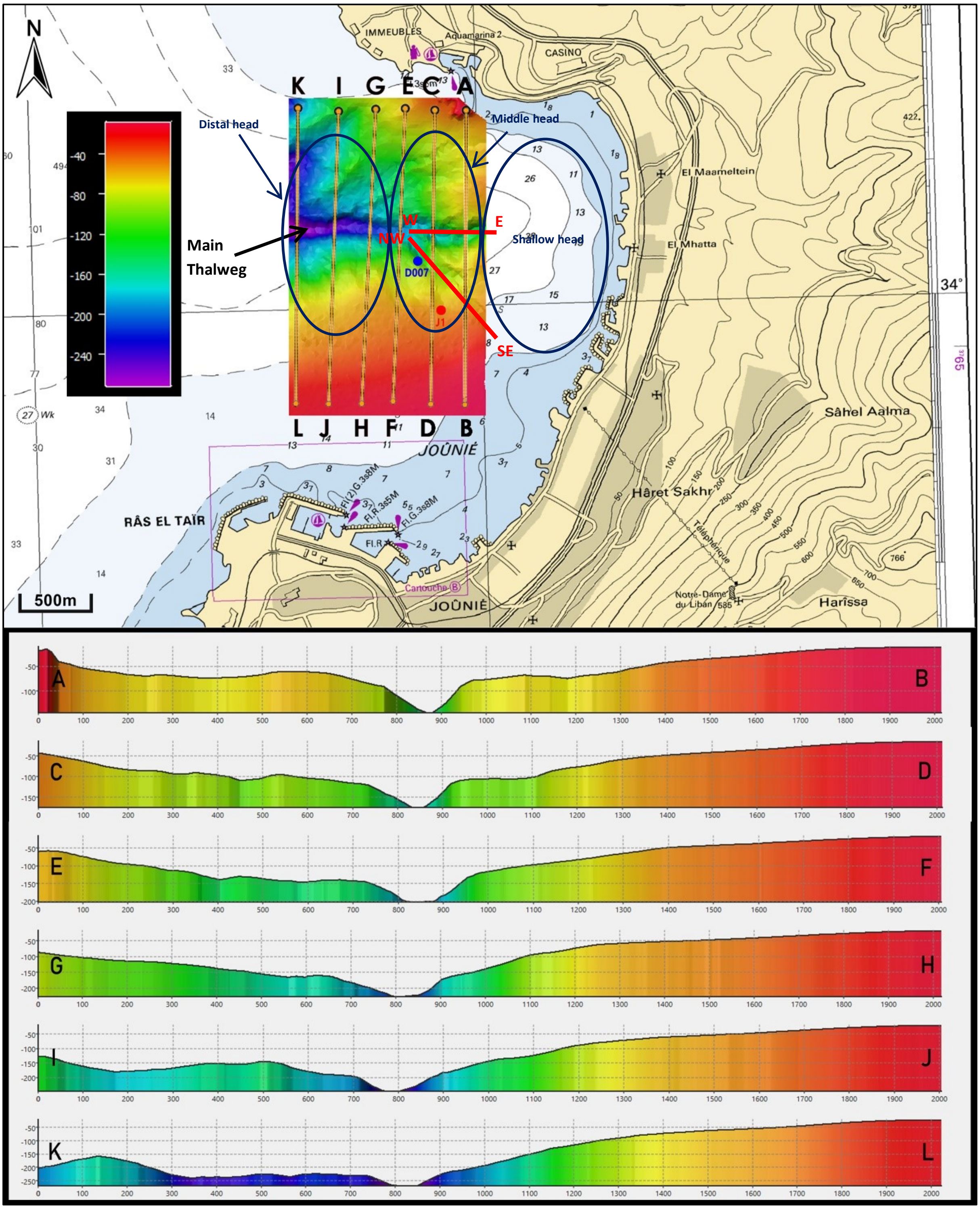


Fig. 7-5. Middle to distal bathymetry head of Jounieh canyon illustrating, (top frame) the main branches and tributaries at depth range between 40-240m, (bottom frame) 6 series of cross section profile including 2 sediment samples (blue and red dots) are also shown.

The cross section profiles (AB-CD-EF) in the figure 7-5, drawn at middle head, demonstrate the steepness of the head canyon flanks illustrated by the V section shape, and the passage from V to U section shape, at 150m depth, appeared in the cross section profiles (GH-IJ-KL) drawn at distal head. Surface sediment samples D007 (medium silt) and J1 (coarse silt) grabbed respectively at depths 96m and 53m are positioned on the bathymetric map at the southern branch.

The Jounieh canyon shallow head, highlighted in figure 7-5, shows two main branches (Fig. 7-6) that have developed from the northern main branch described earlier, and incising the inner shelf. The northern branch (Fig. 7-6, I) has a NE-SW orientation and run mostly perpendicular to the coastline, while the southern one (Fig. 7-6, II) has a S-N orientation, running roughly parallel to the coastline until reaching J9 at depth of 52m; at this level, it turns east and follows an SE-NW trend reaching a depth of 10m, as close as 20m from a small harbour's breakwater. These branches can be identified at larger scale through a high definition resolution grid of 1.5m, and converge at 100m bathymetric depth in one Thalweg path (northern branch in the figure 7-5) demonstrating two sharp bends in the SW and NE directions respectively, where the canyon become wider and characterized by sharp gradient.

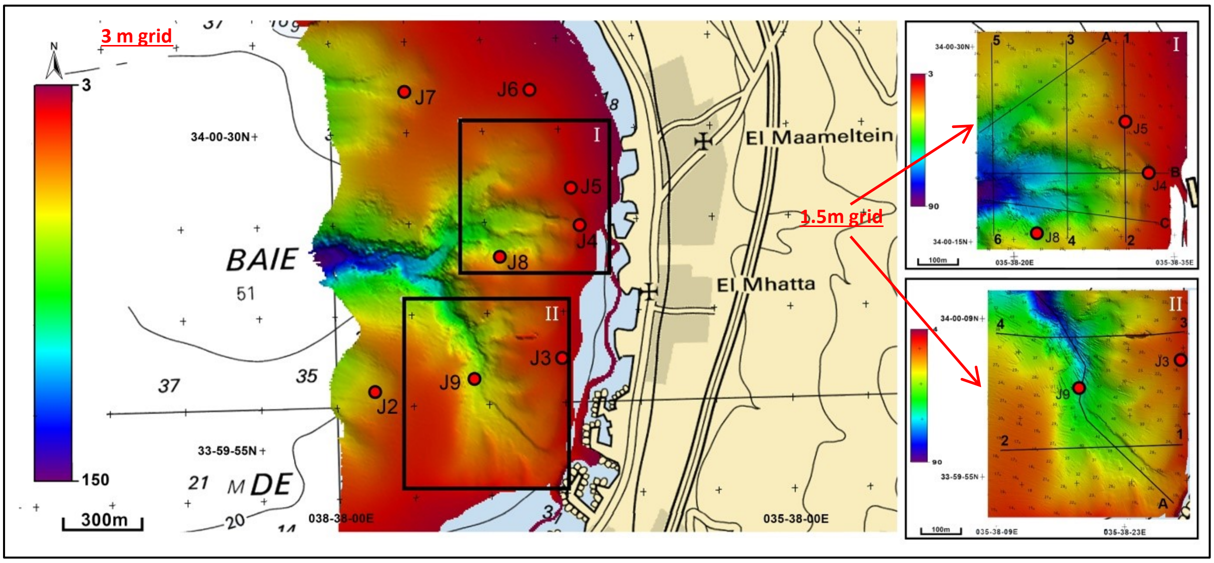


Fig. 7-6. High definition resolution of 3m grid showing shallow head part morphology and branches found at the inner shelf off Jounieh area: from the Jounieh canyon shallow head (I) and (II), achieved surface at resolution of 1.5m grid. Bathymetric profiles, transects and 8 sediment samples (red dots) are also shown.

8 surface sediment samples (J2-J9), ranging from a depth of 14 to 53m, taken and analysed at the shallower part of Jounieh Bay (February 2018) and described in the Table 6-4 of the Chapter 6, prove the abundance of sand at the continental shelf and inside canyon head branches (Fig. 7-6). After the plot of samples on the grid, we deduced that J2 at a depth of 36m (very coarse silt) belongs to same branch of samples J1 and D007 (Fig. 7-5) and are all well sorted logically from shallow to deep part at 96m; this branch head did not capture any major sediment transport event except the normal sorting. J6 (fine sand) and J7 (fine sand) at respective depths of 14 and 38m are aligned from E to W; the presence of fine sand at J7 is usually controlled by the SW current that is the main governing cause of sediment movement alongshore inside Jounieh Bay. The presence of fine sand at J3, J4 and J5 at depths respectively 16, 20 and 15m is also controlled by SW current. Sample J8 at depth of 40m belonging to the Thalweg of northern branch and sample J9 at a depth of 52m belonging to

the southern one are identical to sample J2 (very coarse sand); the surface sediment collected along the Thalwegs of the 3 main branches head demonstrate that no major transport event of sand has recently occurred. Also, no winter river flood events occurred in the bay of Jounieh during the collection of samples.

Bathymetric cross profiles and transects across northern head (Fig. 7-6, I and Fig. 7-7) and southern head (Fig. 7-6, II and Fig. 7-8) revealed that bedforms are not present in this area of head canyon, which means that washing is always present in this part of Jounieh Bay (semi-circular shape), at depths shallower than 50m, due to the wave action on the seabed. One relevant feature (ship wreck) about 75m long is to distinguish at southern head in section 3-4 in the figure 7-8.

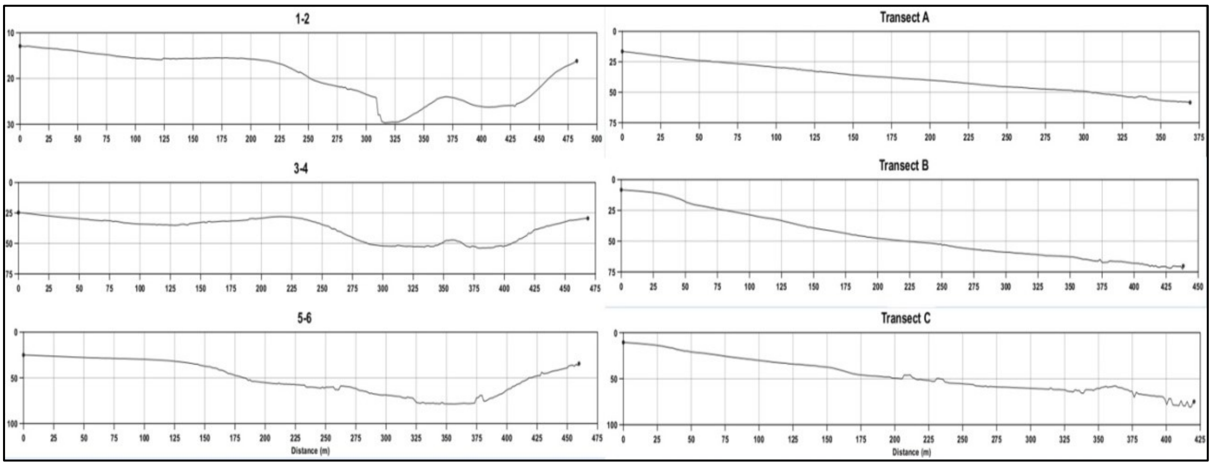


Fig. 7-7. Three series of bathymetric cross profiles (alongshore) and three transects (across-shore) plotted at northern head of Jounieh canyon.

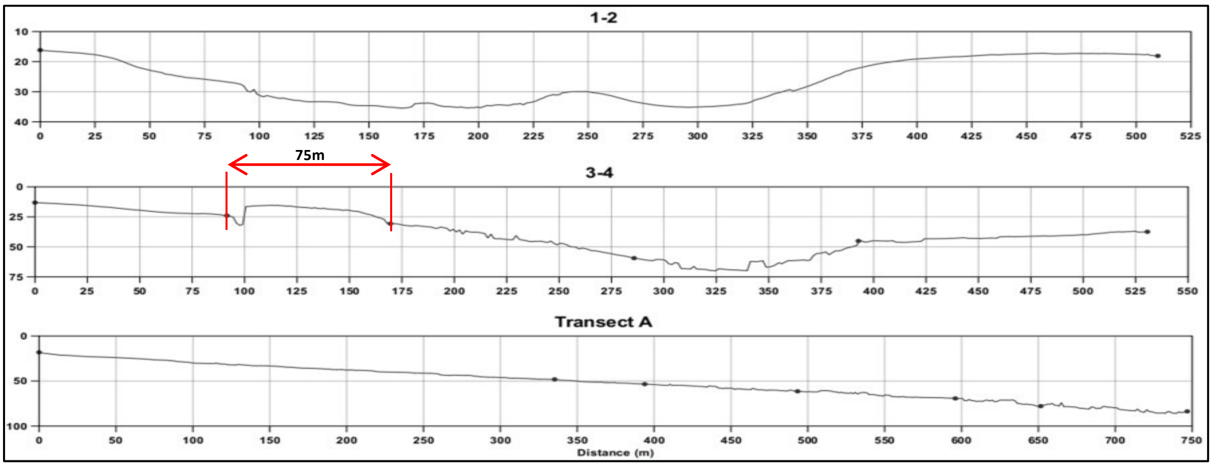


Fig. 7-8. Two series of bathymetric cross profiles (across-shore) and one transect (alongshore) plotted at southern head of Jounieh canyon.

7.5.4. Nahr El Kalb canyon head

Nahr El Kalb canyon is connected to an active driver; a living river that forms a huge sediment plume after heavy rains. It can be considered as a big branch from Jounieh canyon since the two canyons joins together at 1000m depth (Fig. 7-1). Nahr El Kalb canyon shows three branches at the middle head, cutting the inner shelf at depth of 80m. The upper canyon branch runs NE-SW (Fig. 7-9), aligned roughly perpendicular to the coastline until reaching

150m depth where it joins the main Thalweg of the canyon head following a SE-NW trend, while the middle one follows the same direction of the main Thalweg and reach the shallower part of canyon (to be developed later). Diversely, the lower canyon branch runs parallel to the coastline reaching at its northern part 180m depth, while its southern part reaches 80m and stops to develop.

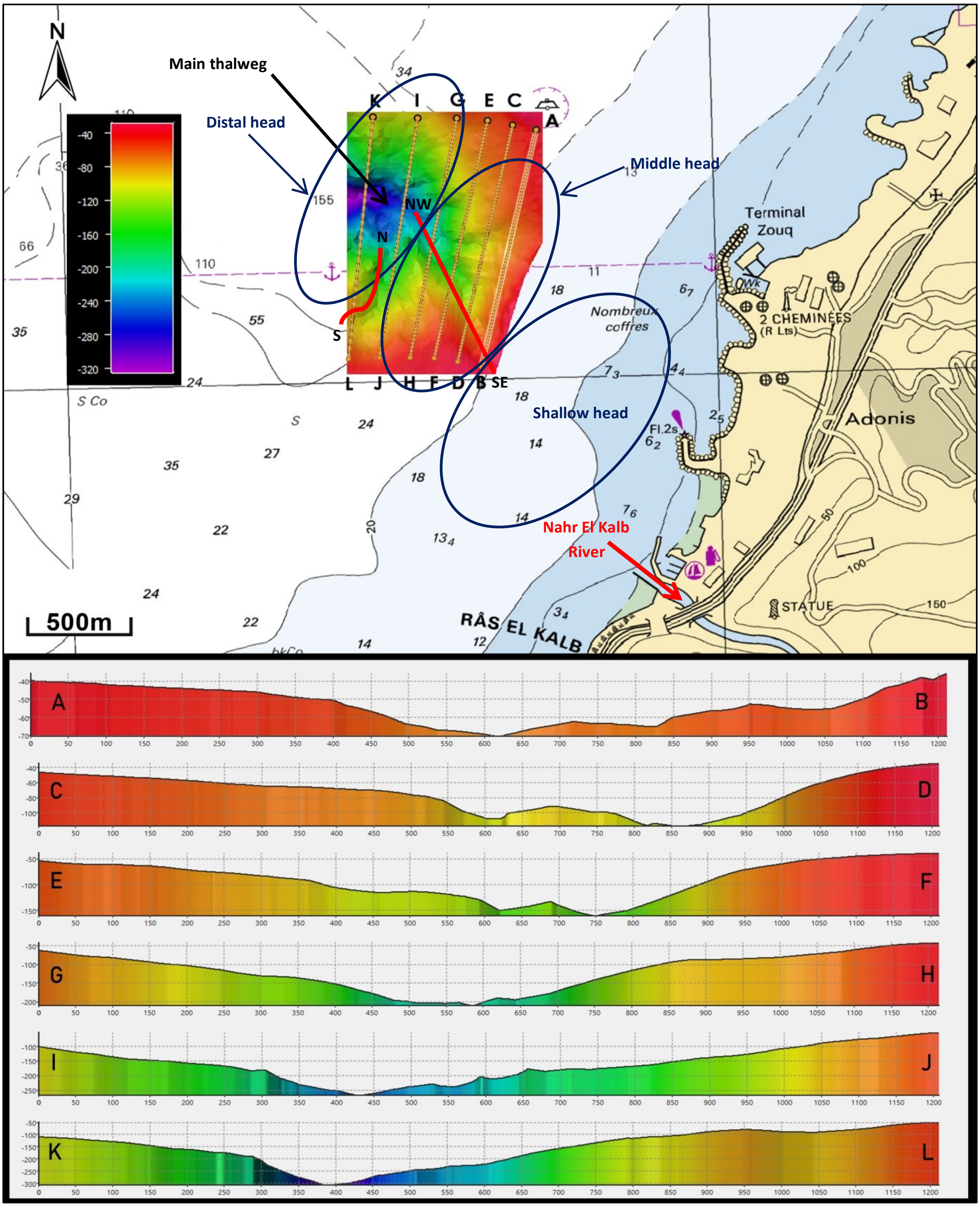


Fig. 7-9. Middle to distal bathymetry head of Nahr El Kalb canyon illustrating, (top frame) the main branches and tributaries at depth range between 40-320m, (bottom frame) 6 series of cross section profile are also shown.

The cross section profile (AB) in the figure 7-9, drawn at middle head, shows the upper and middle branches at depths respectively at 70 and 65m and appear as one big branch of 800m width; it can be considered as big probable container of sediment. When reaching the distal head, the described two branches join together to form the main Thalweg (350m width) at 180m depth. In the profile (IJ) the main Thalweg goes wider (700m width) due to the joining of the lower branch, while in the profile (KL) it reaches again a width of 350m at its deepest point of 300m. All cross profiles drawn in the figure 7-9, demonstrate, contrarily from Jounieh canyon head, the gentle gradient of head canyon flanks illustrated by the wide U section shape, and the passage from U to V section shape appeared to happen at late stage in KL profile at 300m depth.

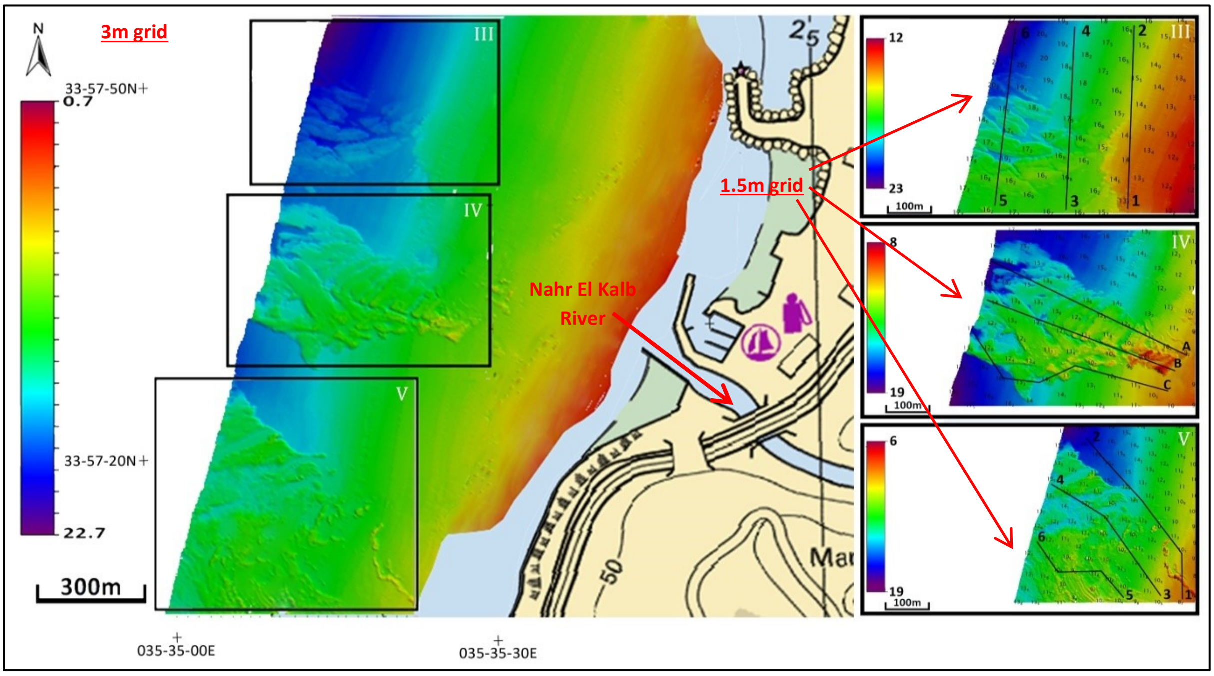


Fig. 7-10. High definition resolution of 3m grid showing shallow head part morphology and branches found at the inner shelf off Nahr El Kalb area: from the Nahr El Kalb canyon shallow head (III), (IV) and (V), achieved surface at resolution of 1.5m grid. Bathymetric profiles and transects are also shown.

Towards the shallow head area highlighted in figure 7-9, three main heads branches (Fig. 7-10) have developed from the middle branch described earlier, with different morphologies from Jounieh shallow head (Fig. 7-6). They are characterized by the presence of Nahr El Kalb river that furnishes a significant amounts of wave sediment, therefore they represent a shallow bathymetric depth area (5 to 23m); this shallow part of the head shows unclear incision in the inner shelf. Such shallow canyon head tributaries seem to evolve through series of bedforms.

Bathymetric profiles across the northern shallow head (Fig. 7-10, III) tell that these bedforms can reach 2.5m high and have wavelengths of 50m (Fig 7-11, Profile 3-4 and 5-6). Looking at the middle shallow head (Fig. 7-10, IV); we can notice slightly different head morphology, where the incision of the inner shelf is more relevant. The main axe of the Thalweg (Fig. 7-12, Transect B) starts to develop at 8m depth and shows bedforms reaching 4m high and

100m of wavelength. This result is more evident in (Fig. 7-12, Transect C), where the transect was drawn to highlight the volume of bedforms.

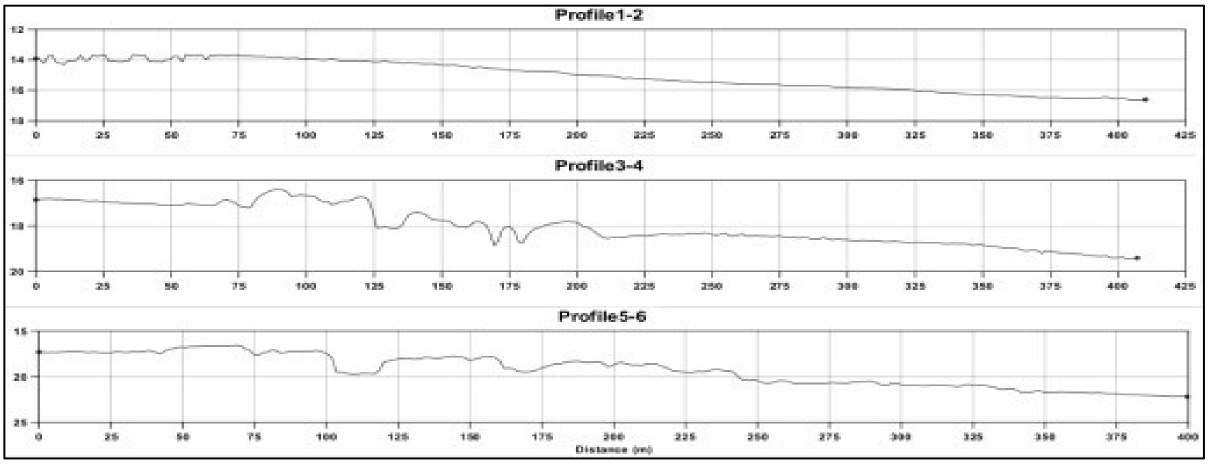


Fig. 7-11. Three series of bathymetric cross profiles (alongshore) plotted at northern shallow head (Fig. 7-10, III) of Nahr El Kalb canyon.

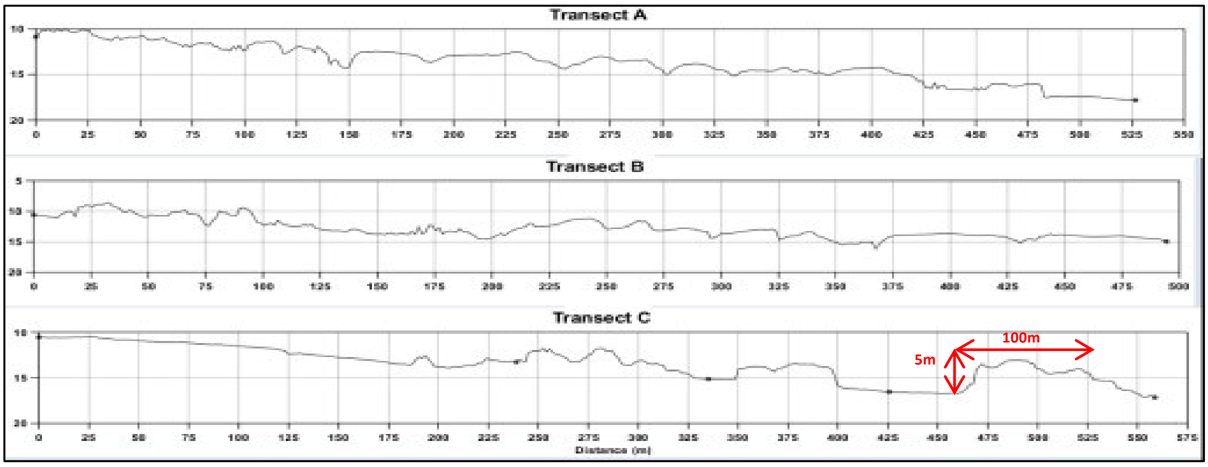


Fig. 7-12. Three series of transects (across-shore) plotted at middle shallow head (Fig. 7-10, IV) of Nahr El Kalb canyon.

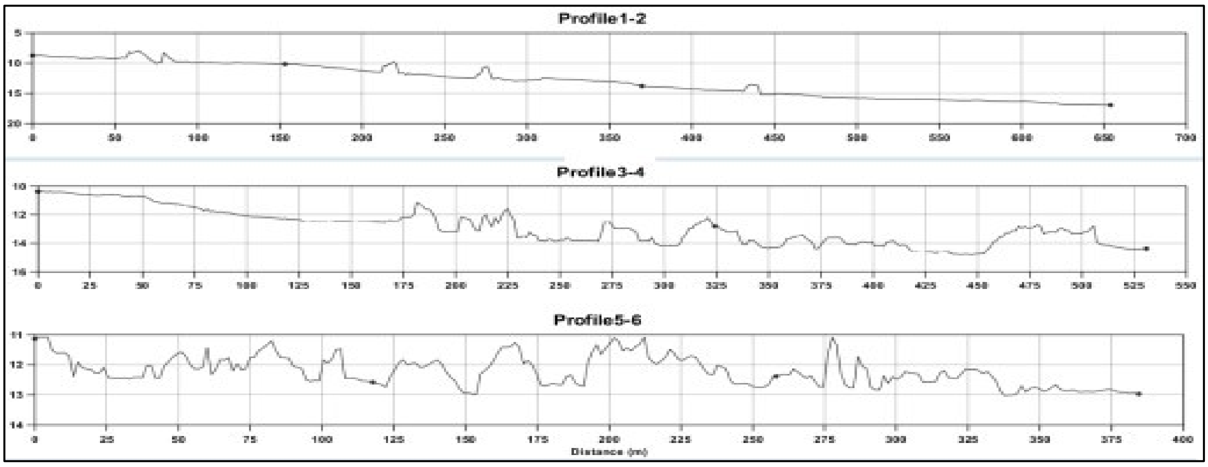


Fig. 7-13. Three series of cross profiles (across-shore) plotted at southern shallow head (Fig. 7-10, V) of Nahr El Kalb canyon.

Globally, at shallow head canyon Nahr El Kalb, several alignments of scars progressing gradually into narrow paths of bedform, intersect or no with the main incision of the Nahr El Kalb canyon middle head illustrated in the figure 7-9. Different soundings classifications at this area reveal the importance of these bedforms. Moreover, to highlight the last shallow part (southern part) of the mentioned canyon, series of profiles across-shore were taken in a stochastic manner to put more in evidence the thickness and wavelength of bedforms (Fig. 7-13, Profile 5-6).

7.5.5. Saint George canyon head

Many gullies cut the outer shelf between Nahr El kalb and Saint George canyons; they are untitled and we do not integrate them in the study because we took only in consideration canyons cutting the inner shelf, where the head is related roughly to the coastline (Fig. 7-1).

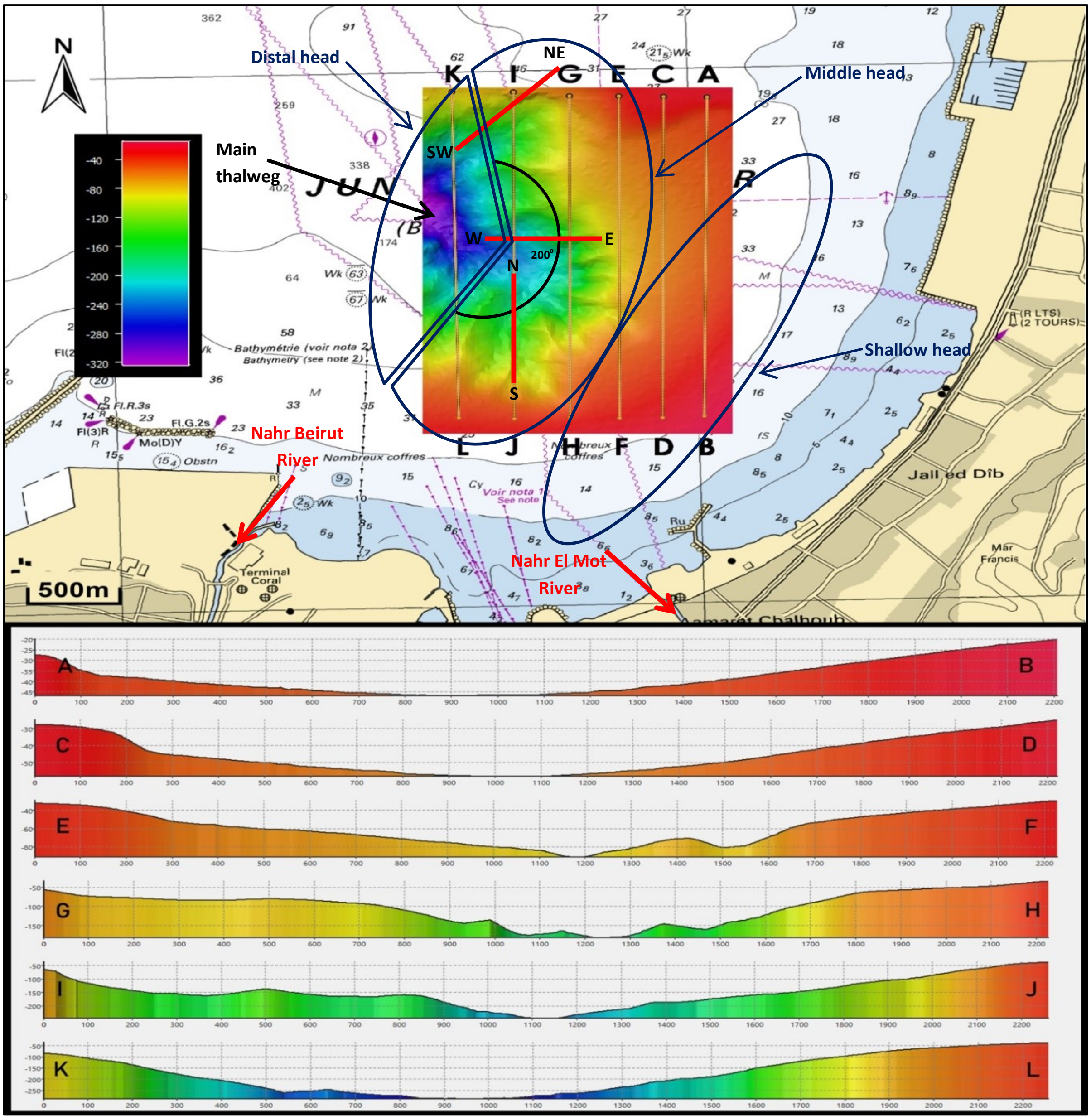


Fig. 7-14. Middle to distal bathymetry head of Saint George canyon illustrating, (top frame) the main branches and tributaries at depth range between 40-320m, (bottom frame) 6 series of cross section profile are also shown.

Saint George canyon is one of the biggest Lebanese canyons in the region with a length of 13 Km and a surface of 26 Km^2. It constitutes the main underwater feature of the historical bay of Saint George and has many tributaries and branches; we notify specially the branch forming from Ras Minat El Houssein connected at its distal part.

In the study area, south rivers (Nahr El Mot and Nahr Beirut) (Fig. 7-1 and Fig. 7-14) have the largest watershed and drainage system developing a prodeltaic deposit on the continental shelf. Diversely from the two previous canyons, Saint George canyon shows no connection with the coastline 1200m away from the shallow head (Fig. 7-14). This is due to the low circulation of the main SW current in the bay of Saint George isolated by the advancing of Beirut city into the Mediterranean Sea. The main focus will be on the middle part of Saint George canyon head, where the head is spread from NW to SW (200°) (Fig. 7-14). It can be grouped into three mains group of branches; the north one with a NE-SW orientation at depths between 80 and 200m, reaching the main Thalweg at 320m depth, the centre one with an E-W orientation at depth range from 80 to 180m and forming at 280m the main Thalweg of the canyon, while the south branch has a S-N orientation between 60 and 140m and is connected to the centre branch at about 180m depth. In the figure 7-14, and throughout cross profiles (AB) and (CD), which demonstrate a wide U shape extending about 2000m, we can see the shape of the shallow head part at its starting stage. The formation of the three mentioned branches are visible in the cross profiles (EF) and (GH) in the figure 7-14, where the head is getting narrower until reaching the Thalweg at 300m depth.

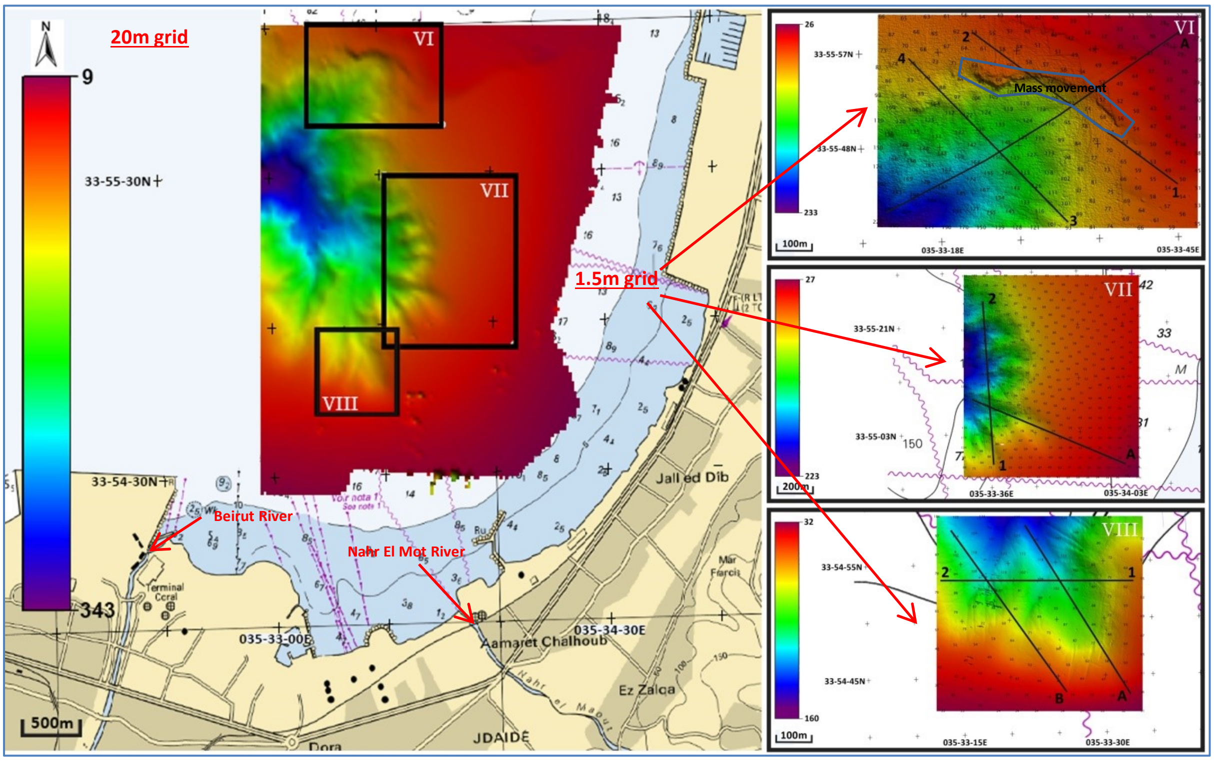


Fig. 7-15. High definition resolution of 20m grid showing shallow head part morphology and branches found at the inner shelf of the Saint George bay: from the Saint George canyon middle head (VI), (VII) and (VIII), achieved surface at resolution of 1.5m grid. Bathymetric profiles and transects are also shown.

The three large branches cited before at middle canyon head spread into many feeders; a high resolution surface of 20m grid put them in evidence at the middle head part (Fig. 7-15). Although, the canyon head is positioned close to two rivers (Nahr El Mot and Nahr Beirut), the human impact in the area, considering all chaotic infrastructures and human activities along the adjacent coast and rivers, blocks the natural cycle of sediment washing and nourishment.

The north middle branch reaches 2500m to shore, where its width is 300m. The morphology in the blue area marks the signature of a mass movement (Fig. 7-15, VI), and where depths range between 25 and 230m. It merges with the main Thalweg at 300m depth. No rivers input are found close to the north middle head. The main characteristic of the centre middle branch, at 2000m from the coast, is its expansion into many feeders that follow all an E-W direction with an overall width of 1000m, reaching the main Thalweg and forming its main axis at 250m depth (Fig. 7-15, VII). The southernmost branch is the closet to the shore at 1500m. It has two major channels with 300m width without any additional feeders. Naturally, this branch should be the more affected by the winter flow of the two adjacent land rivers.

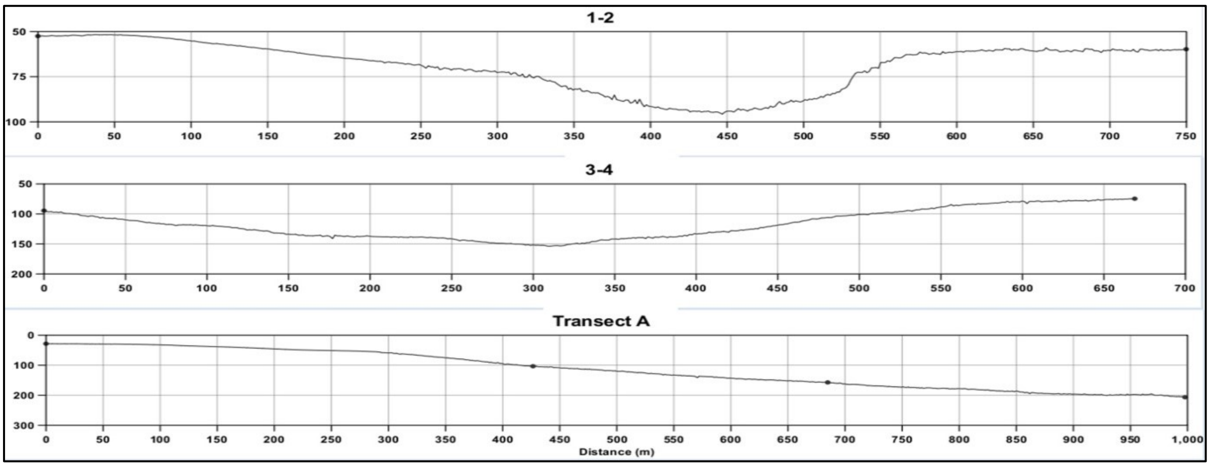


Fig. 7-16. Two series of cross profiles (alongshore) and one transect (across-shore) plotted at northern middle head (Fig. 7-15, VI) of Saint George canyon.

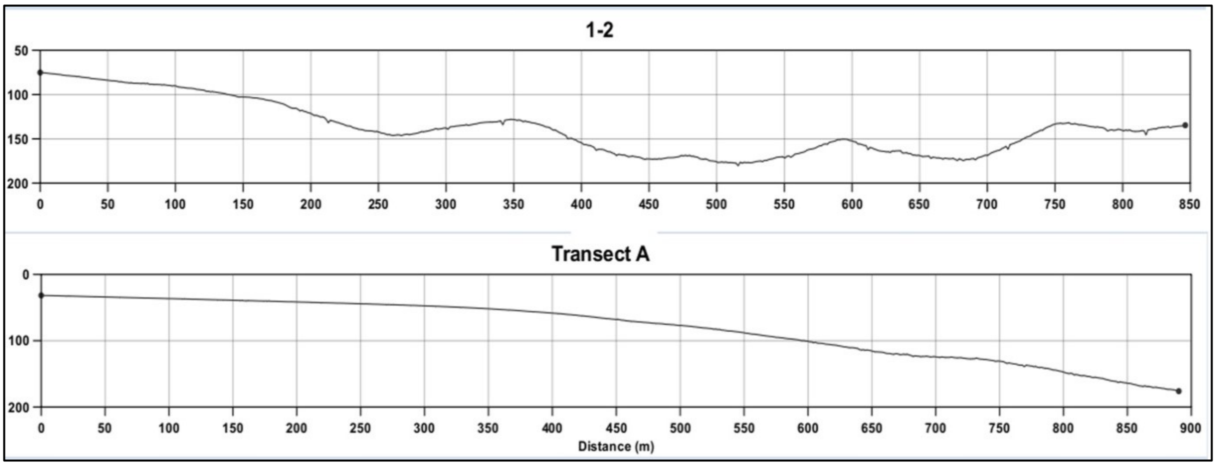


Fig. 7-17. One cross profile (alongshore) and one transect (across-shore) plotted at centre middle head (Fig. 7-15, VII) of Saint George canyon.

All branches at Saint George canyon head show no obstructions at all levels (Fig. 7-14). This is due to the steepness of the canyon main axis. Cross profiles and transects, conducted at middle head (Fig. 7-16, Fig. 7-17 and Fig. 7-18), demonstrate the nonexistence of bedforms because of the weakness of the current flow regime in the bay of Saint George.

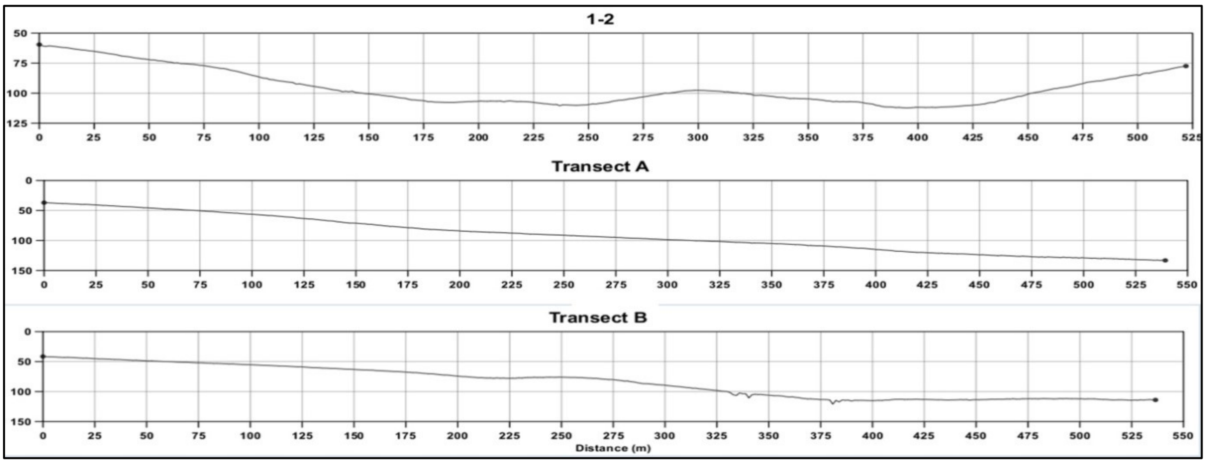


Fig. 7-18. One cross profile (alongshore) and two transects (across-shore) plotted at southern middle head (Fig. 7-15, VIII) of Saint George canyon.

7.6. Discussion: Sedimentary Processes In The Canyon Heads

The morphological analysis revealed the presence of several submarine canyons heads related to common sedimentary history, continental margin and basin. Unlike Nahr El Kalb canyon head and Saint George canyon head, the head of Jounieh canyon shows a V section shape that turns into a U section shape at 150m depth. This change in valley shape is unlikely due to eustatic sea-level changes as data shows that even during the Quaternary the lowest Sea-Level reached a depth of about 130m below present level (Antonioli, 2012). However, in a tectonically active area like the Lebanese coast, faults in conditions of low sea-level at around 140,000 BP may have caused changes in the base levels of the rivers that cut the canyon across the continental shelf, like the important fault and shear zone near Ras-el-Maameltein, roughly aligned with Jounieh canyon head, and described by Goedick and Sagebiel (1976). Present-day activity of Jounieh canyon head is reduced due to its isolation from the main sediment sources. Probably this canyon overall represents relict features, in contrast with its steep average slope and walls. The S-W current is the main governing cause of sediment movement alongshore inside Jounieh bay. Diversely, the Nahr El Kalb and Saint George canyons heads, are still participating in sediment movement through their connection with land rivers sources (Fig. 7-1); Nahr El Kalb, Nahr El Mot and Nahr Beirut rivers, which control the sediment across shore movement from inshore through shoreline, heads of canyons, down to middle and distal canyons. Future studies are needed, however, to identify the behaviour of two adjacent fields; the canyon field and the open slope field, by calculating the amount of sediment entering one canyon head and compare it to surrounding adjacent slope.

Goedicke and Sagebiel (1976) investigated in detail three canyons, the Jounieh Bay canyon, the Saint George Bay canyon and the Beirut Canyon located off the north shore of the headland of Ras Beirut (Fig. 7-19 and Fig. 7-20); the last canyon is presented in the figure 7-1, facing Ras Minat Al Houssein.

Samples of bottom sediments from the three canyons were obtained by means of a cone dredge developed by the authors and a small gravity corer (the core samples were x-rayed). The dredge samples were washed to remove interstitial water, then dried and sieved. The fine fraction, less than 4Φ, was analysed by the pipette method. The size distribution curves were drawn from the results of the combined dry sieving and pipette analysis.

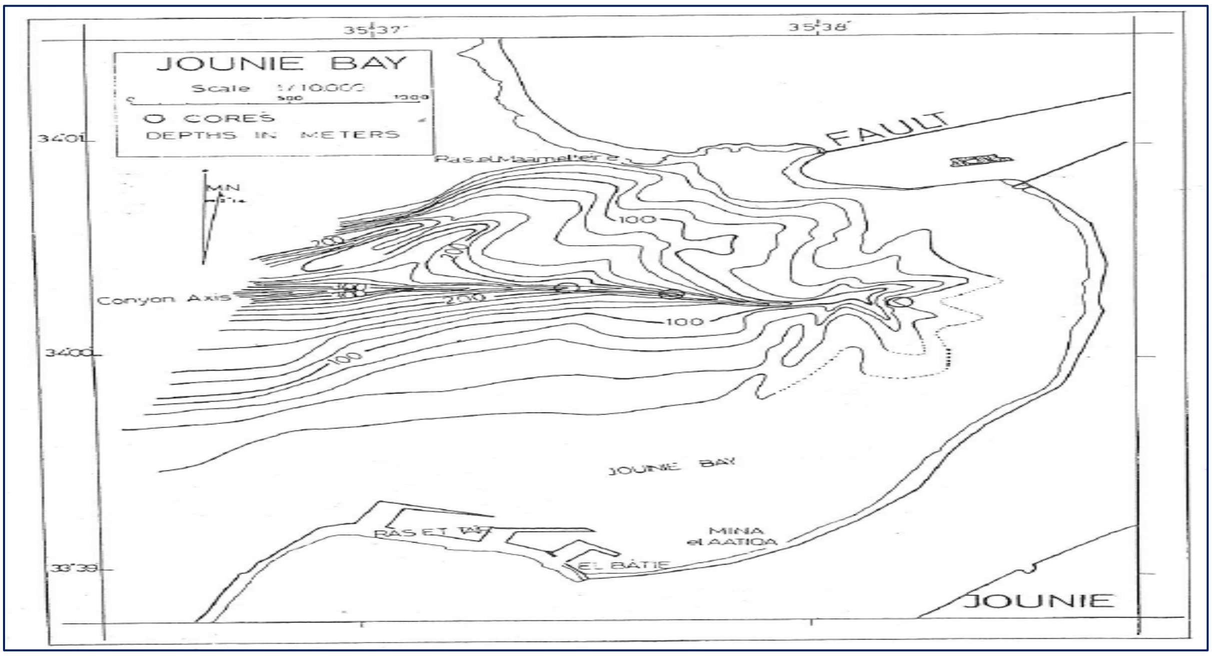


Fig. 7-19. Submarine topography of Jounieh Bay and the location of the gravity cores samples on the axis of the Jounieh canyon at depths of 40, 200 and 230m. (Goedicke and Sagebiel, 1976).

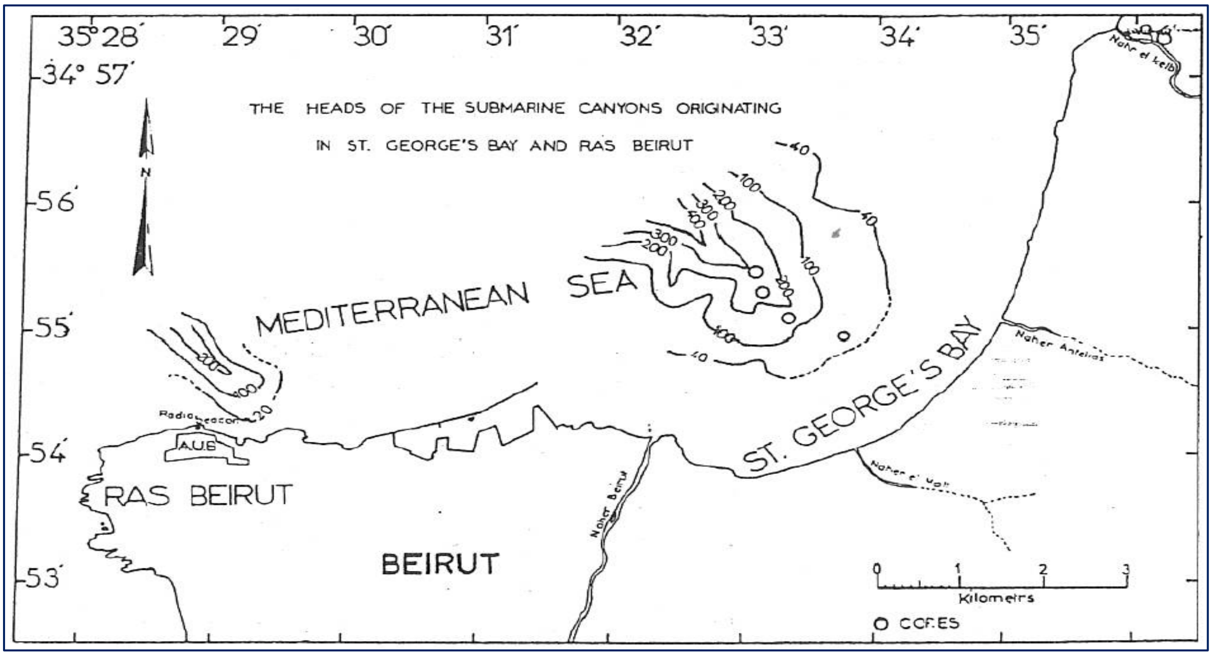


Fig. 7-20. Submarine topography of Saint George Bay and the location of the gravity cores samples on the axis of the Saint George canyon at depths of 45, 153, 240 and 284m. (Goedicke and Sagebiel, 1976).

According to Geodicke and Sagebiel (1976), and by analysing dredge and core samples for organic content, stratification and grain size, came to the conclusion of the very pronounced periodicity of the climatological pattern of Lebanon with its long period of drought during the summer, heavy rains with considerable runoff and erosion during the winter interspersed with periods of violent storms, high storm waves and swell along the Lebanese coast may have a marked effect on continental shelf sedimentation. Sediment movement including sand falls in submarine canyons have been observed to be connected with storm waves (Shepard and Dill, 1966).

The work of Geodicke and Sagebiel (1976) correlates with our research. It is known that submarine canyons channels transfer sediments from the continental shelf to deep water. Whenever a submarine canyon expands into shallow water cutting the continental shelf, like our case study canyons, its head intercepts long-shore drift sediment, removing it from the littoral zone. The sediment does not move directly into deep water, but remains stuck in the canyon head for a definite period ranging from months to years. According to Inman et al. (1976), the filling of the head continues until a combination of air, land, and sea conditions flushes away sand into deeper water, creating turbidity currents strong enough to highlight the role of submarine canyon head in the sediment movement. Transects conducted at different branches of canyons heads demonstrate the direction of the ‶gravity driven″ or/and ‶current driven″ downslope movement of sediment accumulated into the heads (Dingler and Anima, 1982).

Tributaries also enter our system canyon along its entire length; shallower ones, nearshore ones lay close to a series of historical sandy pocket beaches, disappeared now because of human impact. Water depth at the canyon rim, or shelf break, varies with location; it is less than 15m at its shallowest point in Jounieh Bay (Fig. 7-8, Transect A). Although the wave climate at the canyon heads is restricted by its location within respectively Saint George and Jounieh bays, storm waves from the southwest reach the area.

7.7. Conclusion

The Lebanese active margin plays a major role in the underwater dynamics being responsible for the main morphological features, thus it is the utmost cause of the sediment movement inside Lebanese submarine canyons. Therefore, major historical earthquakes appear to be the most probable mechanisms causing major slumps and providing sediments from the upper canyon reaches towards the basin. Despite that, there is a strong link between sediment supply from adjacent rivers, beaches, continental shelf and canyons, where a less energetic process provides an accumulation of shallow depth sediment inside canyons heads waiting to be moved down-canyon by a sort of failure (submarine landslide).

Our dissection of various canyons heads belonging to the Beirut-Jounieh canyon system (Fig. 7-1), and by using a combination of detailed morphological mapping (reaching 1.5m grid resolution) in addition to series of cross profiles and transects, indicates the presence of three different heads dynamics: the Jounieh canyon head that is affected mostly by the along-shore sediment transport (SW dominant current inside Jounieh Bay), the Nahr El Kalb canyon head where adjacent river flooding plays the major role in the movement of sediment in addition to alongshore movement blocking the prodeltaic deposit formation, and finally the Saint George canyon head isolated from the main land and continental shelf sediment transportation due to low energetic current circulation that does not deliver any sediment belonging to the emerging prodeltaic deposit on the adjacent shelf.

Conluding remarks

Throughout this study, a geomorphic and sedimentological characterization of the area between Jounieh and North Beirut in the Eastern Mediterranean sea has been conducted, mainly by means of a standard hydrographic approach. Despite the achievement of an environmental classification of the historical bay of Jounieh according to the remarkably characteristic as a memory recorder of the sediment in the area, this project aimed at monitoring the sediment movement inside the Lebanese submarine canyons (Jounieh-Beirut basin), both along and across the continental shelf with focus on the canyons heads according to a geomorphic approach.

Principles of hydrographic surveying are the key of this project to obtain data with high spatial resolution in order to evaluate the main geomorphic features such as sea bottom geometry. Moreover, the grid resolution to be used for seabed mapping should be directly linked to the scope of the analysis e.g. high resolution bathymetric survey allows the morphological characterization of the shallower part of the canyons heads (1.5m grid resolution), while it was sufficient to use a 25m grid resolution to define the canyons with their flanks and tributaries. Therefore, the results depend on the scale of the bathymetric grid used, the programs/algorithms used, data quality and on methodology applied taking into consideration that a proper interpretation of the possibility of artefacts was needed for a good interpretation of the continental shelf morphodynamics. Geomorphic structures identified from acoustic data contribute significantly to the knowledge base needed at coast, continental shelf and deep basin.

It is known that the wave action is a principal hydrodynamic phenomenon responsible for the bottom sedimentary processes in shallow waters (Furtado and Mahiques, 1989) and turbidity currents redistribute the trapped organic matter into deeper levels (Buscail et al., 1995). Therefore, in addition to the environmental analysis of the Bay of Jounieh which has proved that hydrodynamic factors combined to the narrowness of the continental shelf inside the bay played the major role in the distribution and deposition of particles, carrying the lighter particles away from the coast, the Lebanese active margin took also a part in the underwater dynamics; it is responsible for the main morphological features, thus it is the utmost cause of the sediment movement inside Lebanese submarine canyons. Major historical earthquakes appear to be the most probable mechanisms causing major slumps and providing sediments from the upper canyon reaches towards the basin. We deduce that the different interplay between tectonics and sedimentary processes is recognized as the main geological factor for distinguishing the evolution of these canyons (Lo Lacono et al., 2013), taking into consideration the strong link between sediment supply from adjacent rivers, beaches and continental shelf, where less energetic processes provide an accumulation of sediment inside canyons heads (shallow waters) waiting to be transported down-canyon by a sort of failure (submarine landslide).

A previous study on this same margin by Goedicke and Sagebiel in 1976 revealed a seasonal sediment movement downslope along canyon axes, reaching its maximum during winter months due to heavy swells which induce a resuspension of nearshore sediment in the bays surrounding the heads of the submarine canyons. This study correlates with our results, where the application of high resolution Multibeam bathymetry revealed the presence of several submarine canyons western Lebanon in the area between Jounieh and North of Beirut.

Although these canyons in the area of research belong to the same continental margin, share the same morphology characteristics and are located few kilometres apart, they display relevant differences in sedimentary processes. In the framework of this study the application of the same methodological approach to these canyons with same environmental characters allowed the following considerations:

- Our dissection of various canyons heads belonging to the Beirut-Jounieh canyon system, and by using a combination of detailed morphological mapping (reaching 1.5m grid resolution) in addition to series of cross profiles and transects, indicates the presence of three different heads dynamics:
    a. The Jounieh canyon head that is affected mostly by the along-shore sediment transport (SW dominant current inside Jounieh bay).
    b. The Nahr El Kalb canyon head where adjacent river flooding plays the major role in the movement of sediment in addition to alongshore movement impeding the prodeltaic deposit formation.
    c. The Saint George canyon head isolated from the main land and continental shelf sediment transport due to low energetic current circulation that does not deliver any sediment belonging to the emerging prodeltaic deposit on the adjacent shelf.
- The present-day activity of Jounieh canyon is reduced. It is due to its isolation from the main sediment sources due to human activities. The SW current is the main

generator of sediment movement and accumulation inside the canyon head waiting to be moved downslope inside the canyon.

- The Nahr El Kalb canyon is still a living canyon due to its relation with an active driver (Nahr El Kalb river), which controls the sediment across shore movement from inshore through shoreline, head of canyon, down to middle and distal canyon.
- The Saint George canyon, where its sediment movement is controlled by the geometry of the area.

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