This book is dedicated to the memory of Honor Frost and features her archeological bibliography plus a previously unpublished article on the relationship between Byblos and Egypt, one of her favourite themes. In addition to the excavation of two Punic warships at Marsala, Sicily, Honor Frost concentrated much of her research on marine anchors. Following a presentation by an oceanographic team from the University of Patras of the underwater context of Alexandria, its geomorphological formation and the dangers for navigators, the volume includes a catalogue of 100 anchors. These have been discovered along 15 km of coastline, between the area of the Eastern Harbour and Maamura, by three underwater archaeological missions, Egyptian, French and Greek. The finds bear witness to the strong concentration of maritime trade in the vicinity of this major Egyptian city.
This work has enjoyed the financial support of the Honor Frost Foundation.

Dédié à la mémoire de Honor Frost, cet ouvrage comprend sa bibliographie archéologique, puis un article inédit de sa main sur les liens entre Byblos et l'Égypte, l'un de ses thèmes de prédilection. Outre la fouille de deux bateaux de guerre puniques à Marsala (Sicile), Honor Frost a consacré une grande partie de ses recherches aux ancres marines. Après la présentation par une équipe d'océanographes de l'Université de Patras du paysage sous-marin d'Alexandrie, de sa formation géomorphologique et de ses dangers pour la navigation, le volume comprend un catalogue raisonné d'une centaine d'ancres découvertes depuis les abords du Port oriental jusqu'à Maamura, sur plus de 15 km de côte, par trois missions archéologiques sous-marines, égyptienne, française et grecque, témoignages de la forte concentration du commerce maritime aux abords de la mégapole égyptienne.
Cet ouvrage a bénéficié du soutien financier de la Honor Frost Foundation.

تخليدا لذكرى هونور فروست نقدم هذا العمل الذى يحتوى على قائمة أعمالها في علم الآثار ومقال لها غير منشور عن العلاقة بين بيبلوس ومصر وهو أحد المواضيع البحثية المفضلة لديها. فبالإضافة الى حفائرها على حطام السفينتين الحربيتين الفينيقيتين الغارقتين قرب سواحل مارساله بجزيرة صقلية، فقد ركزت فى معظم أبحاثها على المرساوات البحرية. ويحتوى الكتاب على دراسة لمجموعة من علماء البحار من جامعة باتراس اليونانية عن المشهد السكندرى تحت الماء من حيث تكوينه الجيومورفولوجى واخطاره على الملاحة ثم كتالوج لنحو ١٠٠ مرساة كشفت على سواحل الاسكندرية فى المنطقة الواقعة بين قلعة قايتباى غربا والمعمورة شرقا بواسطة ثلاث بعثات مصرية وفرنسية ويونانية. وهو ما يعد دليلا على قوة وضخامة النشاط التجارى البحرى لهذه المدينة العظمى.
هذا العمل مدعوم ماديا من مؤسسة هونور فروست.

Cover: Ships outside Alexandria's harbour in 1838
(David Roberts, 1846)

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Alexandria under the Mediterranean

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Archaeological studies in memory of Honor Frost

Centre d'Études Alexandrines

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Hellenistic Alexandria

A palaeogeographic reconstruction based on marine geophysical data

Introduction

Relative sea-level (RSL) variation is the combined result of: (i) eustasy which refers to the addition/subtraction of water to/from the global ocean due to the melting/forming of continental glaciers, (ii) glacio-hydro-isostasy which represents the response of the earth to changes in the surface ice and water loading during glacial cycles and (iii) local factors (sediment loading, tectonism-vertical displacement). Furthermore, short-term rapid natural hazards such as earthquakes, tsunamis, river flood and winter storm surges additionally contribute to subsidence (Stanley and Bernasconi, 2006). Particularly in the Mediterranean Sea, where the tidal excursion is low, the above long and short term processes have profoundly modified the coastal geological environment. Given the presence of strong geological indicators and archaeological remains, the Mediterranean coasts are considered an ideal environment for the reconstruction of past sea levels.

Ancient settlements and harbours originally placed at or near low-lying costal margins could be partially or completely submerged due to local relative sea level rise and/or subsidence of the land. In almost all of these cases, the determination of the relative sea level changes emerges as fundamental in the reconstruction of the ancient coastal geography. Tidal gauge data seems to be the most reliable method for the determination of relative sea level change (Wöppelmann *et al.*, 2013). However, the information obtained from this method covers only the time interval of the last century. For older time intervals, the usual methodological framework incorporates the detection

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and the detailed study of the submerged archaeological remains and/or the application of "land-based" classic geological methodology involving, for example, sediment coring and the study of coast geological markers (i.e. beachrock formations, notches; Empereur, 1998, 2000, Tzalas 2000, Vött, 2007, Nixon *et al.*, 2009, Desruelles *et al.*, 2009). Lithologic analyses of dated material collected mainly onshore (and rarely offshore) can provide reliable evidence for the rates of relative sea level changes. However, the results of this method can prove misleading in the determination of the regional chronostratigraphy. This is due to the fact that the organic material that is available for dating has often been reworked by sedimentary (in particularly in deltaic environments) and biological processes (i.e. in cases of beachrock formations) and thus incorporates uncertainties in the dating analysis. In addition, depending on the geomorphological characteristics of the study area and the quantity and locations of the selected samples for analysis, the information for the coastal palaeogeography can incorporate the risk of an extremely local value. In this context, Stanley and Toscano (2009) proposed that the subsidence rates derived from basal radiocarbon dates in sediment cores represent long-term average rates rather than the shorter, more-precisely and well-dated intervals derived by archaeological data. Therefore, if the exact ancient location and elevation of the detected coastal archaeological sites or remains are determined in relation to sea level then these sites can prove excellent sea level markers.

On the other hand, the refinement of applicable "marine-based" high-resolution seismic techniques and the improvement of visual inspection techniques have prompted the investigation of offshore sites. Marine remote sensing techniques such as side scan sonar and seismic profiling systems are capable of detailed mapping of the seafloor texture and stratigraphy, thus providing information for the configuration of the coastal palaeogeography and the detection of human presence along ancient coastlines. A synthesis of marine geophysical data and sedimentary data appears as the most reliable evidence in the construction of the evolution of the submerged landscape incorporating documentation of the relative sea level variations (Van Andel and Lianos, 1984, Shennan *et al.*, 2000, Papatheodorou *et al.*, 2008).

This paper presents the results of the application of marine remote sensing techniques to offshore Alexandria. Alexandria was founded by Alexander the Great in 332-331 BC and soon became a metropolis in the Hellenistic and Roman periods. Detailed descriptions of ancient writers and ruins of palaces, statues, obelisks and tombs are the silent witnesses of the famous city. In a distinguished position is the famous Lighthouse of Pharos, which was destined to be one of the seven wonders of the ancient world. Alexandria owed its vigour largely to its port, the *Megas Limen* (Eastern Harbour), which controlled trade in the eastern Mediterranean in antiquity. In the coastal zone of Alexandria, almost all the ancient coastal developments have been detected in underwater sites indicating a marine transgression in the last 2300 years (Empereur, 1998, 2000, Goddio, 1998, 2000, Tzalas, 2000). This suggests that part of Ptolemaic Alexandria is currently below present sea level and thus the coastal margin of Alexandria is one of the most promising areas in the world for archaeological studies.

So far, investigations into the coastal palaeogeography of the Alexandrian and Nile Delta coastal margin have been based on sediment core analyses and submerged archaeological sites. To calculate subsidence rates and to reconstruct the palaeogeographic evolution along the coastal zone, the studies have tended to concentrate on (i) Holocene radiocarbon dates and litho-stratigraphies (Flaux *et al.*, 2012, Marriner *et al.*, 2013, Sneh *et al.*, 1986, Stanley and Warne,

1993, Stanley *et al.*, 1996, Stanley *et al.*, 2007, Stanley *et al.*, 2008), (ii) benthic biofacies and pollen proxies (Bernasconi *et al.*, 2006, Stanley and Bernhardt, 2010), (iii) geochemical proxies (Pb, 204Pb/206Pb) (Stanley *et al.*, 2008, Véron *et al.*, 2013) and (iv) GPS and PSI (Persistent Scatterer Interferometry) measurements (Wöppelmann *et al.*, 2013).

The aim of this paper is to reconstruct the coastal palaeogeography of Alexandria at the time of its foundation using marine-based geophysical data and thus to obtain the sight view of Alexander the Great at the time he chose to occupy this site and to develop there a city named after himself. The deductions of the present study will be based on detailed bathymetric, geomorphological and geological data collected offshore from Alexandria in conjunction with the subsidence rate derived from the submerged archaeological sites of the study area.

Coastal configuration of Alexandria during the Hellenistic and Roman periods

Alexandria was developed on a tombolo, which is located in a strip of land limited by the eastern Mediterranean Sea to the north and Lake Mariut at the south (**fig. 1, 2**). A small village called Rhakotis existed there (Strabo, XVII, I, 6) and just opposite it, a small island called Pharos. Pharos Island is cited in Homer's Odyssey (IV, 354-355), indicating that the area was familiar to ancient Greek mariners. Little is known about Rhakotis because the site has yet to be clearly identified beneath the modern city (Stanley *et al.*, 2007). Recent studies have suggested that Alexandria arose from a pre-existing population nuclei whose inhabitants had long before recognized the favourable harbour potential of this part of the Egyptian coastal sector. Based on Pb isotopic analyses, Stanley *et al.* (2007), have confirmed human activity in the coastal zone where Alexandria would later be established at least seven centuries before 332 BC (ca. 1000 BC).

The construction of Alexandria led to the first change in its coastal zone. Dinocrates, the architect of Alexandria, linked the Pharos Island to the mainland by a narrow causeway-aqueduct complex, called Heptastadion (*seven stadia* long, 1300 m) (**fig. 1**). The Heptastadion was built on a pre-existing shallow marine topographic elevation and its construction separated the coastal waters of Alexandria into two parts forming two harbours; the eastern Great Harbour (*Megas Limen*) and the western harbour or *Eunostos*. A monumental lighthouse with a height of over 100 m was constructed at the eastern end of the island of Pharos and gradually became the landmark of Alexandria. The Eastern Harbour was the main port of Alexandria and by Roman times the coastline bordering the harbour had been distinctly reshaped. The palaces of the city, the royal gardens and the government buildings were built along its coastline and mainly on Cape Lochias, a promontory bordering the eastern side of the harbour.

Strabo (XVII, I, 9) left a picturesque description of the survey area as it was around 25-20 BC: "In the Great Harbour at the entrance, on the right hand are the island and the tower Pharos, and on the other hand are the reefs and also the promontory Lochias with a royal palace upon it; and on sailing into the harbour one comes, on the left to the inner royal palaces which are continuous with those on Lochias and have groves and numerous lodges painted in various colours..."

In the course of time the Eastern Harbour has been modified. The Pharos lighthouse does not exist anymore. It seems that it was completely destroyed between 1303 and 1349 AD by an earthquake and at its site the Mamluke Sultan Qaitbay built a fort (Qaitbay Fort) in 1480. Cape Lochias has been reduced in extent to the present-day el-Silsileh promontory. The Heptastadion became wider due to progressive silting up and loss of the original linear shape.

The island of Pharos is today a heavily urbanized peninsula, 3.2 km long by 1 km wide, linked to mainland Alexandria by a 1.2 x 0.7 km isthmus (Mansheya isthmus), which developed around the ancient Heptastadion. The Eastern Harbour is now a shallow and almost enclosed, elliptical basin with a width of about 2.5 km from the western coastline (*Heptastadion*) to el-Silsileh promontory at the east. The Western Harbour (10 km long by 2.5 km wide) is deeper than the Eastern and constitutes the main port of the modern city of Alexandria.

Geological background

Alexandria is positioned on a straight SW to NE-oriented low-lying coastline at the western part of the modern Nile Delta. A thin (10-40 m) Holocene sequence of unconsolidated deposits covers Quaternary and Tertiary sequences of the Nile Delta (Stanley and Warne, 1993). The thickness of the Holocene sequence and the depositional environment within vary considerably across the northern Delta. The thickness increases eastward, reaching a maximum of about 50 m in the modern Manzala lagoon and a minimum (<10 m) in the extreme west of the Delta, in the Alexandria and Abukir regions. The fivefold thinning of the Holocene deltaic sequences from east to west indicates differential subsidence resulted in a general north-eastward tilting of the Delta plain surface (Stanley and Toscano, 2009).

The coastal zone of Egypt from the Arab's Gulf to Abukir is dominated by a series of long coast-parallel ridges (at least, eight in number) of carbonate sandstone (Stanley and Bernasconi, 2006 and references within) (**fig. 2**). Such coastal ridges are moderately to well-cemented limestone that was formed mainly of whole and broken shell, pellets and oolites along with some quartz and heavy mineral grains. These features have been interpreted as shallow marine bars, mixed beach and aeolian ridges (El-Asmar, 1994), or as non marine coastal dunes. However, the presence of the beach boulders at the bottom of ridges and the existence of foraminiferal limestones and molluscs support the marine origin of the ridge core, while the development of aeolianites and paleosols suggests that wind action and soil processes contributed to further development of these ridges during periods of lower sea level (Hegab and El-Asmar, 1995). These ridges are commonly called *kurkar* in the eastern Mediterranean.

Two of these ridges, Ridge I and II seem to have been the main factors which shaped the coastal configuration in the area of Alexandria (**fig. 2**). Ridge I is located offshore and constitutes the northern margins of the two ports of Alexandria by the forming of linear, discontinuous, emerged to shallow submerged, islets and reefs (**fig. 2**). The age of Ridge I ranges from 4360±40 to 600±100 yr BP (El-Asmar and Wood, 2000).

Ridge II or el-Maks-Abusir Ridge is of late Pleistocene age (about 90±15 ka, 110±5 ka BP; El-Asmar and Wood, 2000) and forms a linear high-relief carbonate (**fig. 2**). This ridge separates the shallow brackish Mariut lagoon, to the south and the open marine shelf to the north and forms a zone of land upon which the cities of Alexandria and Abusir (45 km westwards) were built.

Alexandria's Tombolo

From a geomorphological point of view, Alexandria, ancient and modern, is positioned on a tombolo that interrupts the straight SW to NE-oriented low-lying coastline at the western part of the Nile Delta. The geomorphologic evolution of that tombolo has played an important role in the habitation of this Egyptian coastal sector as well as the establishment and development of the city of Alexandria. The tombolo separates the Western and Eastern Harbours of Alexandria and the Heptastadion was built on a sand spit linking the mainland with the Pharos barrier island.

Sediment core data collected in the proximity of Heptastadion has shown a series of phases in the formation and evolution of Alexandria's tombolo (Marriner *et al.*, 2008). Phase 1 is attributed to marine flooding (8000 to 6000 cal yr BP) and is well correlated to the flooding of deltas throughout the Mediterranean Sea. Phase 2 corresponds to the accretion of the proto-tombolo (6000 to 2400 cal yr BP). Between 5400 and 4200 BP a biodeposition took place due to the erosion of bioherms. Between 4000 and 2000 BP, a very important sediment hiatus was recorded. This decrease of sediment supply, which began 5000 yrs BP (Marriner *et al.*, 2013), could be correlated to the drowning of Pharos barrier island and consequently with the enhancement of the westerly long shore currents that prevent the sediment deposition. At this period, an open marine environment was established inside the eastern bay (harbour) (Bernasconi *et al.*, 2006). Isotope data collected from Lake Mariut further support the fall in sediment supply 5000 yrs ago since a striking increase in marine inputs has been recorded in the lagoon (Marriner *et al.*, 2013). The 4000 cal BP decrease in sediment supply has also been observed in other East African palaeoclimatic archives (Thompson *et al.*, 2002).

During Phase 3 (after 2400 cal yr BP) Alexandria's tombolo has been heavily modified by human intervention and by a very high subsidence rate due to a tectonic collapse (Marriner *et al.*, 2008).

Relative sea level (RSL) and subsidence rate

The wider area of the Nile Delta has received considerable attention with regards to the evolution of sea level rise. Although the study area is located on a relatively tectonically stable margin of NE Africa, instabilities have resulted from readjustment to downwarping of the thick sediment sequence (4000 m) due to isostatic lowering, faulting and sediment compaction. The relative sea level rise seems to be the main factor for the predynastic occupation of the Nile Delta. Stanley and Warne (1993) suggest that the change in sea level rather than regional climate factor is the driving force in the accumulation of Nile silt, the creation of the widespread and fertile delta plain and therefore the predynastic occupation of the Nile Delta. Sea level rose rapidly from 125 to 16 m below its present stand, between 18000 and 8000 years BP, reaching a rate of 9 mm/yr. The rate of sea level rise decelerated to 1 mm/yr, from about 7000 to 5000 BC. The sea level rose to about 12 m below present stand at 6000 BC. At that time river gradients decreased and a system of meandering Nile distributaries began to deposit large volumes of nutrient-rich sediments. By 4 ka BP the sea level continued to rise slowly and by 2 ka BP sea level had risen to about 2.5 m below present level. By that time, the Nile Delta had developed to a wave dominated system and the human population had increased, particularly in the Alexandria sector.

As mentioned above, in the north-eastern part of the Nile Delta, the high thickness (60 m) of the Holocene deltaic deposits is responsible for the high subsidence rates (5 mm/yr) (Stanley and Toscano, 2009). On the contrary, at the north-western part of the deltaic plain in Alexandria, the very thin Holocene layer which covers the *kurkar* and the Pleistocene sandstone permits an assumption of a considerably lower subsidence rate. Although the general westward thinning of the Holocene deltaic sequence indicates a minimum rate of subsidence (<1 mm/yr) in Alexandria and Abukir region, archaeological and oceanographic data suggest a considerably higher rate of subsidence for the coastal area of Alexandria.

The subsidence of the coastal zone of Alexandria is well documented by short-term (tide-gauge data) and long-term (archaeological data, radiocarbon-dated sediment cores) observations **(table 1)**. Tide-gauge records are a valuable source of sea level rise over multi-decadal to century timescales. Tide-gauge data suggests that Alexandria has been subsiding during the last 60 years at a rate of 2 mm/year (Frihy, 1992). In a more recent work, Frihy *et al.* (2010) suggest that the Alexandria coastal plain is considered to be relatively stable with a land subsidence ranging from 0 to 0.5 mm/yr. The combined analysis of GPS and PSI (Persistent Scatterer Interferometry) data has shown that most of the Alexandria coastal region can be considered as stable or undergoing moderate subsidence and only locally can reach higher values of up to 2 mm/yr (Wöppelmann *et al.*, 2013). Greek and Roman settlements along the coastline are 5 to 8 m below the present sea level (Frihy, 1992). Jondet (1912, 1916, 1921), the Chief Engineer of the Department of Ports and Lighthouses, mentioned the presence of linear rocky formations at a water depth ranging between 6.5 and 8.5 m below the sea surface in 1915. He interpreted them as submerged ruins of an ancient breakwater of the western port of Alexandria, but according to recent research, these submerged formations are natural rocky features that probably belong to a drowned part of Pharos Island. Submerged ancient harbour facilities were discovered in the Eastern Harbour at a water depth of about 6-7 m (Goddio, 1998, 2000). All the above suggest that the coastal morphology of Alexandria is now markedly different from what it was 2300 BP.

Archaeological background

The Eastern Harbour of Alexandria has undergone three underwater archaeological surveys in the last 15 years. Jean-Yves Empereur (1998, 2000) has uncovered 2500 pieces of stonework of archaeological interest, scattered over 2.5 hectares off Qaitbay Fort **(fig. 1)**. These include columns, capitals, bases, statues, sphinxes, and some blocks of granite that were probably elements of the great Pharos Lighthouse. The Institut Européen d'Archéologie Sous-marine under the direction of F. Goddio detected, located and mapped submerged harbours, jetties and dock works in the southern and south-eastern sectors of the Eastern Harbour of Alexandria which are considered to be remains of ancient Antirhodos and Timonium, and submerged port facilities, probably ancient *navalia*, in the western sector of the harbour (Goddio, 1998, 2000) **(fig. 1)**. Tzalas (2000) discovered three architectural elements weighing 4, 10 and 12 tons, which are located on the seafloor adjacent to the eastern side of el-Silsileh promontory at a water depth of 7 m **(fig. 1)**. These pieces are probably remnants of the Temple of Isis Lochias, which was located at the tip of ancient Cape Lochias. The northern part of the ancient Western Harbour (*Eunostos*) was studied by G. Jondet (1912, 1916, 1921) during his work on improving and expanding the modern harbour. He claimed to have discovered two submerged breakwaters almost parallel to each other; (i) the inner ancient great breakwater extending 2360 m at a water depth of about 4.5 m and at a distance of 300 m north of the coastline and (ii) the outer submerged ruins of the breakwaters, 200 m to the north of the inner and at water depths ranging from 6.5 to 8.5 m. However, his definition of these features needs to be reassessed by an underwater survey with facilities which were not available in the 1910s. Lastly, Empereur (2000) has discovered four Greek and Roman shipwrecks 300 to 600 m to the north of the entrance of the Eastern Harbour. The most striking fact of this discovery is that the ships sank close to the Pharos lighthouse and at a time when the lighthouse was operational.

Material and methods

Survey area

The geophysical survey was conducted on board two zodiacs and a 10 m-long vessel that were suitably modified for the needs of the survey, over an area of approximately 32.5 km^2 in the coastal zone of the city of Alexandria **(fig. 3)**. The survey area extends from Qaitbay Fort site, where the ancient Pharos lighthouse used to stand, to Stanley Bay about 4.6 km to the east of el-Silsileh (ancient Cape Lochias) promontory and from a water depth of about 2-3 m to about 45 m **(fig. 8)**. Numerous underwater discoveries have made the study area one of great archaeological significance.

Instrumentation and survey design

The Laboratory of Marine Geology and Physical Oceanography of the University of Patras carried out geophysical surveys during seven campaigns from 1999 until 2006. The scientific campaigns took place in partnership with the Centre d'Études Alexandrines (CEAlex) under the direction of J.-Y. Empereur, the Hellenic Institute of Ancient and Medieval Alexandrian Studies (H.I.A.M.A.S) under the direction of H. Tzalas and the Department of Underwater Archaeology of the Supreme Council of Antiquities of Egypt.

The geophysical survey was carried out using two acoustic systems: (i) a side scan sonar system consisting of a dual frequency E.G&G 272 TD towfish **(fig. 4a)** and an analogue corrected image graphic recorder E.G&G 260 **(fig. 4b)** and (ii) a high frequency 3.5 kHz sub-bottom profiling system consisting of an O.R.E. model 132A/132B over-the-side four transducer array **(fig. 5a)** with a model 1600 EPC "S" type Graphic Recorder **(fig. 5b)** and a model 5430A GeoPulse Transmitter and a model 5210A GeoPulse Receiver **(fig. 5c)**. Positioning data was obtained by a Trimble 4000 Differential Global Positioning System (DGPS) **(fig. 6)** with an RMS accuracy of 2 m and a Magellan NAV 6500 GPS **(fig. 7)** with an accuracy of about 10 m. The data were collected at a boat speed of about 4 knots.

Side scan sonar has been defined as an acoustic imaging device used to provide two-dimensional, high-resolution images of the seafloor. Under optimal conditions it generates an almost "photo-realistic picture" of the seabed, commonly called a sonograph, that provides information on sediment texture and seafloor morphology. The E.G&G 260/272 TD side scan sonar is a dual frequency system operating at 100 and 500 kHz. Only the 100 kHz signal was interpreted because this frequency provides a wide spectrum of acoustic backscatter pattern regarding the variety of seabed texture. In the Alexandria side scan sonar survey, high backscatter (hard seafloor) is represented by dark tones and low backscatter (soft seafloor) by light tones, on the sonographs. The same side scan sonar acquisition settings were used during each survey period.

A total area of 32.5 km2 was insonified by over 50 tracklines. The majority of them were running parallel to the coastline while about 20 lanes were running vertical to the northern breakwater of the Eastern Harbour of Alexandria (**fig. 8a**). The water depth varied between 2 and 45 m. In most tracklines, the range of each lane was 100 m for each side and the lane spacing was 150 m providing a 50% range overlap. The towfish was towed above the seafloor at a height ranging between 10 and 50% of the slant range.

A high-resolution sub-bottom profiling system provides an acoustic profile of a narrow section of the sub-bottom beneath the path over which the device is being towed. Sixty 3.5 kHz sub-bottom profiler lines covering a total area of about 21 km² were surveyed (**fig. 8b**). The seismic lines were running perpendicular to the north breakwater of the Eastern Harbour with a spacing of 50 to 100 m. A time base of 0.1 s and a 0.1 ms pulse length were used. The vertical resolution of the system was less than 0.5 m and even in water depths less than 10 m, a maximum penetration of about 4-5 m was achieved.

All side scan sonar and seismic data were recorded in analogue format and stored as paper copies. For the post-survey processing analogue data were scanned, imported and georeferenced into the ArcView environment. A detailed description of the data post-processing approaches has been presented by Chalari *et al.* (2008).

Similar geophysical techniques have been used in underwater archaeology in order to reconstruct the coastal palaeogeography (Van Andel and Lianos, 1984) or to detect archaeological sites in shallow and deep waters (Quinn *et al.*, 2000, Papatheodorou *et al.*, 2005, Sakellariou *et al.*, 2007).

Results

The interpretation of side scan sonar data has shown that the seafloor is covered by rocks and loose fine-grained sediments (**fig. 9**). The rocky seafloor covers about 70% of the surveyed zone and is characterized by areas with highly irregular rocky relief and areas with smooth relief (**fig. 10**). About 30% of the surveyed zone is covered by sand and sandy-mud sediments, as is indicated by the low backscatter (light tones) on the sonographs (**fig. 11**). Within the sand covered seafloor, there are large areas, where the sand is rippled by the waves (**fig. 12a**) and large areas characterized by scattered rocks (**fig. 12b**).

Sonographs collected from the same areas during three successive (04/1999, 10/1999 and 11/2000) small-scale surveys conducted at selected sites of potential interest, showed differentials in the backscatter response of the sandy-mud floor. The variation in the acoustic signature of the seafloor with time corresponds to changes in variations of the sediment texture. For example, a low-relief (few tens of cm) target which had been detected during the first survey period (**fig. 13a**) appears on sonographs to be covered by loose sediments during the second (**fig. 13b**) and the third (**fig. 13c**) survey periods. Similarly, a low backscatter (light tone) area of the seafloor, which had been detected in the first survey period, portrays a completely different acoustic backscatter pattern on sonar images in the next two periods (**fig. 14**). Scattered high reflectivity patches had been detected inside the light-toned area of the seafloor (**fig. 14a**). These patches were not detectible on sonograph during the second period (**fig. 14b**) but exhibited narrow zones of acoustic shadow on sonograph collected during the third period (**fig. 14c**). The fact that narrow acoustic shadows accompany those patches suggests that they can be considered as shallow crater-like features. The origin of these patches was unknown at the time of the side scan sonar survey.

The potential factors, which appear responsible for the temporal backscatter variation and the distribution of low and high backscatter areas, are hypothesized to be the wave-induced sediment transport and the untreated sewage input of the city of Alexandria. The latter hypothesis is further supported by the visual inspection of the second selected area. The seafloor is covered by black cohesionless organic mud of anthropogenic origin. Small dish-shaped craters were observed on the seabed that may be related to gas (H_2S, CH_4) seepage due to the degradation of organic matter.

The combined study of the bathymetric, morphological and seismic data collected along a very dense grid of tracklines showed that the morphobathymetry of the survey area can be focused on four morphological sectors (**fig. 15**):

(i) a dipping rocky seafloor, surrounding the Eastern Harbour and the straight coastline of Alexandria (eastwards of Cape el-Silsileh), down to a water depth of about 16 m (**fig. 15**). This morphological element appears more steep north of the Eastern Harbour (and in particular off its entrance) and wider (1.0 km) eastwards, along the straight coastline (**fig. 15**). Within this zone there are extensive areas of highly irregular rocky relief and small areas of smooth rocky relief. Among the most important highly irregular rocky relief areas in the coastal zone of Alexandria is el-Hassan reef. El-Hassan reef is an elongated ridge, which extends vertically to Alexandria's coastline and almost parallel to el-Silsileh (ancient Cape Lochias) (**fig. 16**). The minimum water depth of this reef is about 8 m. The reef has an irregular rocky relief as is indicated by its particular acoustic pattern (high reflectivity-acoustic shadow) on sonographs (**fig. 16**). A very sharp limit between the north-eastern side of the reef and the sandy seafloor was observed on the sonographs (**fig. 16**). In el-Hassan reef, Tzalas (2013a) mentioned the presence of a Roman shipwreck with a scattered cargo of broken amphorae and an enormous amount of broken pottery. The shipwreck dates to the 2nd-3rd century AD and is lying at a depth of 9 m to 13 m. Moreover, the seafloor adjacent to the eastern coast of the el-Silsileh exhibits a unique backscatter geometrical pattern on the sonographs (**fig. 17**). The Greek mission in Alexandria found 13 architectural elements made of granite in this area (Tzalas, 2013b). Three of them are very large in size, weighing several tons each.

(ii) a well-shaped rocky ridge (Ridge -I), 6-14 m high and about 700 m in width (**fig. 15, 18**). The minimum water depth of this ridge is between 11 and 12 m forming a narrow planar strip (**fig. 19**). Ridge -I is located about 1.0 km north of the Qaitbay fort where the Pharos lighthouse used to stand and about 1.5 km north of the present-day entrance of the Eastern Harbour (**fig. 15, 18**). The Ridge -I runs almost parallel to the contours and present-day shoreline and has a dominant strike direction of about -450 (**fig. 15, 18**). Sonographs display the ridge as highly reflective stripe, sharply contrasting against the low reflectivity of the surrounding seafloor, which is covered by loose sediments (**fig. 20**). Examination of the sonographs showed that the ridge presents a backscatter geometrical pattern made of patches or smaller strips of high reflectivity (**fig. 20**). It should be mentioned that the boundaries configuration of the ridge is also controlled by the wave-induced transportation of loose sediments (**fig. 20**).

(iii) a submerged tombolo-like rocky feature which consists of: (a) the Ridge -I and (b) an elongated rocky ridge of NW-SE direction, 1.5 km long and 300-400 m wide, which runs perpendicular to Ridge -I (**fig. 15**). This feature strongly resembles the Heptastadion-Pharos Island tombolo (**fig. 15**). The NW-SE trending ridge separates two basin-like depressions of about 22 m and 30 m deep (**fig. 15**). The eastern and deeper basin is covered by loose sediments of a thickness of more than 10 m.

(iv) the gently dipping seafloor down to a water depth of 45 m which is bounded upslope by Ridge -I (**fig. 15**). Within this area five individual rocky ridges of low relief were detected. The ridges are between 20 to 650 m wide and about 40 to 800 m apart. These features are located between the 28 m and 45 m isobaths and run parallel to Ridge -I and the present day coastline.

Detailed examination of the 3.5 kHz profiles on the rocky seafloor surface around the Eastern Harbour reveals numerous small scarps which appear as sharp breaks in the overall slope gradient of the rocky surface (**fig. 21**). The spatial distribution of the depth occurrence of each scarp shows that the scarps are not randomly distributed but rather gathered in clusters that correspond to selective water depths. The water depths in which the scarps are clustered are at 16 m, 14 m, 12 m, 10 m and 8 m. The non-random distribution of the scarps with regard to water depth suggests that they have been correctly identified as erosional shore features representing markers of paleoshorelines. The spatial distribution of their occurrence has shown that the palaeoshorelines on the seafloor are continuous for long distances running almost parallel to the present coastline. Among them, the palaeoshoreline at 8 m water depth is the best shaped and defined on the rocky seafloor around the Cape el-Silsileh and the Qaitbay Fort site (**fig. 22**).

Linear elongated targets extending perpendicular to the coastline of Alexandria and parallel to sub-parallel to Cape el-Silsileh, were observed in water depths of 5 to 8 m (**fig. 23a, b**). These linear, ridge-shaped targets were detected on a sandy seafloor, eastwards of the Cape el-Silsileh (**fig 23a, b**). They are at most 135 m long (within the surveyed area) and 5-20 m in width (**fig. 23c**). At least in one case, at a water depth of about 6 m, these features appear to cross each other almost vertically (**fig. 23c**). Their particular acoustic pattern on sonographs (**fig. 23c, d**) indicates that these linear targets consist of big blocks of certain shape and probably represent submerged man-made structures.

Discussion

The combined interpretation of the acquired bathymetric, sub-bottom and side scan sonar data revealed two geomorphological features as the main elements to the construction of the ancient coastal paleogeography of Alexandria: indicators of a series of palaeoshorelines and a

submerged ridge (Ridge -I). The series of palaeoshorelines detected on the seismic profiles are almost parallel to each other and to the present coastline and obtained at water depths of 16 m, 14 m, 12 m, 10 m and 8 m, suggesting that their formation is related to past sea level stands. Ridge -I is almost parallel to the present coastline, of about 3.6 km long, located at around 1.0 km offshore, at a minimum water depth of 12 m. The geomorphological characteristics of that ridge present similarities with the parallel ridges obtained onshore and offshore of the coastal zone of Alexandria. Ridge -I is accompanied by a rocky ridge which runs almost perpendicular to Ridge -I and to the present coastline. This submerged feature present similarities to the present Heptastadion-Pharos island tombolo and although its age is unclear it provides implications for a repeated configuration pattern dominating the coastal zone of Alexandria.

The evolution of the coastal palaeogeography of Alexandria seems to have been affected by climatic changes and relative sea level changes. Global and local climatic changes (i.e. variations in monsoonal precipitation) have caused variations in the dust accumulation (Woronko, 2012) and the sediment supply in the coastal zone (Marriner *et al.*, 2013). The climatic changes also provoked sea level changes in response to eustatic and to glacio-hydro-isostatic impacts. The latter impact is expected to be strong in the study area due to the proximity of the area to the deltaic system of the Nile. The predicted relative sea level change in the last 2500 years due to eustatic and glacio-hydro-isostatic impact is estimated as a rise of between 2.5 m (global sea level rise; Fairbanks, 1989) and 0-0.5 m (eastern Mediterranean regions; Sivan *et al.*, 2001, Lambeck and Purcell, 2005) indicating a maximum rate of sea level rise of 1 mm/yr.

However, the archaeological data along the coastal zone point to a higher rate of sea level rise. The majority of the port foundations, the monuments and the artefacts of the Hellenistic and Roman periods (~2100 BP) retrieved from the Eastern Harbour were detected at water depths between 5.0 and 6.5 m below the present sea level (corrected to about 1.0 m for the elevation foundation of the structure in relation to sea level; Goddio, 1998, p. 23). These observations indicate a rate of sea level rise between 2.9 and 3.6 mm/yr, in the last 2100 yrs.

Higher rates of sea level rise than the predicted eustatic and glacio-hydro-isostatic sea level are also obtained from the tidal gauge data from the coastal zone of Alexandria, in the last 70 years, ranging between 1.6 and 2.9 mm/yr (**table 1**).

The above discussed differences between the predicted rates of sea level rise and those obtained from the submerged archaeological and tidal gauge data indicate a local subsidence contribution up to 1.4-3.4 mm/yr. Vertical displacements of the coasts are often employed to explain relative sea level changes in the eastern Mediterranean region since this area is characterized by highly seismic activity. Implications of the tectonic impact to the relative sea level changes in the coastal zone of Alexandria have been referred to in previous studies. Stanley and Bernasconi (2006) and Stanley *et al.* (2006) indicate that the further subsidence in the coastal zone of the Eastern Harbour is related to collapses of the seafloor and associated gravity movements due to heavy harbour constructions or catastrophic events such as earthquakes and tsunamis. Marriner *et al.* (2008) proposed a tectonic collapse (~6 m) to explain the rapid submersion of the Heptastadion-Pharos tombolo between the 7th to 9th century AD. However, vertical displacement rates averaged over hundreds or thousands of years are not necessarily the same for shorter time intervals since the tectonic movements which are related may be co-seismic and discontinuous incorporating even intervals of inverse behaviour (Tsimplis *et al.*, 2011). Wöppelmann *et al.*

(2013) employ similar suggestions to describe the subsidence rate (0.4 mm/yr in average and up to 2 mm/yr locally) obtained in the coastal zone of Alexandria from the tidal gauge data. The authors suggest that on multi-century to millennia timescales Alexandria is dominated by tectonic setting and earthquakes or gravitational collapse episodes of a growth fault, whereas on shorter inter-seismic decadal to century timescales, subsidence rates are likely steady and moderate, in agreement with natural compaction and dewatering of the observed Holocene sediment layer.

For the previous period, where there are no archaeological remains to serve as sea level markers, the relative sea level change would be based on the sedimentary evidences. Petrological and radiocarbon data retrieved from sediment cores indicate that that Eastern Harbour was flooded by seawater during the Termination 1b event, at about 8000 yrs BP (Stanley and Bernasconi, 2006). The mean age for the same event all around the coastal zone of Alexandria is estimated at 7500-7000 yrs BP. If we consider that the mean thickness of the Holocene sediments in the Eastern Harbour of Alexandria is 12-13 m (assuming not compacted sediments) and the mean depth of water is 10 m, then a relative sea level rise of 23 m in the last 8000 years should be assumed. Based on the global sea level changes, the sea level rose 14 m during the last 8000 years, given a rate of rise of about 1.8 mm/yr. Based on the above, the approximate rate of relative sea level rise in the last 8000 years is about 2.9 mm/yr (23 m/8000 yr). The eustatic contribution is 1.8 mm/yr (14 m/8000 yr) indicating that the local (subsidence) contribution is 1.1 mm/yr. The estimated rate of relative sea level rise (2.9 mm/yr) is in agreement with that proposed by Warne and Stanley (1993; 3.3 mm/yr) for the same area. The detection of the series of palaeoshorelines in the seismic profiles suggests that the relative sea level rise was not gradual but probably accomplished by short time interval of stands.

The discovery of a pre-Alexandrian occupation at 13 m below the present sea level in the Eastern Harbour of Alexandria, dated to 3000 BP indicates also a high rate of subsidence, up to 4.3 mm/yr (Stanley and Toscano, 2009). In addition, the more extensive and younger (2000 BP) post-Alexander occupational level records a subsidence of 7.5 m, suggesting a rate of subsidence of about 3.7 mm/yr.

However, if we assume a rate of subsidence of about 3.5 mm/yr then the well-shaped and spatially-defined palaeoshoreline at the water depth of 8 m should be the coastline of Alexandria at the time of its establishment (**fig. 24**). This proposed average subsidence rate is within the range of the subsidence rates obtained at archaeological sites in the Eastern Harbour (2.9-3.6 mm/yr) and Western Harbour (2.4-4.1 mm/yr) of Alexandria and correlates well with subsidence rates (3.7-4.3 mm/yr) based on radiocarbon dated occupational levels in the Eastern Harbour (Stanley and Toscano 2009).

According to the scenario of 8 m of subsidence during the last 2300 BP, the sea level stand at -8 m coincides with the palaeoshoreline detected at 8 m water depth and thus the spatial distribution of this palaeoshoreline is equivalent with the coastline of that time (**fig. 24**). Then, the expanse of Cape Lochias where the Ptolemaic palaces used to stand was 0.721 km^2 suggesting that 92% of this land is now submerged (**fig. 24**). The plentiful remains of port foundations, monuments and artefacts discovered during numerous underwater archaeological surveys in this area are evidence of the ancient geography (Goddio, 1998, 2000, Tzalas, 2013b). In the present study, the detection of the linear, ridge-shaped targets (**fig. 24, 25**) eastwards of Cape el-Silsileh further supports the archaeological importance of this area. The pass between Qaitbay and Cape el-Silsileh (Cape Lochias), which is the entrance to the Eastern Harbour was narrower (600 m) in relation to nowadays (1700 m) (**fig. 24, 25**). The expanse of the Eastern Harbour (1.3 km^2) was reduced by up to 48% in relation to the present. Assuming that 1-4 m sediments deposited in the last 2300 years (Stanley and Bernasconi, 2006) then the water depth of the port ranged between 3 and 6 m. The low sea level stands would have exposed small islands and rocky islets, located in particular northeast of Cape Lochias (for example el-Hassan). Furthermore, a rocky islet was evident inside the Eastern Harbour and most probably corresponded to the ancient Antirhodos. The above coastal geomorphology matches rather well with the descriptions of the ancient writers, such of Strabo (XVII, I, 6): "Of the extremities of Pharos, the eastern one lies closer to the mainland and the promontory opposite it (the promontory called Lochias), and thus makes the harbour narrow at the mouth; and in addition to the narrowness of the intervening passage there are also rocks, some under the water and others projecting out of it, which at all hours roughen the waves that strike them from the open sea."

In addition, the sea level 8 m below the present, at the time when Alexandria flourished (2300 yrs BP), shows Ridge -I as a natural breakwater (**fig. 24, 25**). The waves in the study area are of wind origin and present a NW direction. They have an average height of 2 m, reaching up 4 m, in bad weather. The wind regime in the coastal zone of Alexandria seems to be steady over the last 2300 yr BP, comparing with the description of Strabo and recent measurements. At about 331 years BC, Ridge -I having a shallow depth (0-4 m) and a direction of NE-SW, almost perpendicular to that of the wind waves in combination to the Heptastadion-Pharos tombolo had developed a natural system, almost encircling the harbour, preventing the entrance of high waves into inshore waters and reducing the coastal erosion (**fig. 24, 25**). This natural structure offered the city of Alexandria the establishment of a safe port, the Eastern Harbour. This great advantage of the coastal zone seems to be what determined the decision of Alexander the Great as to the exact location for the establishment of this magnificent city.

On the other hand, the ridge was a dangerous pass for ancient ships putting in at Alexandria. The discovery of Hellenistic and Roman shipwrecks between the NW part of Ridge -I and Qaitbay Fort might suggest evidence for such unfortunate stories. The ancient mariners had to follow a specific route in order to enter the port in order to avoid Ridge -I and the rocky islets.

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Reference	Region	Time span (yrs)	Method	Subsidence rate (mm/yr)
Frihy (1992)	Alexandria	44	Tide-gauge	2.0
Frihy (1992)	Port Said	50	Tide-gauge	2.4
Frihy (2003)	Alexandria	55	Tide-gauge	1.6
Frihy (2003)	Port Said	48	Tide-gauge	1.0
Frihy (2003)	Burullus	26	Tide-gauge	2.3
Frihy *et al.* (2010)	Alexandria	60	Tide-gauge	0 – 0.5
Wöppelmann *et al.* (2013)	Alexandria	7	GPS and PSI	2.0 (mean 0.4)
Breccia (1922)	Alexandria	3000	Archaeological data	0.8 - 1.2
Goby (1952)	Suez canal	80		1.2
Ibrahim (1963)	Delta plain	1800	Archaeological data	1.4
El Sayed (1988)	Alexandria	2000	Archaeological data	1.2
Stanley (1988)	Manzala lake	8000	radiocarbon dating	3.5 - 5.0
Stanley (1990)	Northern Delta margin	8000	radiocarbon dating	0.4 - 5.0
Stanley and Warne (1993)	Northern Delta margin	8000	radiocarbon dating	<1 - >4
Emery *et al.* (1988)	Port Said	24	Tide-gauge	4.8
Emery *et al.* (1988)	Alexandria	19	Tide-gauge	-0.7
El-Fishawi and Fanos (1989)	Alexandria	23	Tide-gauge	2.9
El-Fishawi and Fanos (1989)	Port Said	21	Tide-gauge	2.2
Stanley and Bernasconi (2006)	Eastern Harbour (Alexandria)	2400	Archaeological data - radiocarbon dating	2.9
Stanley *et al.* (2004)	Aboukir	2500	Archaeological data	2.8
Lawler (2005)	Eastern Harbour (Alexandria)	2400	Archaeological data - radiocarbon dating	3.1
Stanley and Toscano (2009)	Eastern Harbour (Alexandria)	3000 -2332	Archaeological data - radiocarbon dating	3.7-4.3

Table 1: The subsidence rates for certain sites of the northern margin of the Nile Delta based on oceanographical, archaeological and radiocarbon dating data

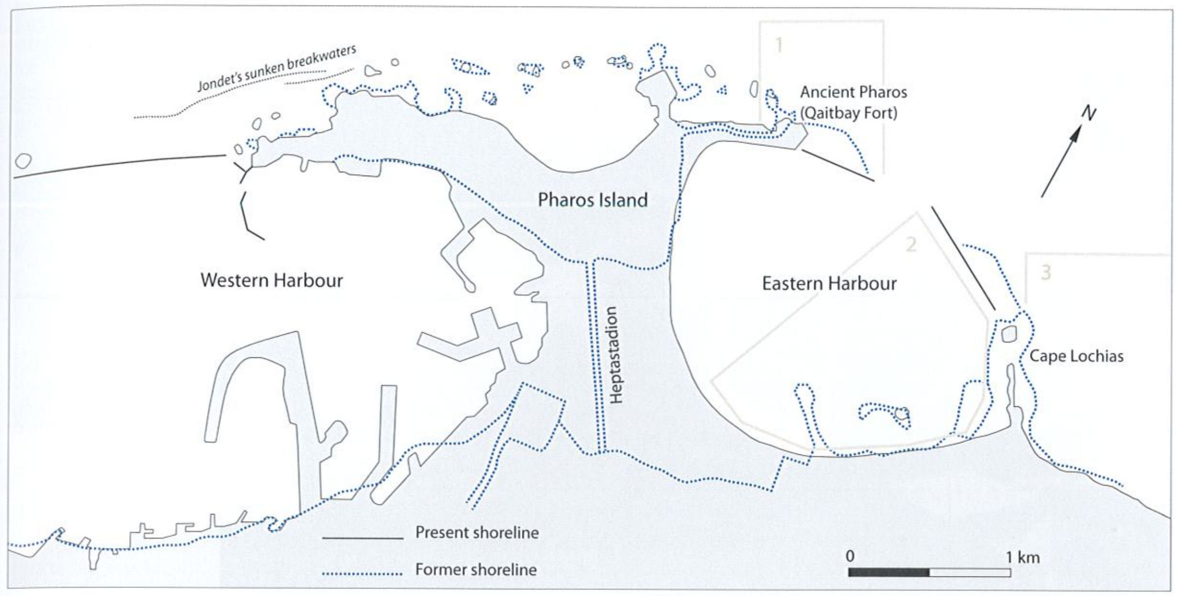

Figure 1: Map showing the location of the study area, Alexandria, Egypt. It presents the locations of the main ancient sites in the coastal zone of Alexandria and the areas of the recent underwater archaeological surveys under the directions of J.-Y. Empereur (1), F. Goddio (2) and H. Tzalas (3)

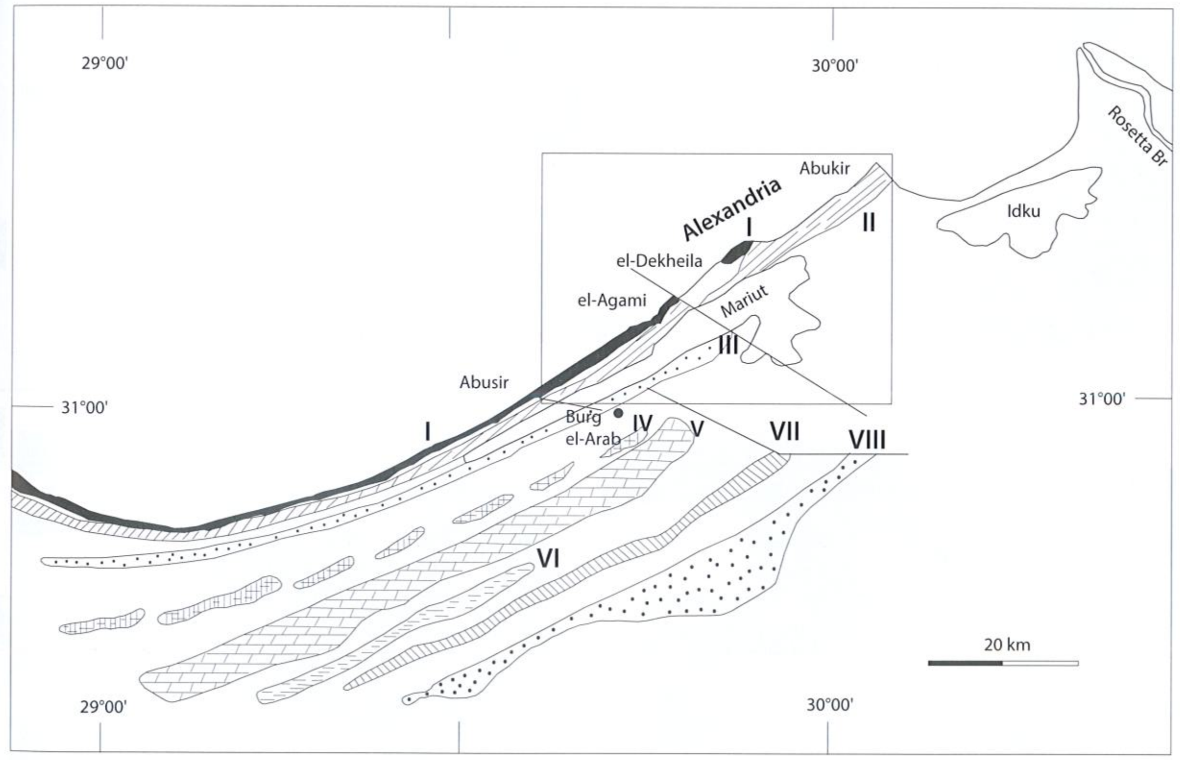

Figure 2: Map showing the eight ridges which are the main geomorphological features in the coastal margin of Alexandria

Figure 3: The two-zodiac and the URANIA vessels used in remote sensing survey at Alexandria

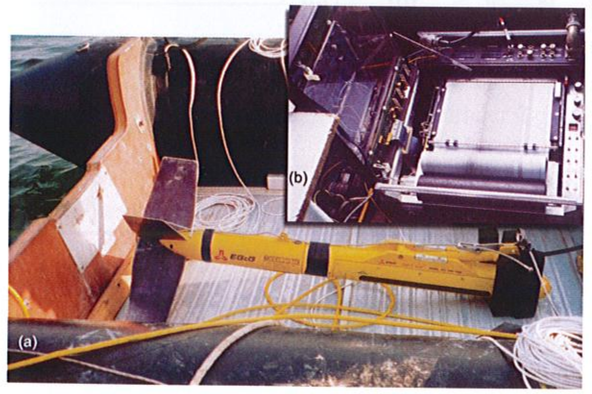

Figure 4: E.G&G. Side scan sonar: (a) 272 TD towfish, (b) E.G&G. 260 Graphic Recorder

Figure 5: 3.5 kHz sub-bottom profiler: (a) an over the side 4-array transducer, (b) E.P.C. Graphic Recorder, (c) GeoPulse Transmitter and Receiver

Figure 6: Trimble 4000 Differential Global Positioning System, which consists of (a) a mobile receiver (differential locator Trimble 4000 II) and (b) a reference receiver (Reference Locator Trimble 4000II)

Figure 7: Magellan GPS: (a) receiver and (b) GPS antenna

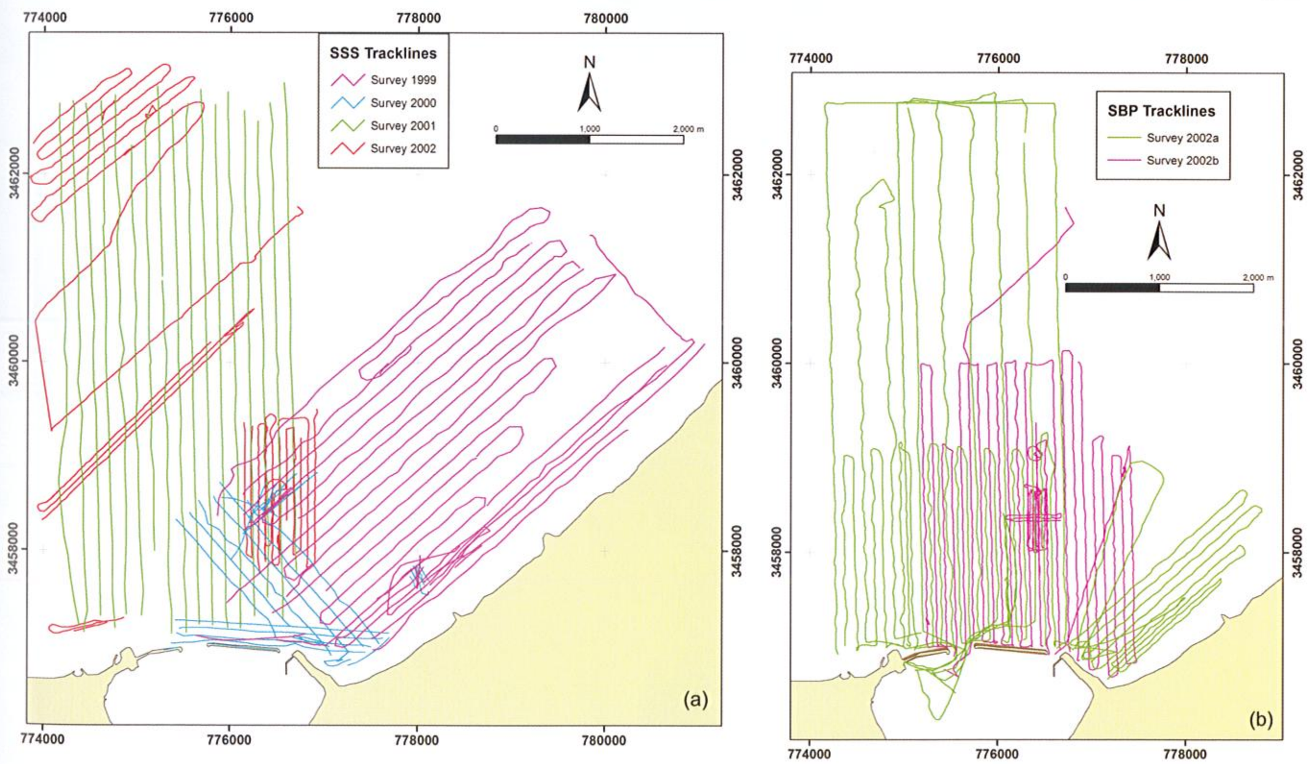

Figure 8: Maps showing (a) the side scan sonar and (b) the 3.5 kHz tracklines of the present study in the coastal zone of Alexandria

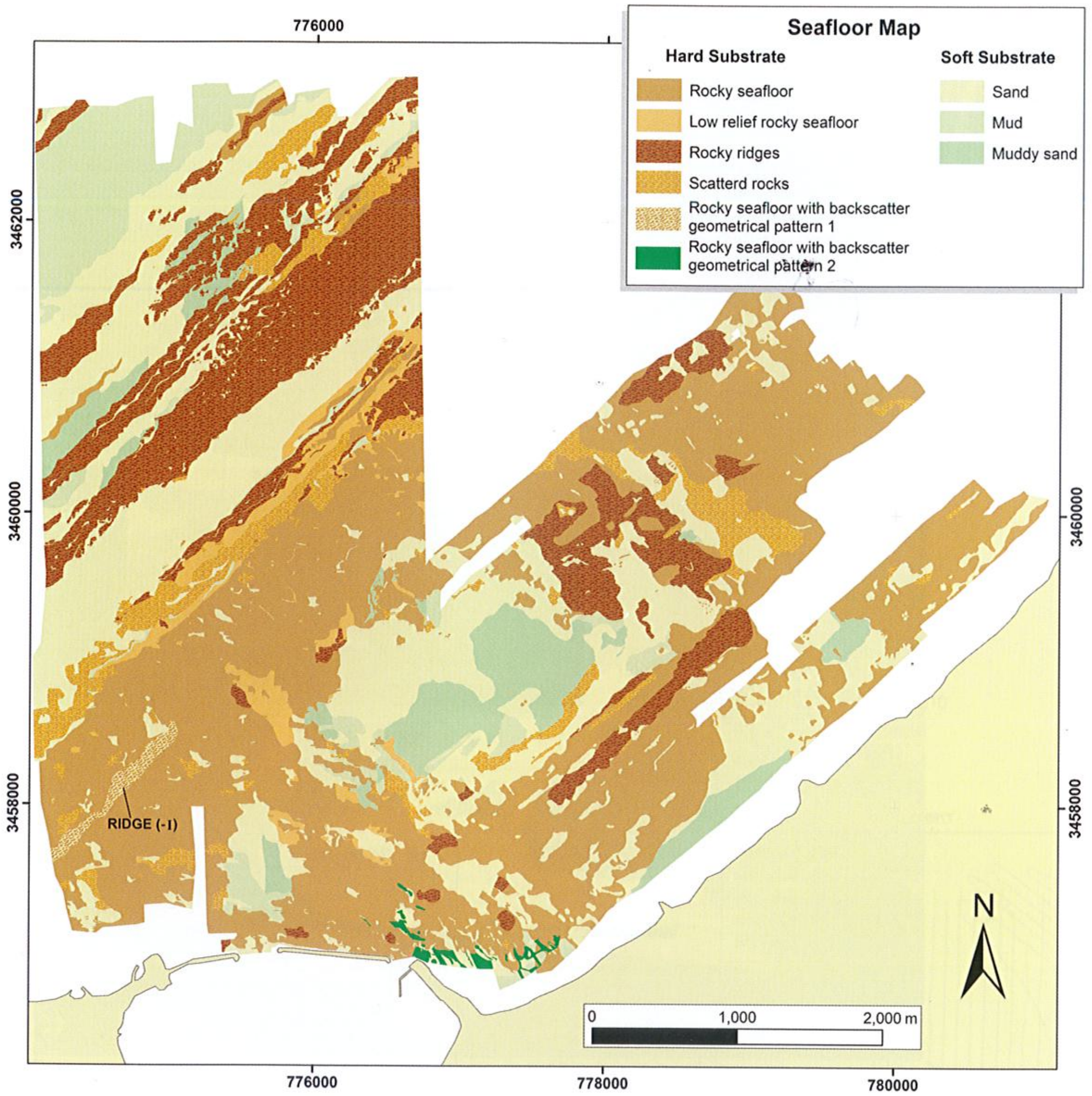

Figure 9: Morphological seafloor map of the survey area based on side scan sonar data

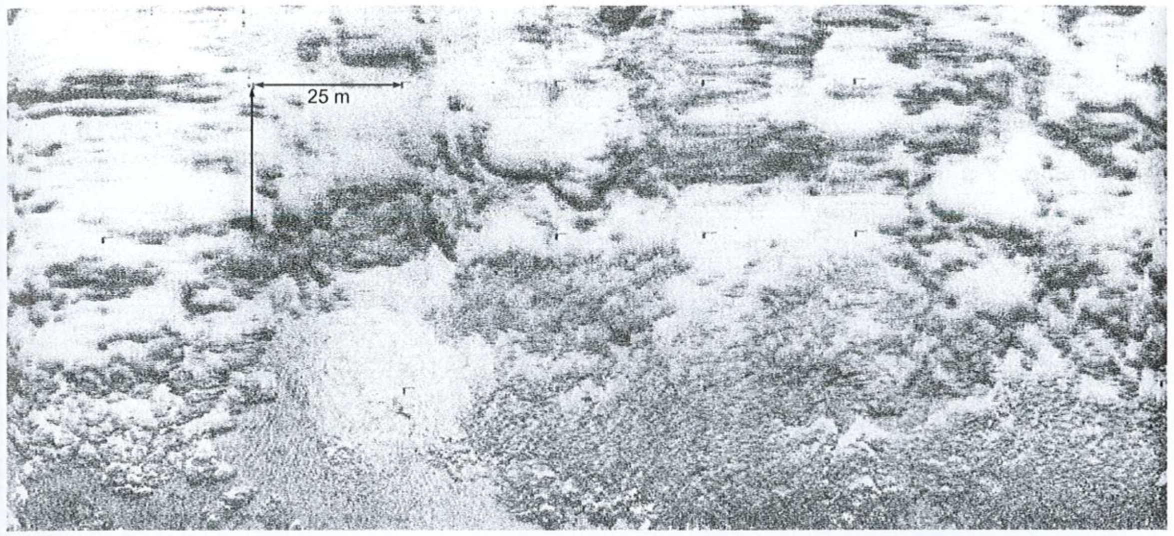

Figure 10: Side scan sonar record showing rocky seafloor

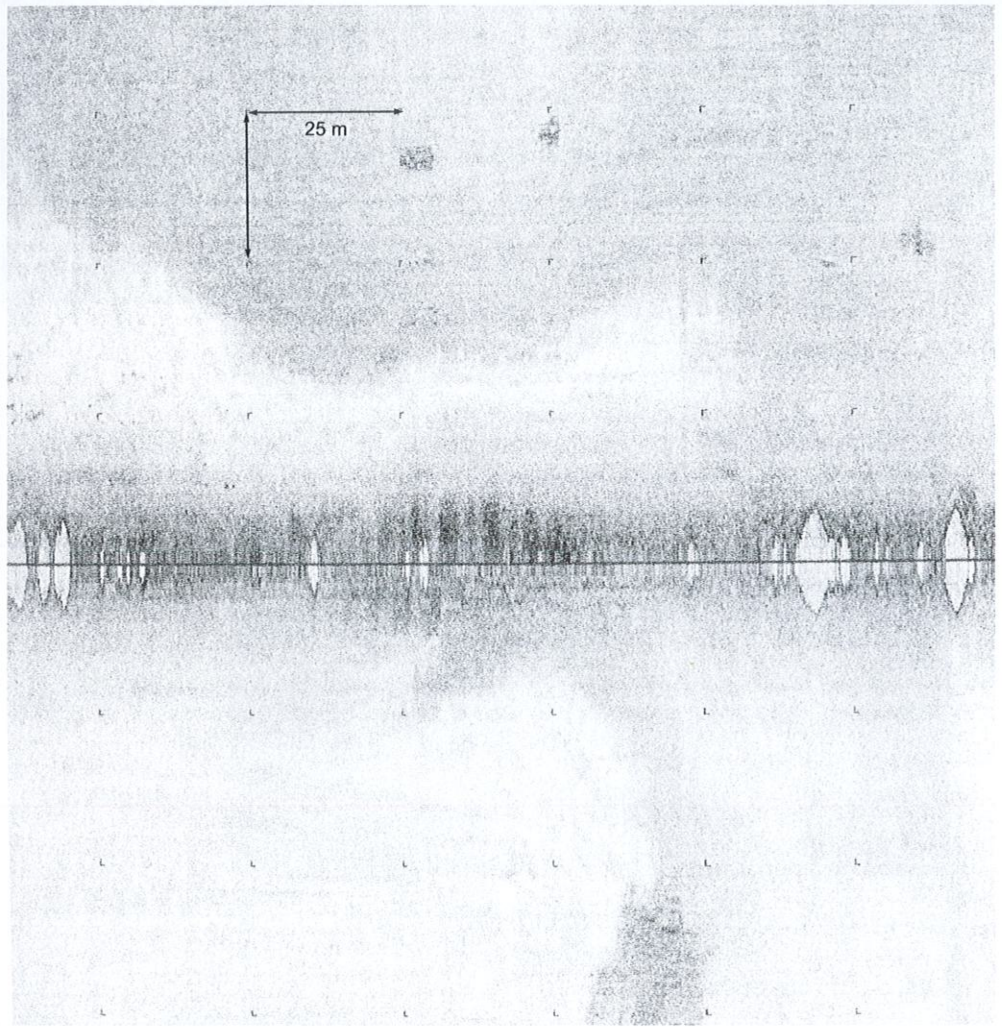

Figure 11: Side scan sonar record showing seafloor covered by fine-grained sediments

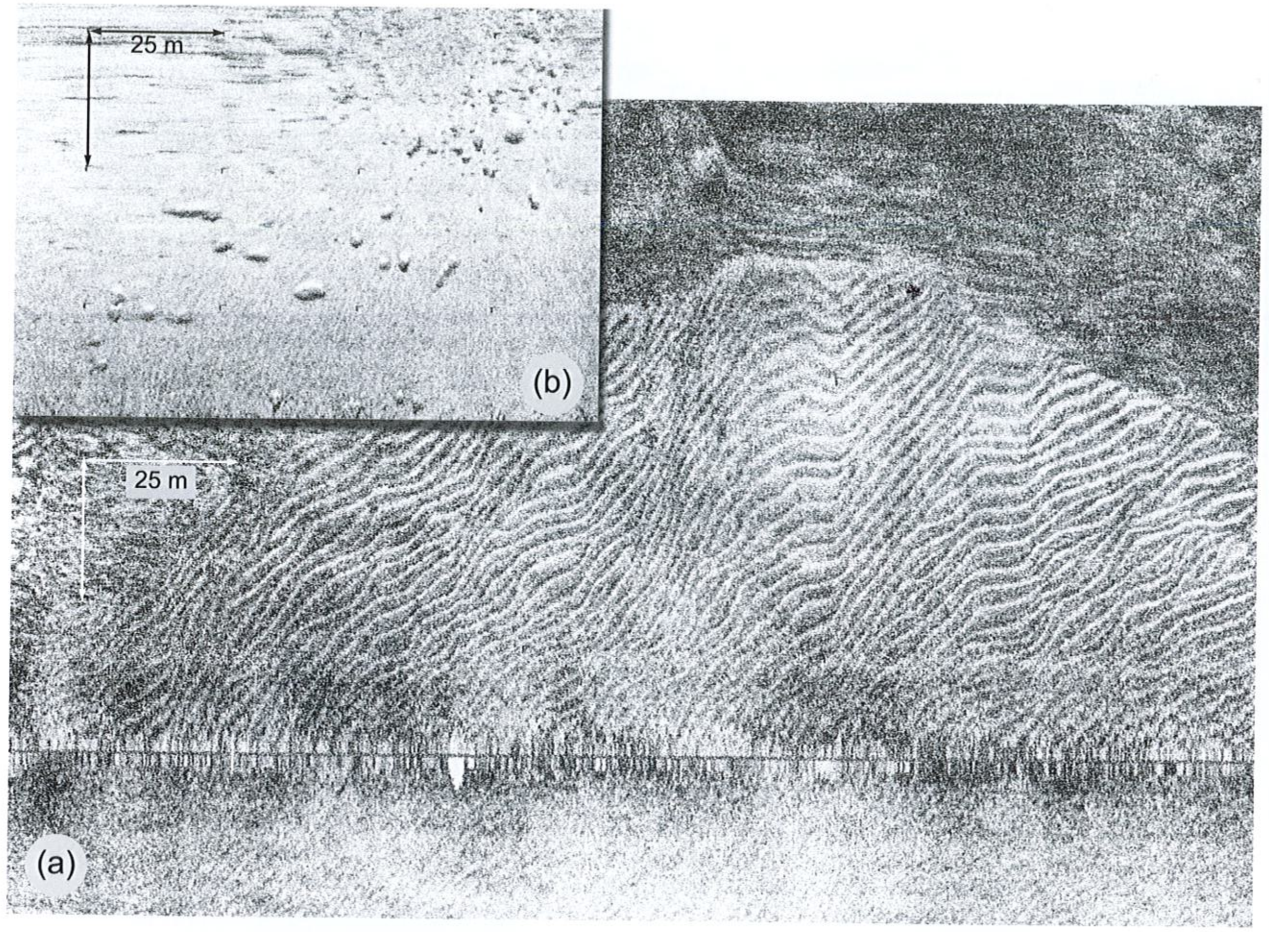

Figure 12: Side scan sonar records showing (a) sand ripples and (b) scattered rocks

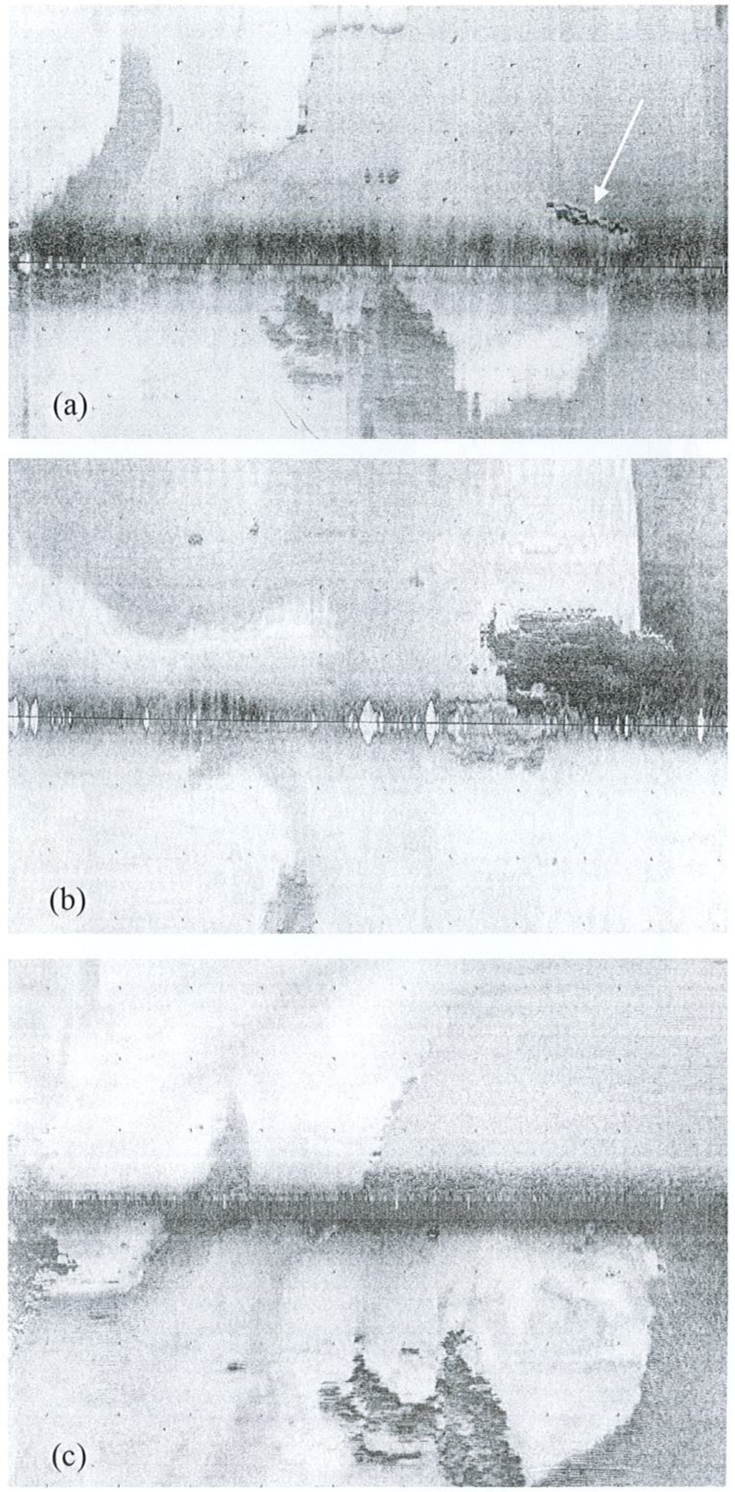

Figure 13: Side scan sonar records collected during three successive survey periods: (a) 04/1999, (b) 10/1999 and (c) 11/2000

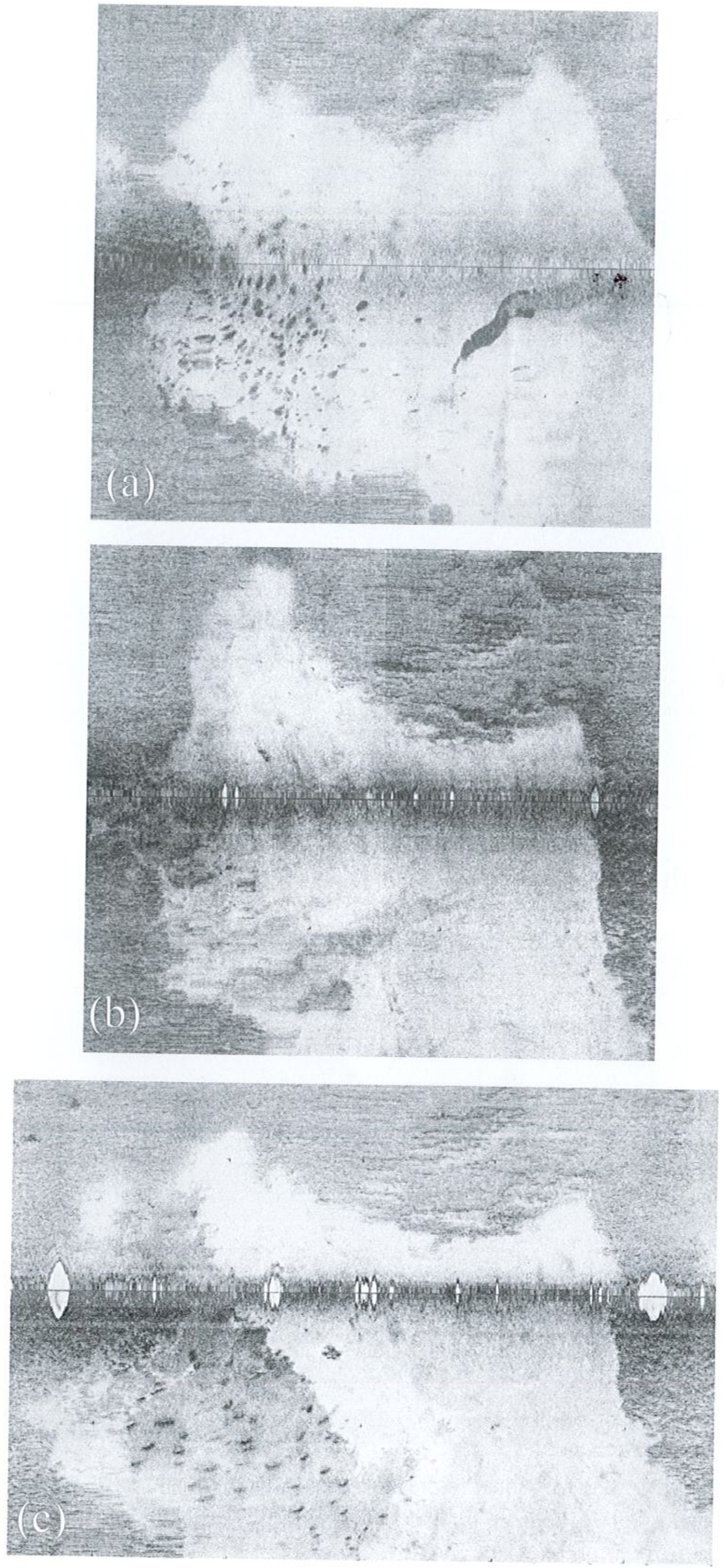

Figure 14: Side scan sonar records collected during three successive survey periods: (a) 04/1999, (b) 10/1999 and (c) 11/2000

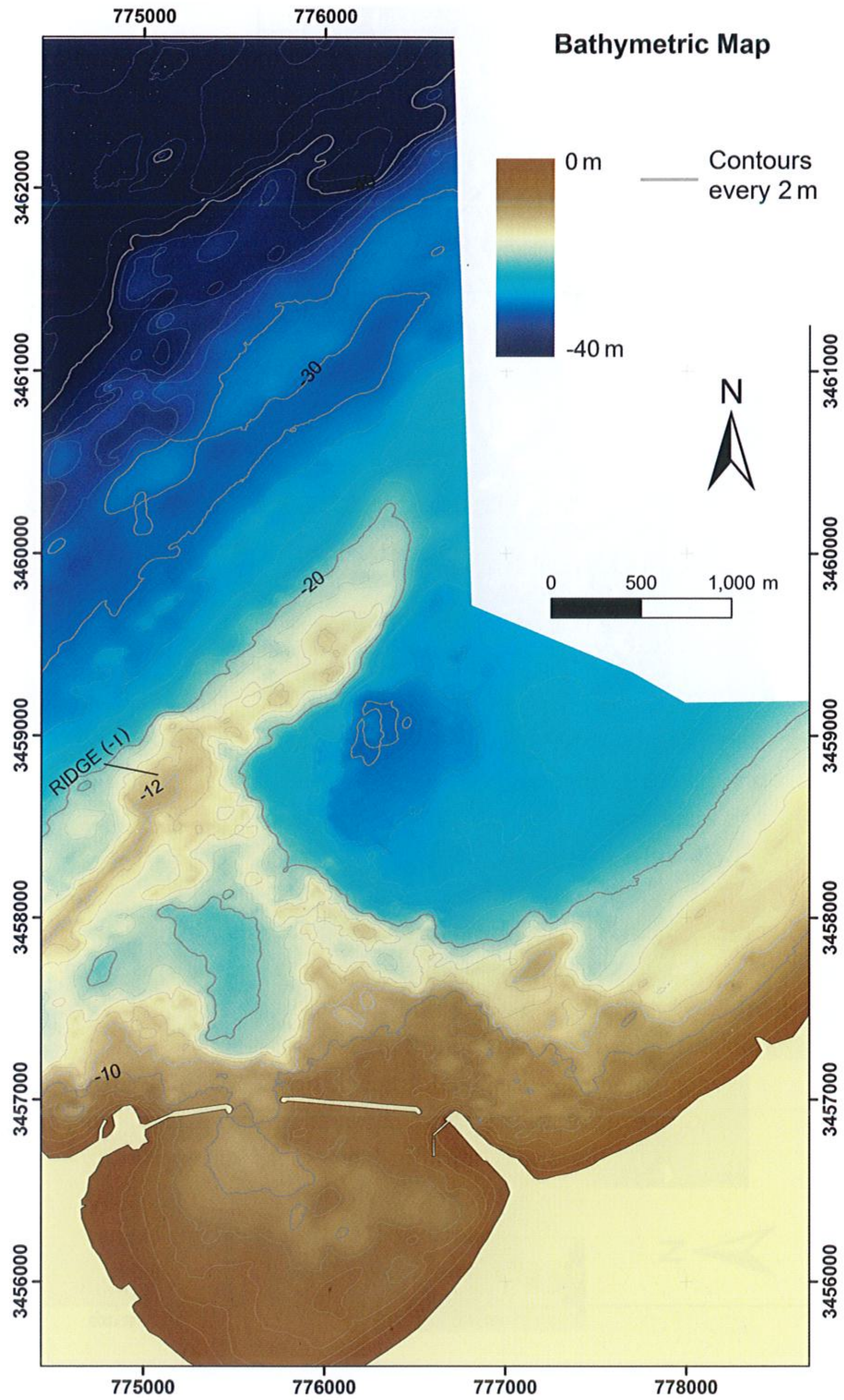

Figure 15: Detailed bathymetric map of the coastal zone of Alexandria

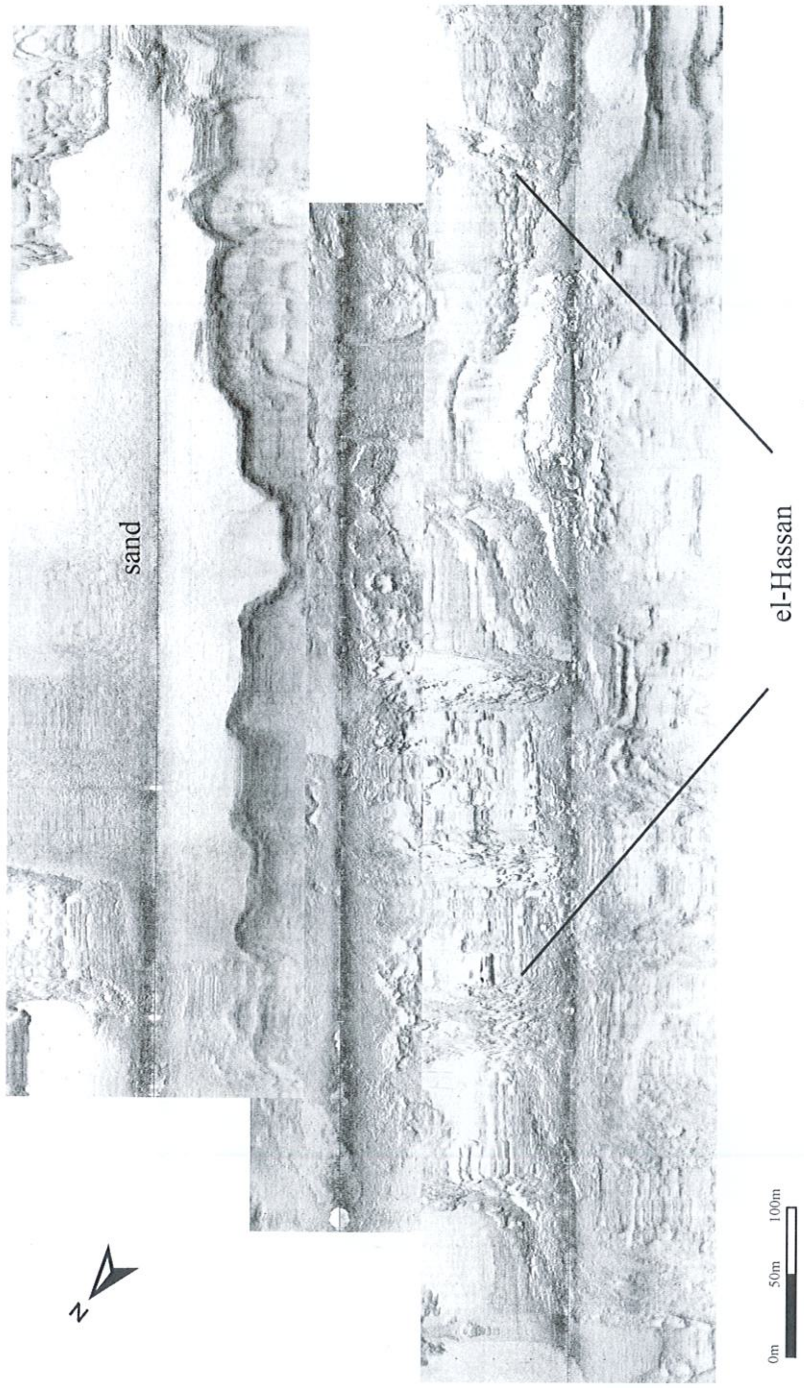

Figure 16: Side scan sonar mosaic showing el-Hassan reef

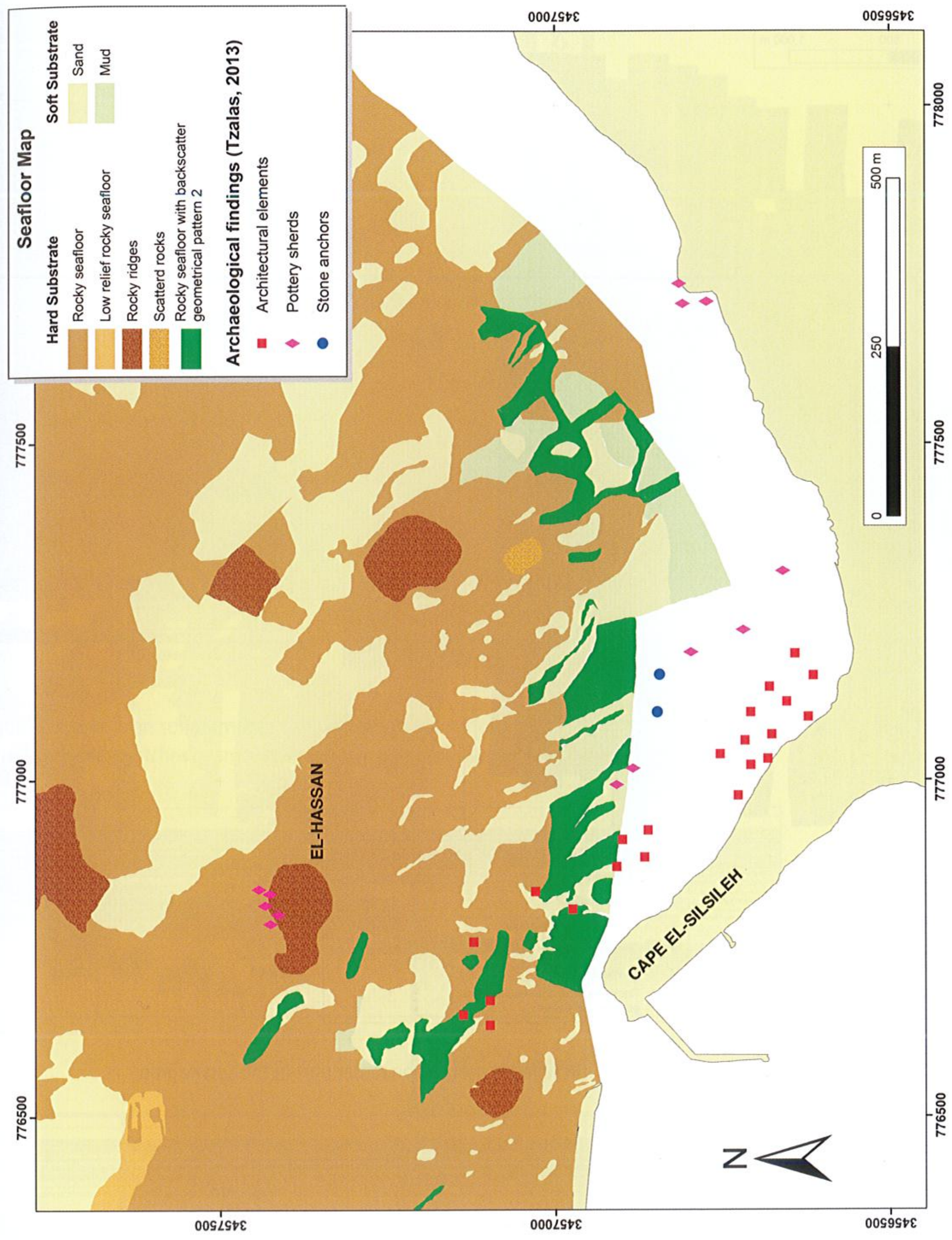

Figure 17: Morphological seafloor map east of el-Silsileh. The archaeological findings of the Greek mission are also shown (Tzalas, 2013a,b)

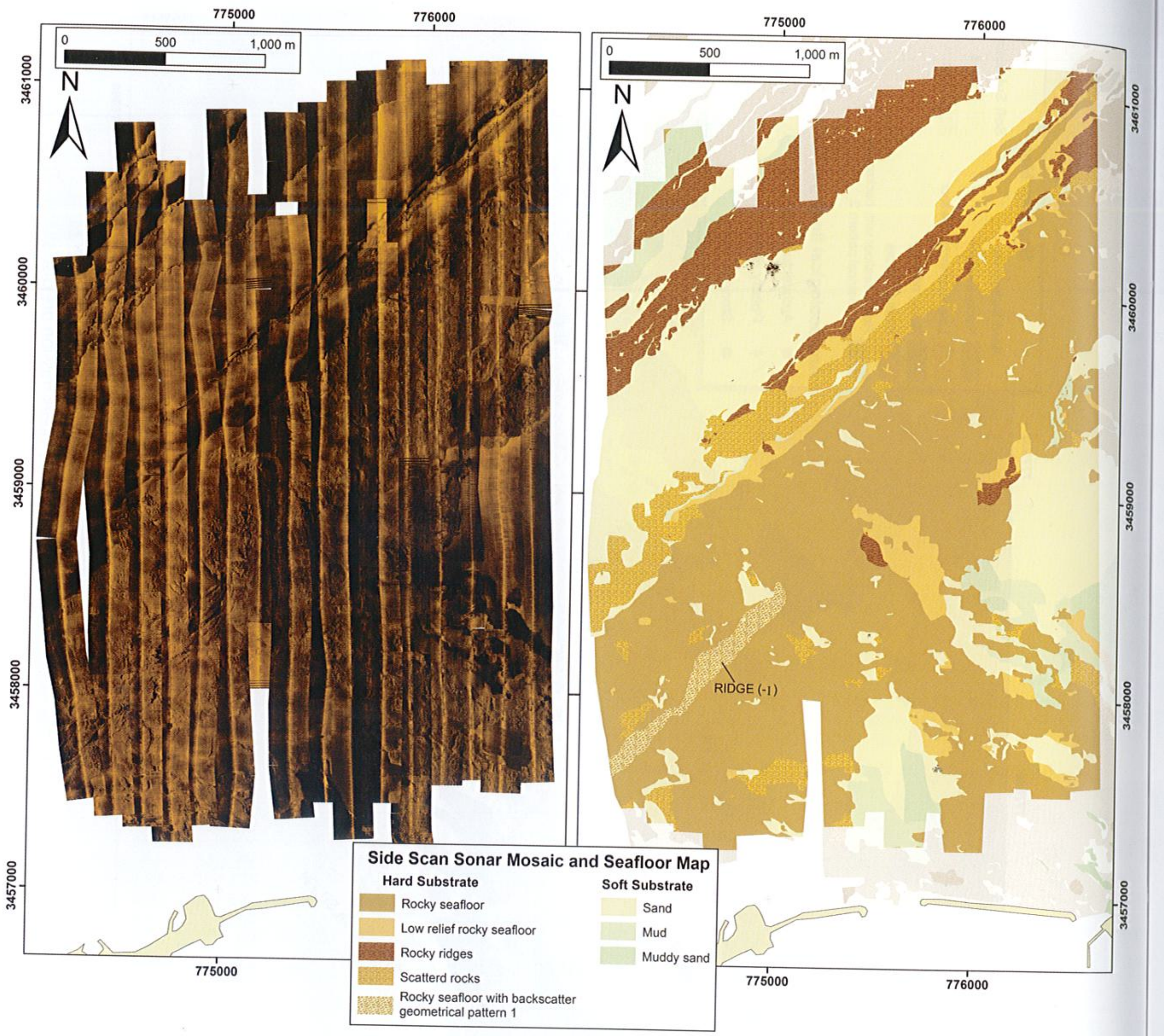

Figure 18: Side scan sonar mosaic and morphological seafloor map of the major part of the survey area

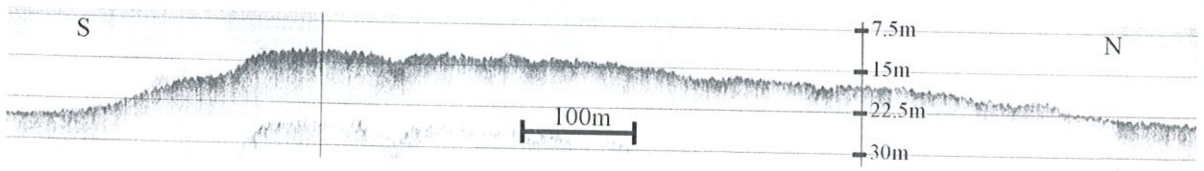

Figure 19: 3.5 kHz sub-bottom seismic reflection profile showing the Ridge -I

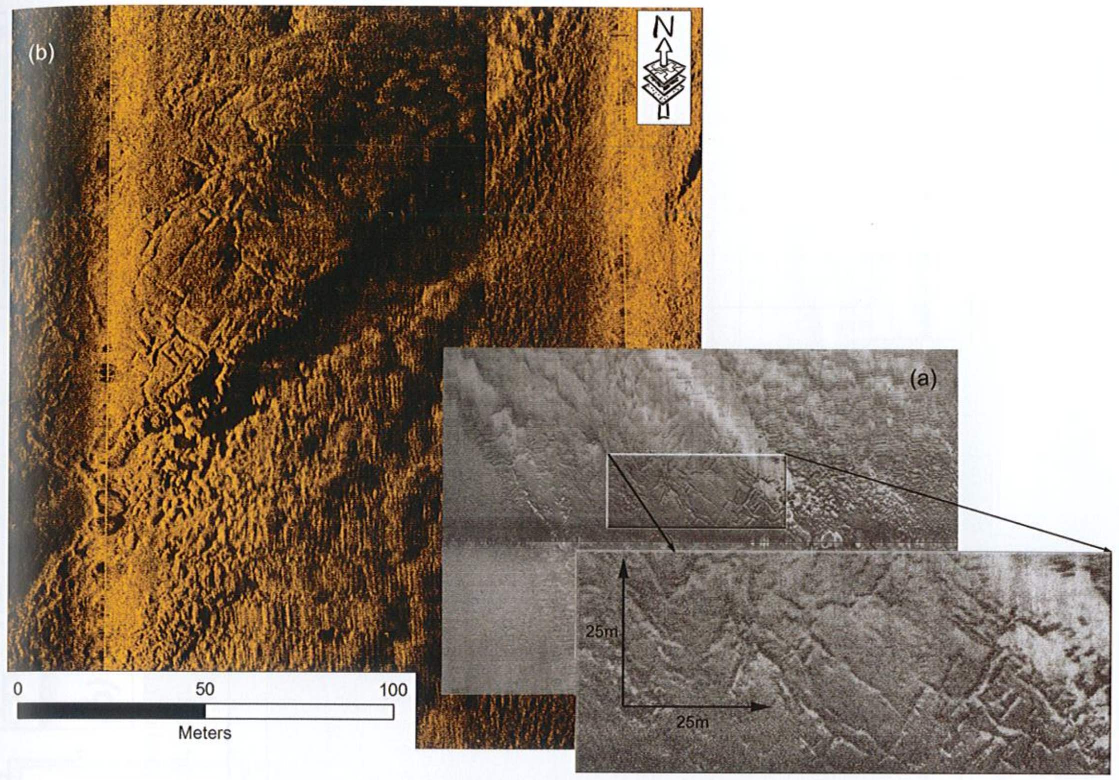

Figure 20: Side scan sonar images (a, b) showing the surface of the Ridge -I. It presents a backscatter geometrical pattern made of patches or smaller strips of high reflectivity

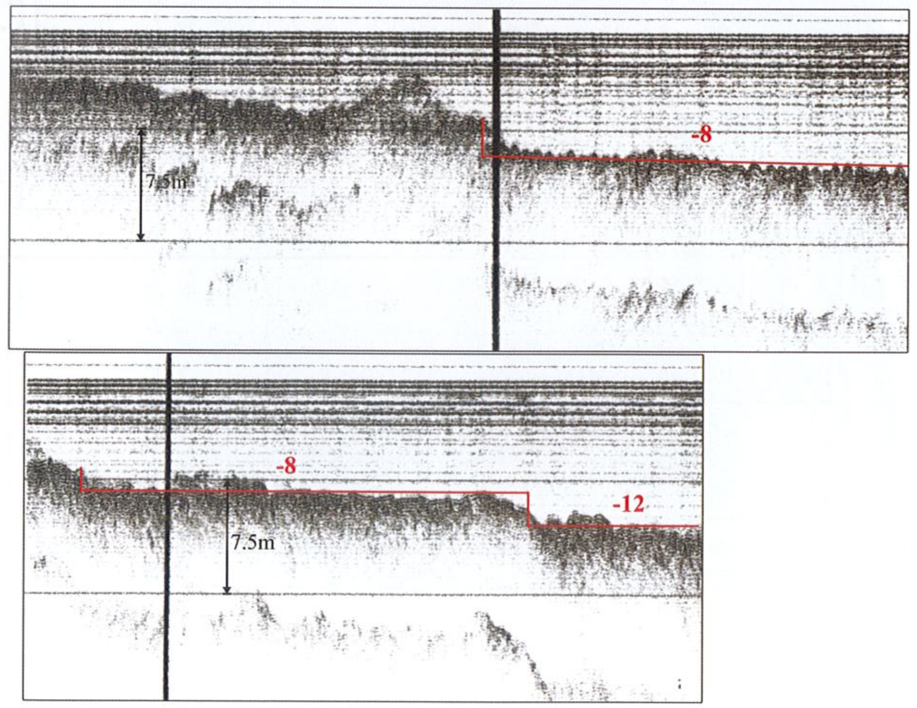

Figure 21: 3.5 kHz sub-bottom seismic reflection profiles showing the palaeoshorelines at the water depths of 12 m and 8 m below the present sea level. The profiles are taken from tracklines vertical to the Eastern Harbour of Alexandria

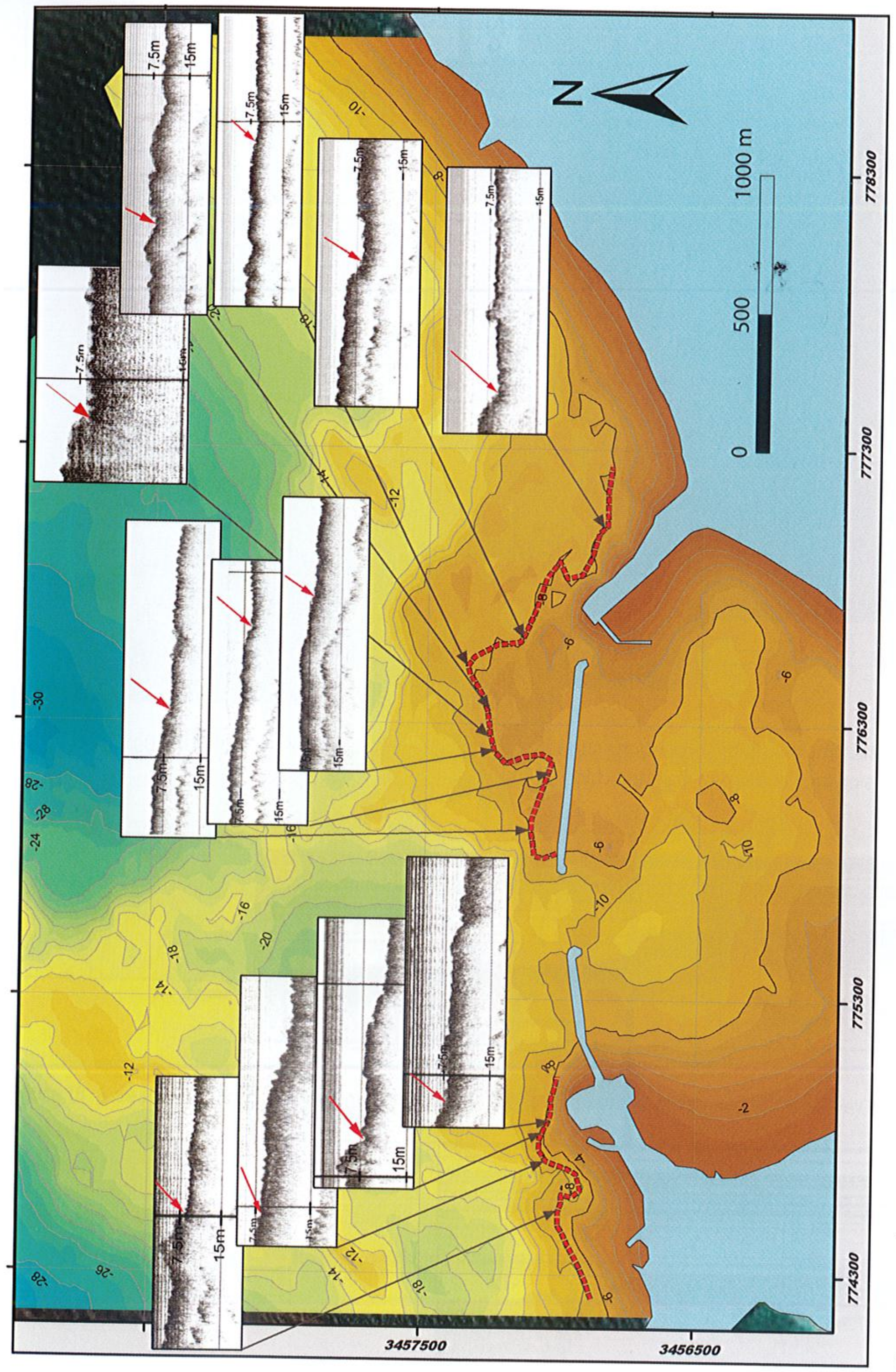

Figure 22: Bathymetric map showing (i) the palaeoshoreline at the water depth of 8 m below the present sea level (red line) and (ii) collection of representative 3.5 kHz sub-bottom seismic reflection profiles, showing the location of the palaeoshoreline at 8 m water depth (red arrows)

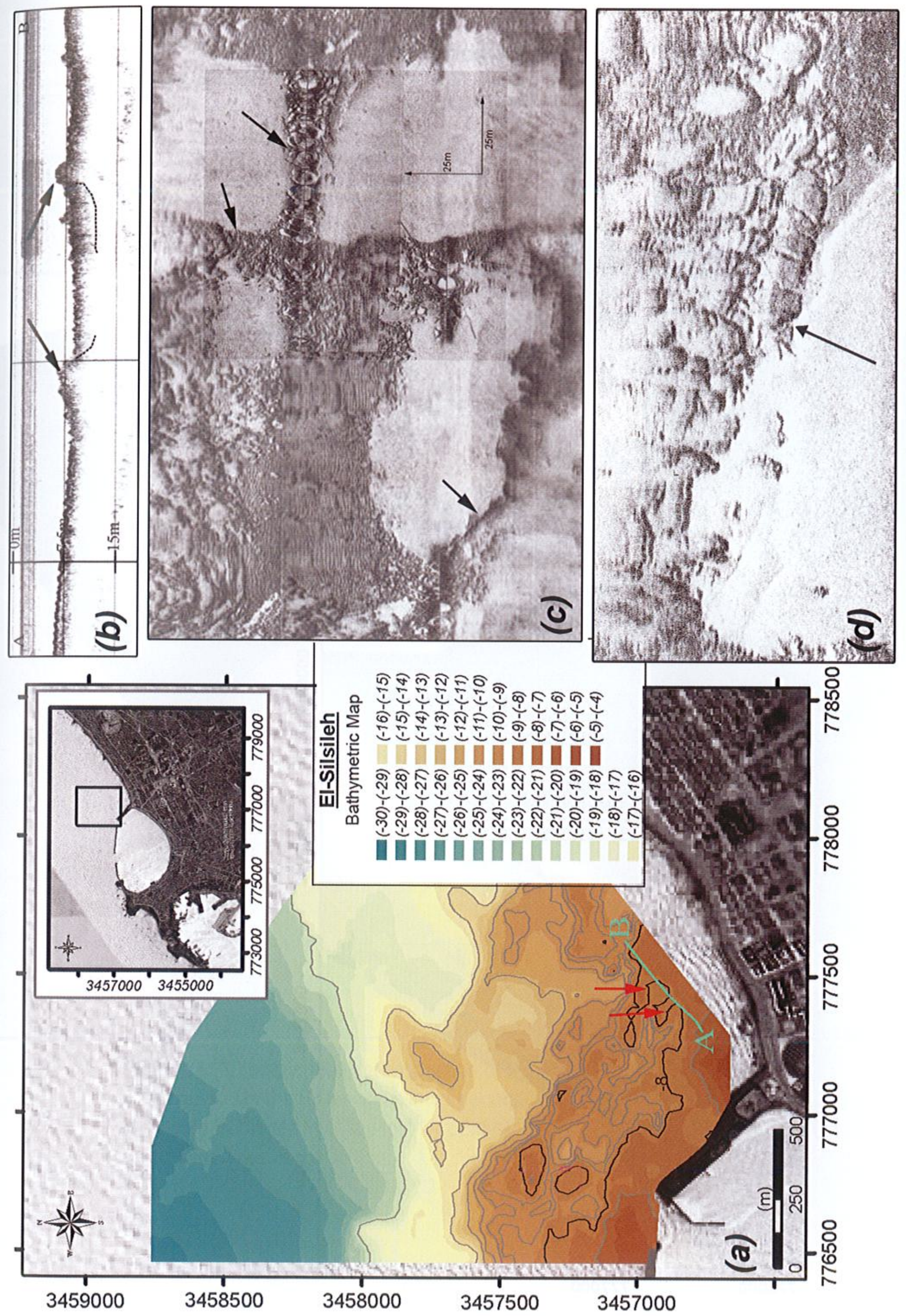

Figure 23: (a) Detailed bathymetric map of the coastal area east of Cape el-Silsileh (ancient Cape Lochias), Alexandria, showing the present-day coastline and the Hellenistic–Roman coastline (isobath 8 m; dark line). The two elongated features, vertical to the ancient coastline, are shown by arrows. (b) 3.5 kHz sub-bottom seismic reflection profile crossing vertically the two elongated features (arrows) and the depression between them filled by loose sediments. The base of the sediments (dashed line) is 4 m below the seafloor. The location of the profile is shown in figure 23a. (c), (d) Side scan sonar records showing the area of the elongated features

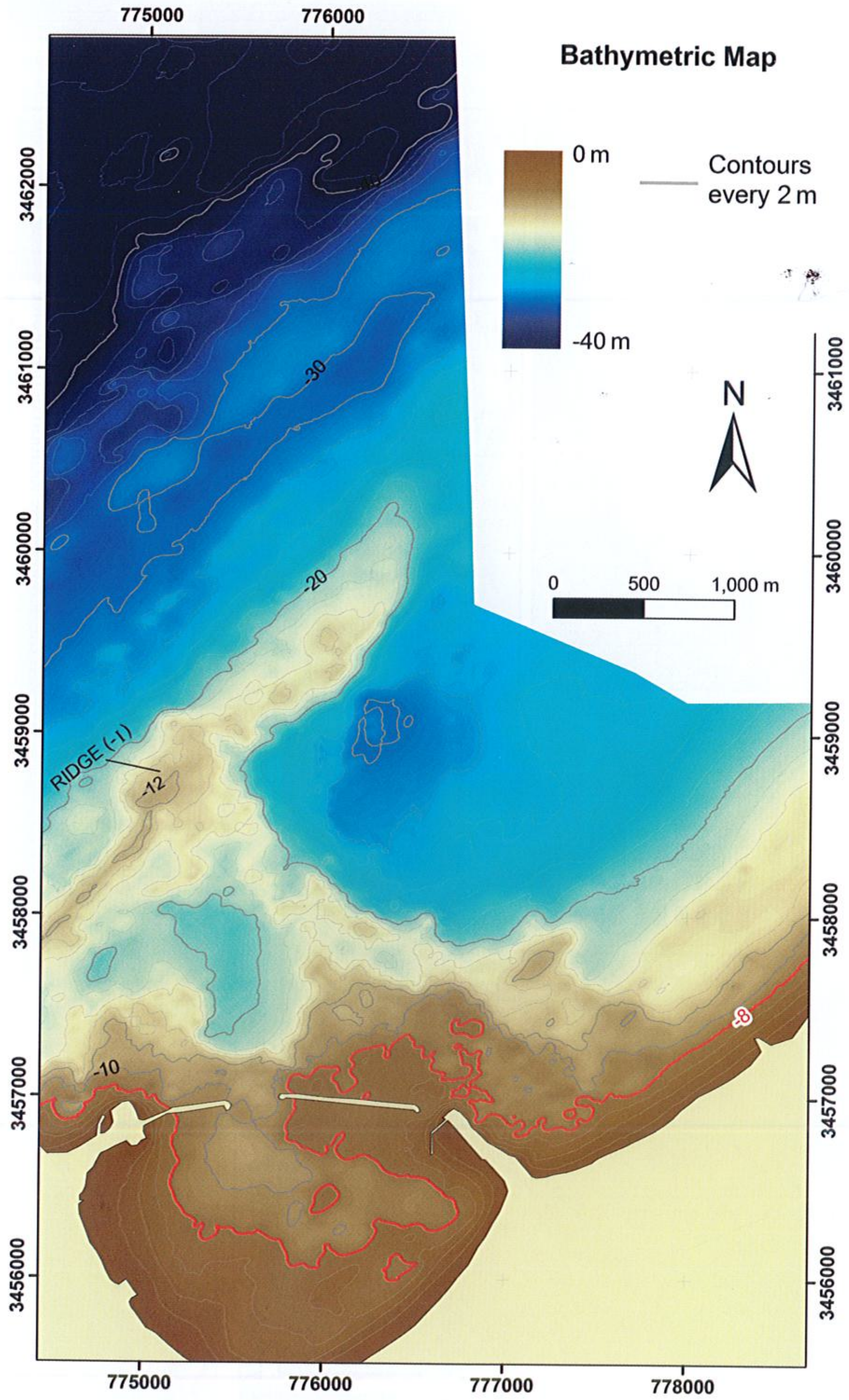

Figure 24: Detailed bathymetric map of the coastal zone of Alexandria. The isobath of 8 m is marked with a red line

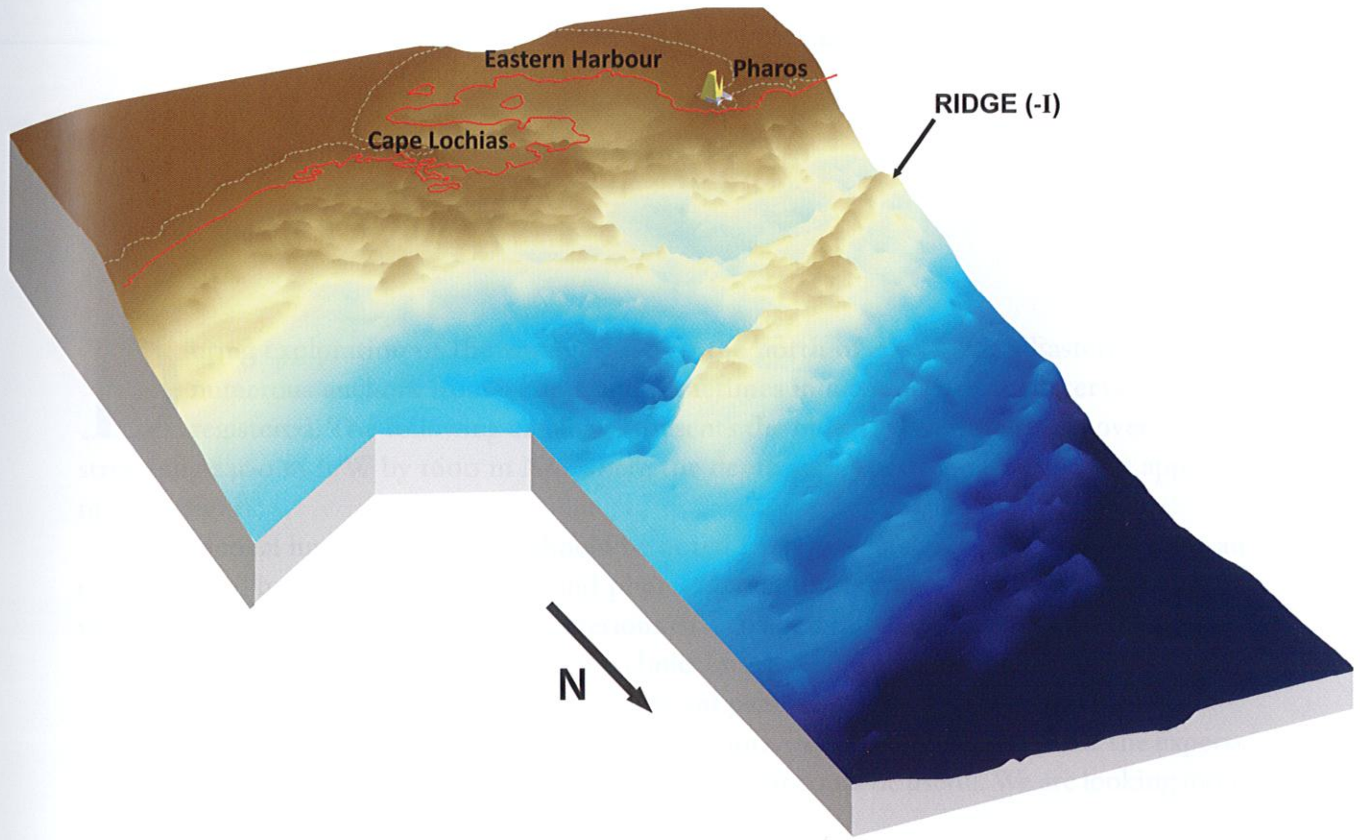

Figure 25: 3D bathymetric reconstruction of the coastal zone of Alexandria in the Hellenistic-Roman periods. The ancient coastline is marked by the red line (see text for details)