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Hydrographic surveys as an art of delineating the impact of climate change on the coastal environment

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1. ABSTRACT: Marine acoustic techniques are quite efficient in remote seabed classifications and hydrographic investigations by providing highly detailed information about broad areas of the seafloor and the subsurface layers in a short period of time. Climatic change is considered as the forcing factor for the eustatic sea-level-rise along the Mediterranean coast, leading to the large coastal inundation and the subsidence of the ancient maritime installations, these ancient sites can be used as indicators for the relative changes in sea-level through later times.

Marine surveys were carried out to delineate the coastal geomorphological changes associated with sea level rises and natural hazards along some areas on the coast of Alexandria during the last two millennia. Hydrographic and seismic surveys were implemented in the study area by using a multi-beam echo-sounder, side scan sonar, and sub-bottom profiler, then the acoustic data were calibrated with dated core samples and ROV camera images. Multi-beam is considered the most commonly used tool in harbor surveys utilizing the returned acoustic signals to measure the depth of the seafloor, while the side scan sonar instrument provides high-resolution images for the elevated structures from the seafloor depending on the backscatter strength of the signal, and the sub-bottom profiler uses chirp waves that deliver high resolution vertical images for the subsurface sediment situation. Results of sonar imaging and bathymetric mapping outlined submerged margins of archaeological remains related to ancient Ptolemaic and Greek ports.

Seismic interpretations revealed significant changes in the coastal geomorphology, where the massive burial of the port structure indicated the occurrence of sudden natural hazards originated from seismic waves; therefore, a destructive tsunami wave accompanied by sediment slumping that followed by eustatic sea-level-rise seems to be the dominant factors for this dramatic burial. The research results showed the potentiality of hydrographic surveys in detecting climate change indicators.

Keywords: *Hydrographic Survey, Multi-beam system, Side scan sonar, Sub-bottom Profiler, Bathymetry, ROV.*

2. INTRODUCTION

The sea level rise impact on coastal zones has become a rising issue of interest in the scientific and public fields. Recent studies have indicated that the sea level mean has remained semi-stable since 2-3 millennia, with rate of change not exceeding 0.5 mm/yr (Kemp et al., 2011). During these periods, the majority of the coastal installations were totally submerged under the sea level and the shorelines eroded. These observations indicate that the sea level rise occurs due to climatic and non-climatic factors, or combination of both factors (Bird, 1996).

In the areas affected by fast sea level rising or have sea level rise values close to the global average, the effect of sea level rise cannot be easily detected as they are masked by the effects of currents, waves, cyclones, and anthropogenic forces (Becker et al., 2012). Submerged and uplifted positions of ancient harbors are key indicators for determining the recent sea level changes and the rates of vertical land movements, also the changes in stratigraphy of coastal sediments highlight the effect of human activities on the coastal environment (Mourtzas, 2012). The Mediterranean Sea coasts have been inhabited since the prehistoric times, and preserve evidences for the ancient coastal settlements and the maritime installations. These ancient sites can be used as indicators for the relative changes in sea level through later times (Mastronuzzi et al., 2017).

Recently, waves of violent weather hit the coast of Alexandria on October 2015 and November 2021, accompanied by thunderstorms, lightning and rising sea waves which flooded the whole coast of Alexandria (Figure 1), and led to the sinking of the roads and the cars and homes of Alexandrian civilians. This sudden natural disaster indicated the vulnerability of the recent coast of Alexandria to definite subsidence at any possible time. Therefore, this study is planned to implement hydrographic and geophysical means to study the geomorphological changes of the ancient coast of Alexandria resulted from sea level changes and natural catastrophes in order to develop perceptions for coastal subsidence indicators which in turn benefits the stakeholders and decision-makers.

Figure 1: Photographs showing the impact of rising sea waves on the coast of Alexandria during the violent weather

In past years, the marine geophysical techniques became quite efficient tools in the remote seabed classifications and sunken objects detection due to their ability of covering large seabed regions in a short period of time, and providing highly detailed information on an unexcavated seafloor and subsurface features (Chalari et al., 2009, Hamouda et al., 2021). Considerable developments have been implemented on the hydrographic and marine geophysical investigations to study the lateral and vertical seafloor features using acoustic tools such as multi-beam echo-sounders, side scan sonars and sub-bottom profilers (Fekry, 2021).

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The hydrographic surveys were extended in the Eastern Harbor over the Egyptian north coast of Alexandria city (Figure 2). The recent oval structure of the harbor was shaped after being isolated from the sea since the 1st millennium BC., pursued by the establishment of the ancient city of Alexandria and its royal ports during the Ptolemaic rule in the 4th century BC (Jondet, 1916), and over an ENE-WSW trending limestone (kurkar) ridge of the Pleistocene age (Goddio et al., 1998). The basin structure of the harbor has been trapped Holocene sedimentations that provides a full record for the early human history of this region, where this basin was considered as a sediment catchment before being modified by human activities in the late Holocene (Hamouda et al., 2016, 2021).

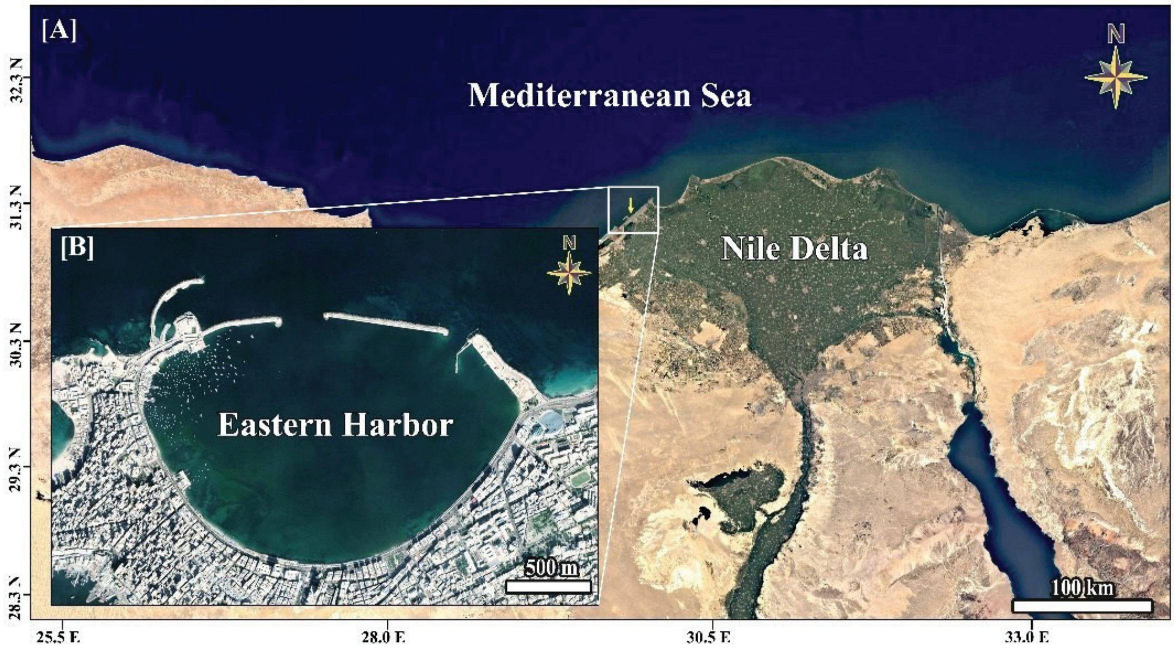


Figure 2: [A] Geographic map of northern Egypt, [B] satellite map of the Eastern Harbor of Alexandria.

Previous geoarchaeological investigations suggested that the area was experienced various subsidences during the last 2000 years. The area of study was affected by post-glacial sea-level rise (~ 2 m) during the late Holocene (Mitrovica and Milne, 2002, Stanley and Landau, 2005), and the sea- level rise caused obvious changes in coastal zones led to the subsidence of ancient settlements and landscapes during the Ptolemaic and Roman times (Lambeck, et al., 2002).

Historical sources recorded a tsunami-genic hazardous event which took place on 21 July 365 AD, these tsunami waves were supposed to be generated by an earthquake near Crete at the Hellenic Arch subduction zone, these tsunami waves traveled run-up height of 9.5 m and arrived from the northwestern corner, killing thousands of people and destroying the ancient coast of Alexandria (Hamouda 2010), other studies proposed tsunamis generated from earthquake-triggered slumps as a result of land sliding followed by the retreat of the seawaters (Stiros, 2020).

Therefore, the ancient royal ports and structures were collapsed and sunk by the action of the destroying waves and the following tectonic activities (Guidoboni, 1994). During these periods, the port exposed to high silting rate leading to the burial of the port structure under sand alluviations.

The main objective of this work was to implement highly detailed marine surveys to map and investigate the seafloor texture and features, aiming to study the impact of sea level rises and natural hazards on the ancient coast of Alexandria during the last two millennia.

3. MATERIALS AND METHODS

Marine surveys were conducted in the Eastern Harbor of Alexandria onboard Salsabil R/V (Figure 3) by using an integration of multi-beam echo-sounder, side scan sonar, and sub-bottom profiler, then the acoustic data were calibrated with dated core samples and ROV camera images to define the acoustic results.

The navigational tracking and sampling locations (Figure 4) were provided by DGPS and specialized navigational software packages. The near shore navigational lines were acquired using a smaller fishing boat (Negm el Bahr) due to shallow water depths.

The Bathymetric survey was performed to measure the depth of the seafloor and determine the submerged borders of the ancient port, the side scan sonar survey was carried out in order to obtain clear seafloor images and detect the submerged artifacts by providing high-resolution images for the seafloor depending on the backscatter strength of the signal, also high resolution vertical images for the subsurface have been delivered by acquiring sub-bottom profiling survey to detect the subsurface discontinuities that might have been changed the ancient coastal geomorphology.

The bathymetric survey was executed using Seabeam 1185 multibeam sonar system, which comprised a set of two transducers, motion sensor and heading DGPS. The transducers were side- mounted with stainless-steel pole to the port side of the survey vessel far away from the turbulences of the engine. The transducer arrays were transmitting narrow beams quasi-simultaneously with a high acoustic transmission level, and the Seabeam surface unit collects a swath of bathymetric data with excess of 150 degrees which offers high resolution seafloor coverage (1.5°) with more than 25 pings per second. The system provides very low error rate due to the utilized superior Signal-to-Noise-Ratio technology and 36 dB side lobe suppression during transmission and reception.

Before initiating the survey, the linear offsets were measured between the transducers, the motion sensor, the GPS antenna and the sea-level. All measurements were done according to the left-hand rule, where offsets below sea-level, forward and starboard the motion sensor take positive number, and vice versa. A sound velocity profile (SVP) was obtained using Valeport profiler, and input into the multibeam acquisition software to account for refraction of the sound waves through the water column.

Figure 3: [A] Salsabil Research Vessel, [B] Acoustic equipment onboard the Vessel.

Also, multibeam calibration known as patch test was done before starting the survey in order to quantify all possible residual installation misalignments to ensure that subsequent data gathered from the multibeam system is correctly geo-referenced in three dimensions, this can be done by measuring the angular offsets of roll, heave, pitch and latency (Hamouda et al, 2016). The procedure involves collecting data over specific types of terrain or seabed features, in typical survey water depths, and processing using processing software and calibration routines. The physical alignment offsets that must be determined are roll, pitch and yaw/heading (Figure 5). When the data collection system is not synchronized to GPS time, it is also necessary to determine the latency in the positioning system.

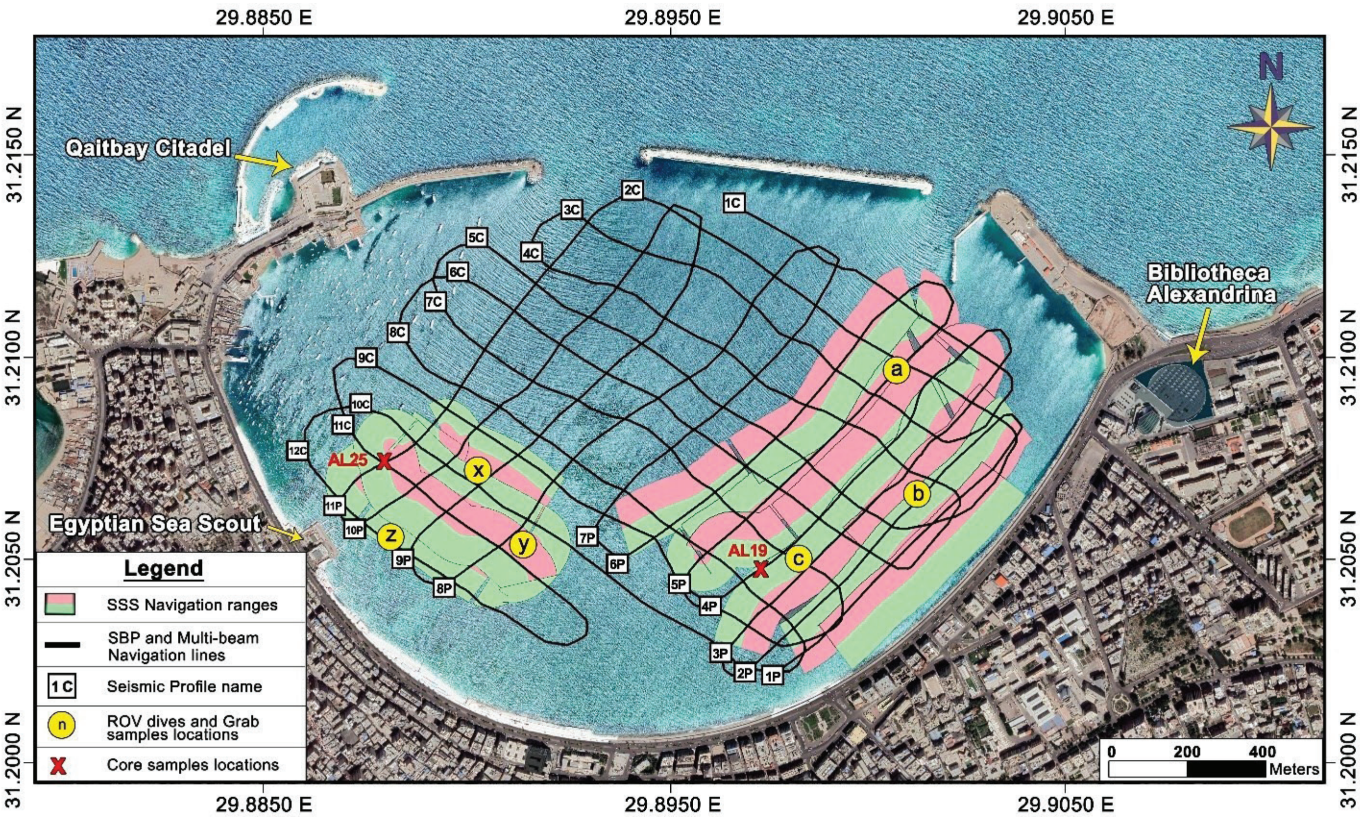


Figure 4: Survey track-lines across the study area.

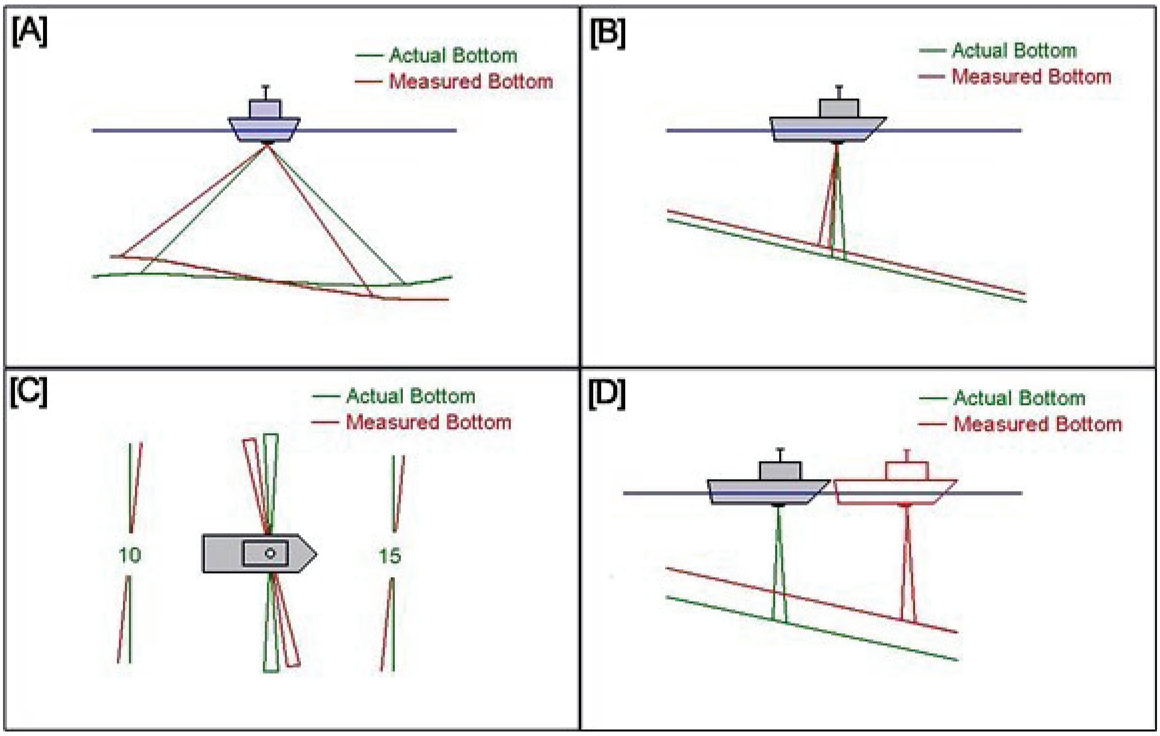


Figure 5: Patch test alignment showing the difference between the actual and measured bottom, [A] Roll, [B] Pitch, [C] Yaw, [D] Latency.

Acoustic imaging survey was carried out using 4200 Edge-Tech side scan sonar (SSS) to identify the seafloor textures and target the submerged artifacts by delivering high resolution sonar images for the seabed up to 18 cm along track and 1 cm across track depending on the backscatter strength (Hamouda et al., 2016).

The system comprised a towed stainless-steel fish which emit fan-shaped pulses towards the bottom and recorded a seafloor swath of 150 m. Ten track-lines were recorded by Discover software in the native JSF format (Figure 4), where six lines were oriented (NE/SW) and four lines were (NW/SE) oriented. Data processing was performed using Hypack® software, where data underwent reformatting then corrected radiometrically and geometrically, also TVG amplifications and slant range correction were applied. A Geotiff mosaic map was then constructed using the high frequency dataset (600 kHz), showing the different seafloor textures according to the degree of backscatter strength.

Different materials carry different reflective (backscatter) properties, where a rough, hard and prominent seafloor produces strong backscatter acoustic signals and light tone on the sonograph, whereas a flat, soft, and concave seafloor generates weak echoes (Hamouda et al., 2016).

Seismic survey was executed using 3200 Edge-Tech sub-bottom profiler (SBP) to measure and identify the different subsurface layers which exist below the sediment-water interface, and provide information on the different geomorphology of the near coastal areas and other deeper environments with 8-20 cm vertical resolution (Wilken et al., 2019). The system comprised a towfish containing a projector, receiver and signal pre-amplifier, and a portable floating buoy was attached to the tow-fish to provide a fixed towing altitude along the survey track. Sub-bottom profiler survey was carried out through twenty-three planned lines, where eleven planned lines [P] were oriented (NE/SW) and twelve cross lines [C] were heading in the (NW/SE) direction. Subsurface data were recorded using Discover software in JSF format, and data enhancement was applied using the sub-bottom Hypack® software, where the processing included TVG and band-pass frequency filtering, also profiles were transformed from the recorded time domain into the depth domain using the average sound velocity value acquired by the sound velocity profiler (Valeport). The ages of the top surfaces of each horizon (Figure 6) have been correlated with previously published core samples across the study area (Stanly et al., 2007). Therefore, the lateral geomorphological variations were deduced across the subsurface profiles.

ROV video camera dives were acquired using (Videoray) submersible vehicle to ground-truth the different geomorphologic features on the seafloor, also, surface sediment samples were collected using a stainless-steel Van-veen grab sampler, the station locations (Figure 4) were determined according to the variability of seafloor textures and determined using DGPS. Grain size analyses were performed and the samples were underwent to the combined dry sieving and pipette analysis technique (Folk, 1974).

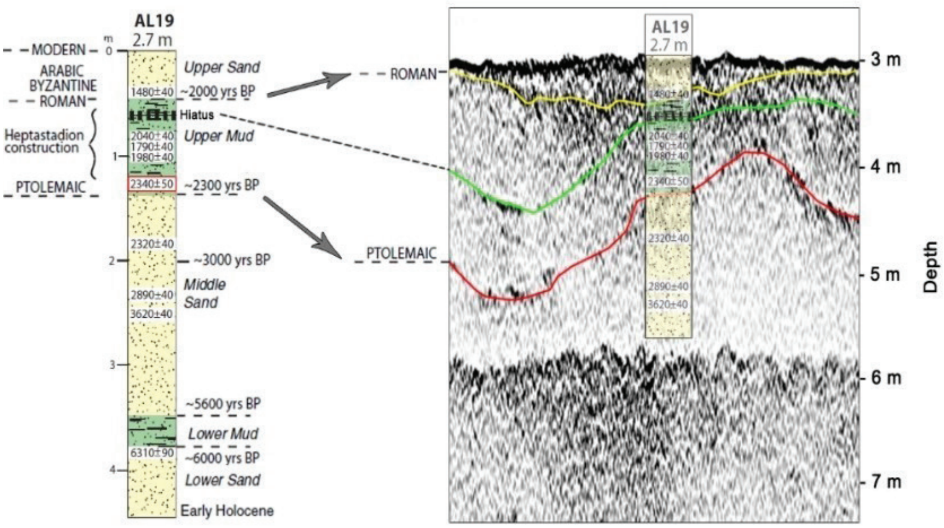


Figure 6: Seismic profile [4P] tie with Core (AL 19) (modified after Stanley et al., 2007).

4. RESULTS AND DISCUSSION

4.1 Bathymetry

The bathymetric map showed the recent topographic situation of the seafloor, where semi-buried relics of submerged ancient ports that once settled above the seafloor were recognized (Figure 7), an eastern Royal Port and other western Greco-Roman port (Goddio et al., 1998). The constructed contours showed depth values ranging from 1m close to the shore down to around 10 m in the northern margins near to the El-Boughaz.

The borders of the submerged ancient ports were outlined by the 4 m contour line, then the depth increases towards the central port basin to reach average values from 6 m to 8 m. Two separated closures with shallower depth values (~ 3.5 m) were recognized to the south of the breakwaters, which may reflect the presence of outcropping reef or ridge area. Generally, the contour lines showed irregular patterns around the submerged relics of the buried ports and the outcropping structure, while showed regular gradient across the rest of the harbor.

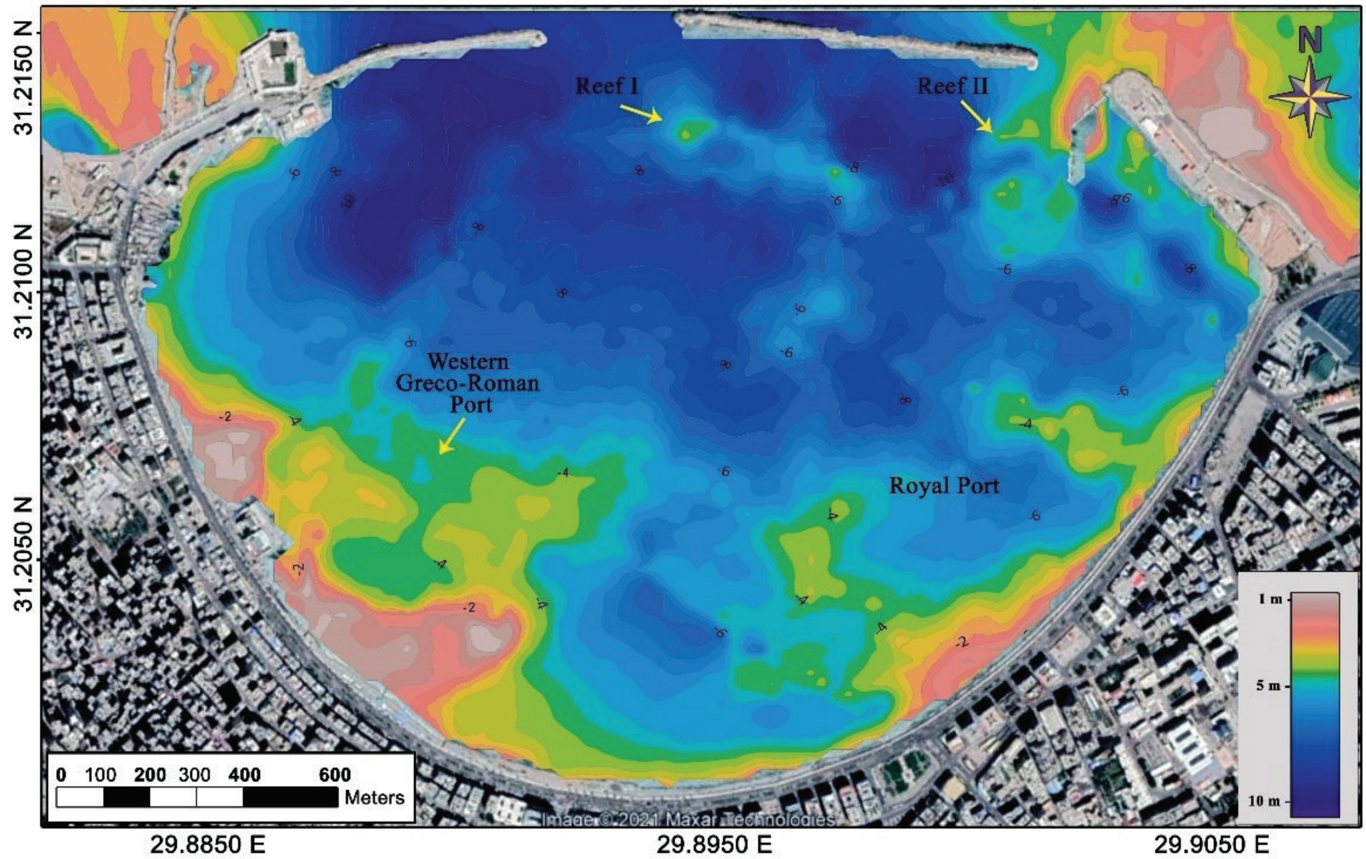


Figure 7: Recent bathymetric map for the Eastern Harbour of Alexandria.

4.2 Seabed imaging

The high-resolution georeferenced map (Figure 8), resulted from the mosaicking of the side scan sonar sonographs of the south-eastern part of the Harbor has defined the recent seafloor acoustic pattern according to difference in the returned backscatter strength. Distinctive backscatter patterns with different color tones were recognized, where distinguished sharp responses were detected along the breakwaters and the exposed ruins of the ancient port, also across the scattered rocks and boulders. The port basin floor and the surrounding seafloor are characterized by patchy tonal backscatter in the form of light tones corresponding to sand ripples intercalated with dark tones corresponding to finer grained sands (Table 1), providing strong and weak backscatter strength respectively.

The mosaic map (Figure 8) showed the exposed ruins of the submerged ancient Royal Port, where two irregular breakwaters were recognized along two opposite sides, separated by entrances (E1 and E2) and marking the borders of the port basin, the position of the ancient Royal Palace in addition to Antirrodus Island, Timonium and Posedium locations were determined across the map (Strabo, the Geography, Vol XVII). Two ancient jetties were detected, one appeared as a chain of boulders

(Figure 9) and the other in the form of an elongated reef. Also, different-sized boulders and blocks were found scattered over the seafloor and around the submerged breakwaters (Figure 10).

The recent seafloor morphology of the study areas which has been revealed from the bathymetric maps along with the high-resolution sonar mosaics, showed the effect of climatic and non-climatic factors on the pre-existed settlements. The irregular surfaces and the non-uniform structural form of the submerged breakwaters of the ports emphasized the effect of past sea level rises and natural hazards on the ancient site, while the scattered boulder debris and buried ancient structures, reflected the impact of the storms and currents on the underwater heritage.

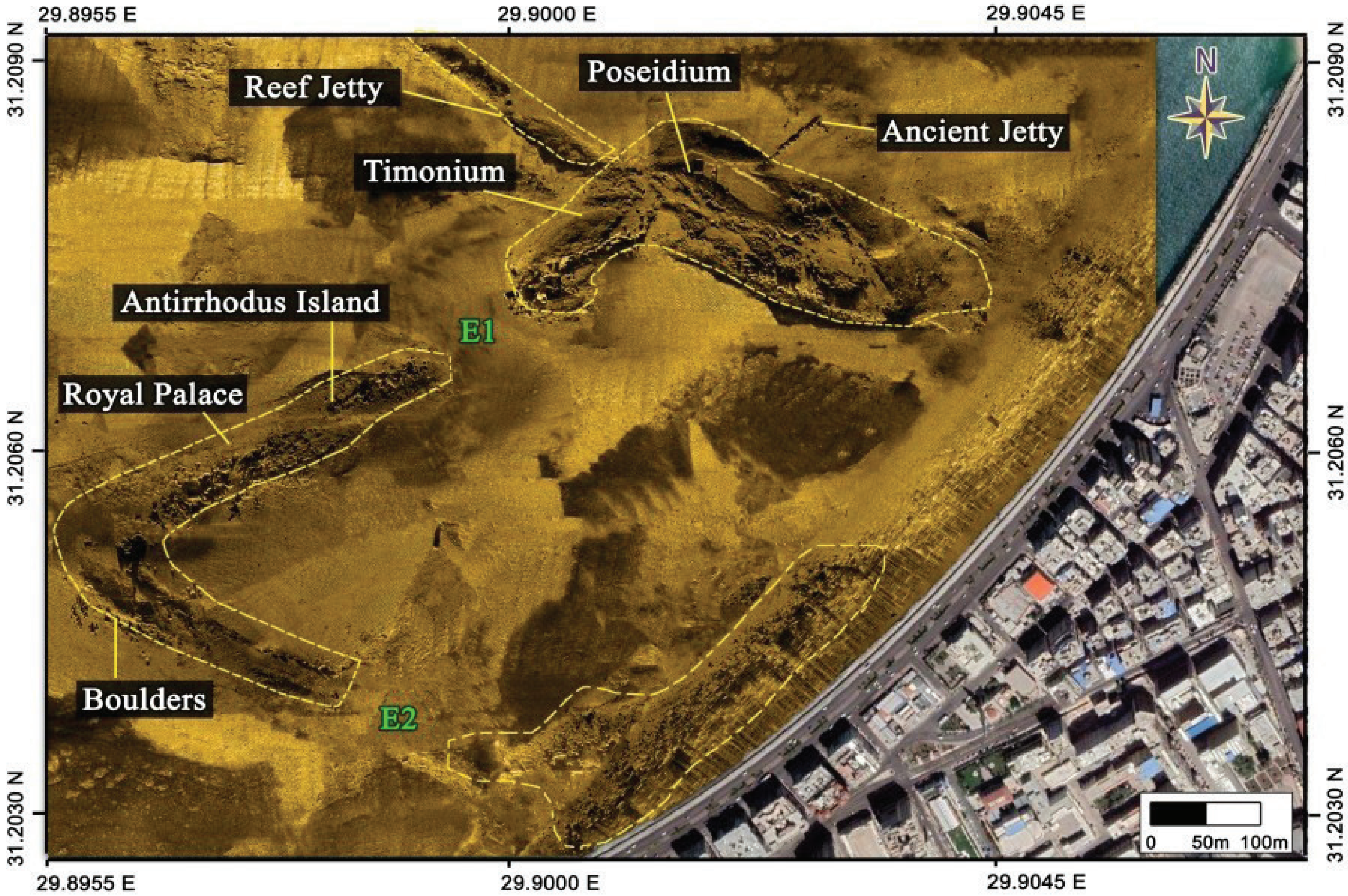


Figure 8: Side scan sonar mosaic of the submerged eastern Royal Port in the Eastern Harbor of Alexandria.

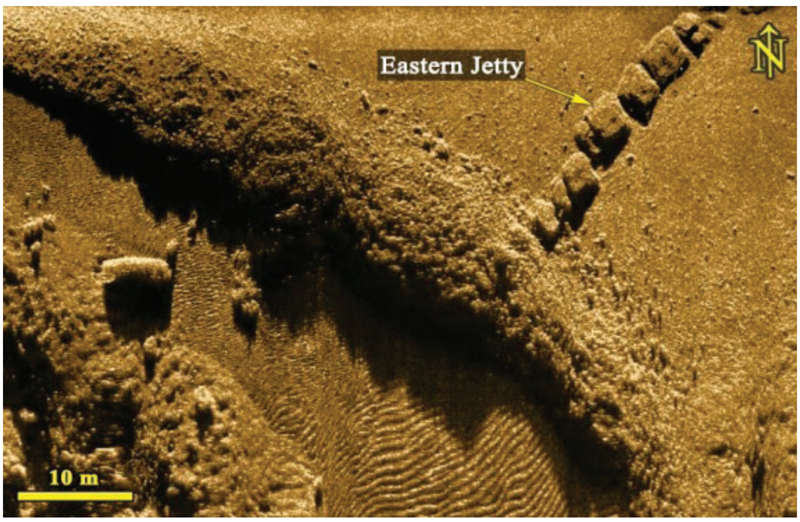
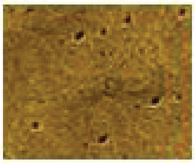
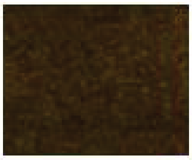
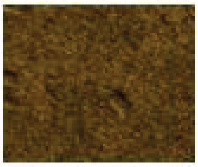
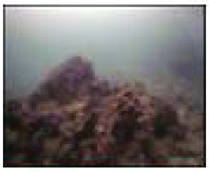
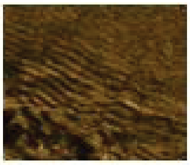


Figure 9: Side scan sonar image showing the jetty boulders which attached to the starboard-side breakwater.

Table 1. Sediment analysis results corresponding to acoustic classes and ROV images in the study area.

Sample no.	Acoustic response	ROV image	Sediment type/ Mean size	Sediment sorting
a			Fine sand	Poorly sorted
b			Very Fine sand	Moderately well sorted
c			Medium sand	Moderately sorted
x			Coarse sand	Poorly sorted
y			Medium sand	Poorly sorted
z			Very Fine sand	Moderately well sorted

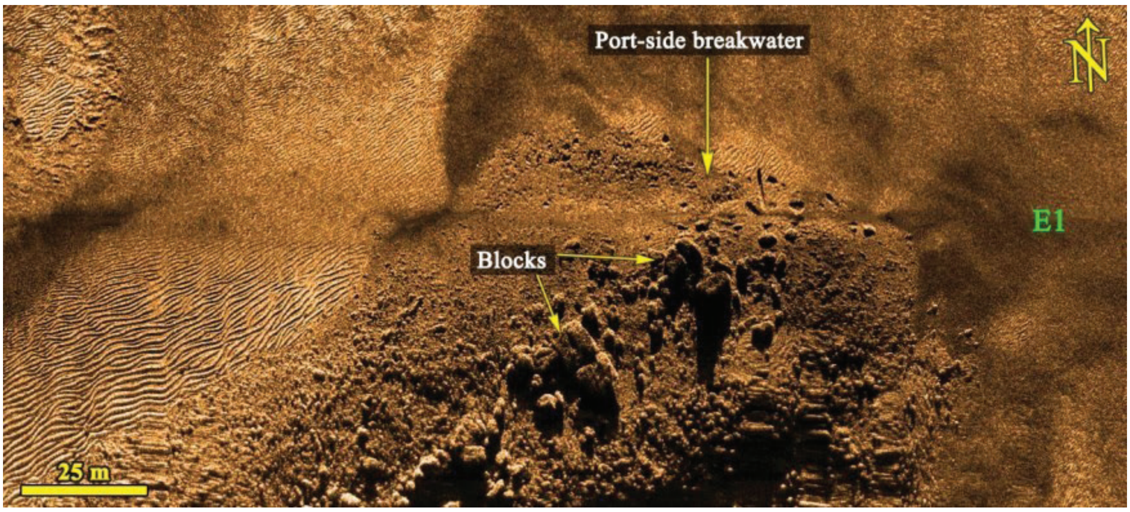


Figure 10: Side scan sonar image showing scattered blocks and boulders around the port-side breakwater.

4.3 Sub-bottom profiling

The seismic profiles explained the top-most stratigraphic succession of the subsurface layers, this depositional succession (Figure 11) was proposed after correlating the acquired seismostratigraphic sections with the previously published core data (Figure 6). Generally, a port foundation (lower) surface representing the Ptolemaic dynasty was detected along the semi-buried margins of the ancient Royal Port, these traces followed by alternative and discontinuous cycles of sedimentation and erosion. Then a port abandonment (upper) surface was detected which marked the upper edges of the ancient port, this surface is recently low-outcropping from specific areas across the sea floor. The uppermost seismic horizon neither showed anomalous sedimentation rates nor remarkable hiatus surfaces during the upper-most Byzantine and Arabic periods, and all the depositional sequence were capped by an undulating surface representing the recent sea floor.

Three-dimensional model was established (Figure 12) after picking the horizon of the initial surface of the Ptolemaic era across the seismic sections of the south eastern part of the study area, this surface showed the ancient topography of the port and delineated the ruins of the submerged Royal port.

In the study area, the coastal geomorphology reveals significant changes since the Mid-Holocene time. Geodynamic processes interacted with natural hazards, global scale climatic changes and human activities are the driving factors for these geomorphological changes. The evaluation of the port site evolution looks crucial in determining the degree of contribution of each factor in the subsidence of the underwater ancient site.

The evolution of the port site from the Late Ptolemaic period (Figure 12) to the period after 365 AD where massive burial for the port structure was existed, indicates the occurrence of sudden natural hazards originated from seismic waves; therefore, a destructive tidal (tsunami) wave accompanied by coastal land-sliding (Stiros, 2001) seems to be the dominant factors for this burial or a sediment substrate failure resulted from the inadequate piling under heavy constructions during Roman period (Guidoboni et al., 1994) or might be both factors. Since this time till the Late Roman period, the eustatic sea level rise had caused the inundation of the coastal area, also the inadequate construction piling and excessive sediments load derived from the Heptastadium tombolo had increased the burial and submergence of the port site (Stanley et al., 2007).

Uniform sedimentations were recognized over the submerged site from the Late Roman period till the recent time (Figure 7), where the seafloor reflected nearly the same morphology but with shallower depth values. This indicates that the global sea level rise was the dominant factor for the complete submergence of the site over time.

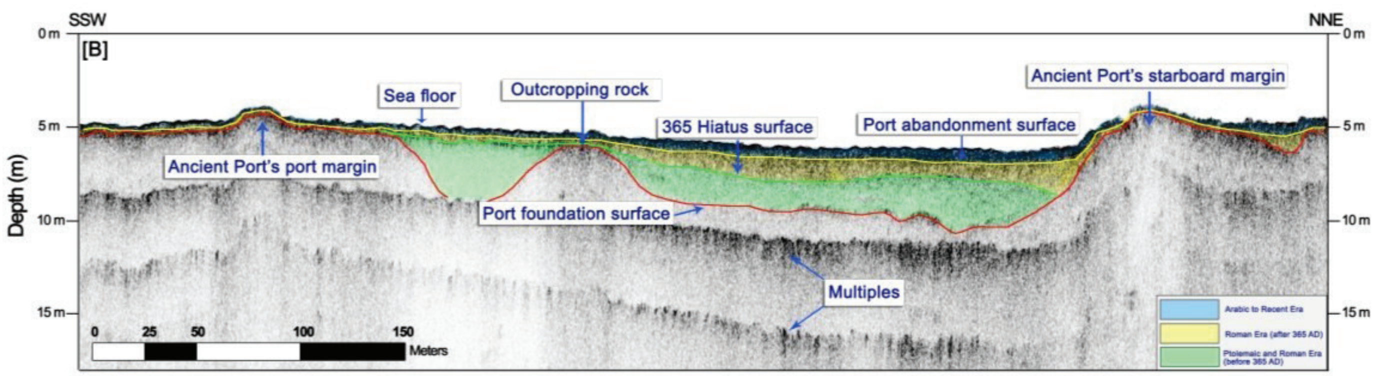


Figure 11: Seismic profile (2P) showing the sediment succession and rock outcropping from the basin of the Royal Port near the shore, [A]: Uninterpreted sub-bottom profile, [B]: Interpreted sub-bottom profile.

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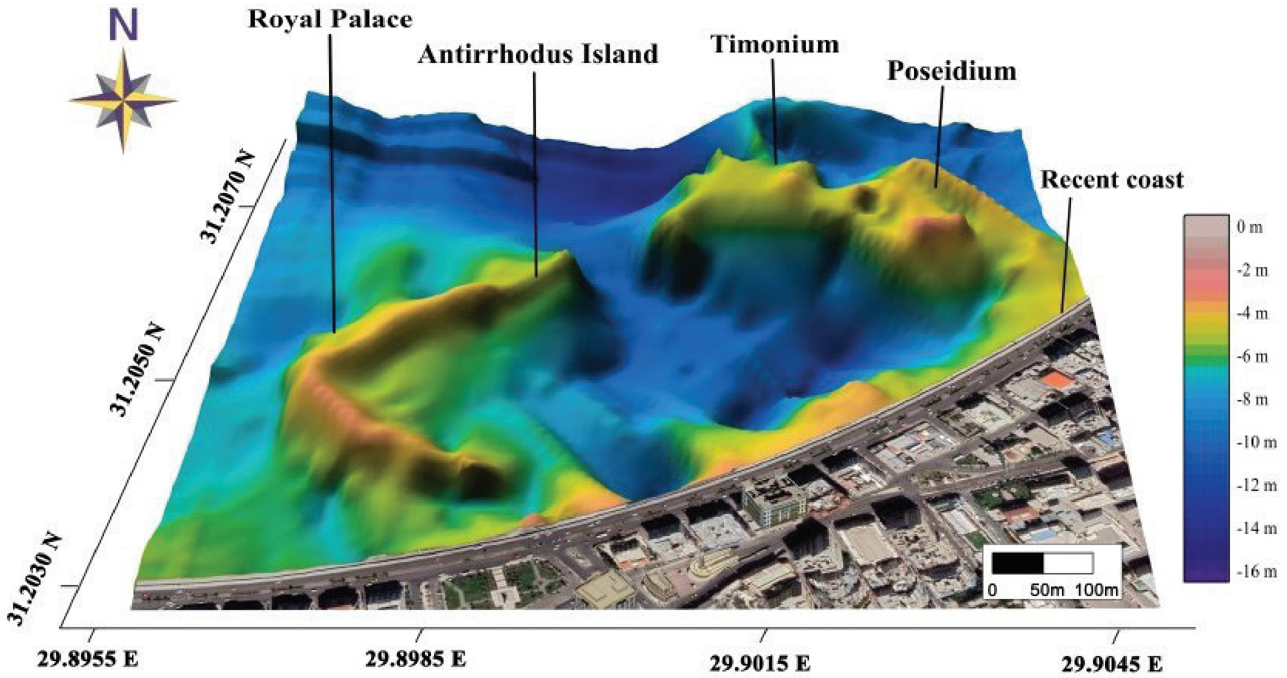

Figure 12: 3D Structural model for the upper surface of the Ptolemaic period (Royal port foundation surface).

5. CONCLUSIONS

Marine geophysical approaches showed significant results in delineating the geomorphological changes associated with sea level rises and natural hazards across the study areas. The developed acoustic methods became largely effective tools in the remote seafloor classifications and the geoarchaeological inspections, by providing highly detailed information about broad areas of the seafloor and subsurface layers in a short period of time.

The research results strongly confirm the exposure of the ancient coast of Alexandria city to submergence and subsidence as a result of relative sea level rises and geo-hazards including, earthquakes, tsunami waves, slumping and sediments mass failure. The research results strongly confirm the exposure of the ancient coast of Alexandria city to submergence and subsidence as a result of relative sea level rises and geo-hazards including, earthquakes, tsunami waves, slumping and sediments mass failure.

The bathymetric maps along with the high-resolution sonar mosaics have revealed the recent seafloor morphology at the study areas, where the recognized features emphasized the effect of past sea level rises, natural hazards, storms and currents on the ancient site. The seismic profiles integrated with sediment core samples had suggested a depositional model for the Royal Quarter at the western study area of Alexandria through the following successive stages : (1) The port foundation surface, representing the construction period of the ancient Royal port during the Ptolemaic dynasty, (2) The 365 AD hiatus surface topping the pre-deposited sedimentation related to the Heptastadium tombolo construction during Ptolemaic and Roman eras. (3) The port abandonment surface, representing the Post-365 AD sedimentations from the Heptastadium tombolo during the Roman period. (4) Upper sediment bedding without significant deformation, representing the period from the Byzantine and Arabic times till the recent.

The outputs of the imaging and seismic surveys demonstrate the efficiency of using side scan sonar and sub-bottom profiler in shallow geoarchaeological investigations, especially in semi-closed and harbor areas. It is clear that, the rapid and massive burial of the submerged sites was resulted from global sea level rises accompanied by seismically-originated tidal waves and land sliding, as the subsurface sediment thicknesses typically matched with the previous records of sea-level rise and land subsidence (± 2 m) during the last 2000 years.

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