Detection of the submerged topography along the Egyptian Red Sea Coast using bathymetry and GIS-based analysis

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Abstract A long time ago the Red Sea was only known by small-scale bathymetric, magnetic anomaly maps and a few seismic reflection or refraction profiles. Therefore, detection of the major submerged coastal features was unattainable. This study is based on the integration of different data sets of topography and bathymetry (e.g. the global bathymetry data set, the SRTM DTED², the soviet military topographic maps of scale 1:200.000 and the US army topographic maps of scale 1:250.000) to reveal the main submarine landforms that marked the continental shelf and its related slopes along the Egyptian Red Sea Coast from latitude 27°17'43"N to the Egyptian-Sudanese border at latitude 22°00'00"N. The study deduced that the continental shelf is noticeably influenced by the surface fault system extending eastward into the main Red Sea depression, showing the continental edge mostly like a fault-scarp of ~60° anticlockwise fault plane. Sea ridges and subbasins were distinguished at the lower toe of the continental slope, which seem to be a result of a regional fold system. Two sea peaks of extinct volcanoes were recognized. Two types of submarine canyons were recognized as deep incised Messinian canyons and shallow canyons. The deep incised canyons (~500 m bsl) carve the continental edge with remarkable steep walls. They might be formed as a result of the Messinian event (~5.59 Ma). The shallow canyons are mostly developed during the Pleistocene lower sea level (~90–130 m bsl) where the major wadis cut their water courses through the continental shelf. Some individual submerged deltas were identified, showing a close relationship with the present-day drainage system, although they were supposed to be produced by an ancestor drainage system. Notable submarine terraces were recognized at depths 20–25, 50–75, and 100–120 m bsl that are in agreement with the generalized global curve of sea-level rise since
1. Introduction

Depths of the Red Sea have been of great interest owing to the great controversy concerning structure and evolution of the Red Sea as the best example of a young ocean that evolved from an intracontinental rift to an axial oceanic trough (Guennoc et al., 1988). A long time ago, the northern Red Sea was only known by small-scale bathymetric and magnetic anomaly maps (Allan, 1970; Laughton, 1970; Hall, 1977) and by a few seismic reflection or refraction profiles (Drake and Girdler, 1964; Knott et al., 1966; Phillips and Ross, 1970; Tewfik and Ayyad, 1982; Guennoc et al., 1988). Therefore, neither the submerged coastal features nor the continental shelf has got serious attentions. The Admiralty chart of the Red Sea (C. 6359) published in 1965 and its updates and/or reprinted versions show many sporadic points that are not convincing or adequate to ascertain the major submerged coastal topography. Another bathymetric map of scale 1:1000000 was published by the International Hydrographic Bureau, Hydraulic Department-UK in 1970. The map was made of 500 m depth interval, showing many steep cliffs along the coastlines and somewhat close to the inshore. Marginal deeps were revealed as well on both sides of the northern Red Sea that may have considerable tectonic significances. The accuracy of the map was poor as no radio aids covered the area and very few soundings were controlled by satellite navigation (Laughton, 1970). Guennoc et al. (1988) established new bathymetric maps of scale 1:250000 at latitude 26° N with a 100 m contour interval based on the base maps of Pautot et al. (1986) and Bäcker et al. (1975) and revised using regional sea-beam surveys. The maps were completed with 12 kHz or 3.5 Hz echo-sounder profiles done during the “Geomerouad” and “Mines” cruises. Recently, the RIV Meteor Cruise M44/3 in 1999 investigated some places in the northern Red Sea using a hydrosweep bathymetric multi-beam system and the narrow-beam parasound sediment echosounder (Pätzold, 2000).

On the one hand, Shukri and Higazy (1944) referred to the Red Sea as probably unique to its very irregular bottom topography (excluding the Gulf of Suez), as nature and distribution of its bottom deposits are unmatched in other seas. Jokela (1963) revealed that the Red Sea bottom topography is rough except below the shelves. He distinguished narrow shelves in the northern Red Sea; wide shelves and narrow median valley in the south. Braithwaite (1987) stated that depths of hundreds of meters are generally reached within a few kilometers of the shoreline and there is commonly no effective continental shelf. In the northern Red Sea, Tewfik and Ayyad (1982) referred to the presence of northwest trending negative gravity anomalies, which are believed to represent subbasins. These subbasins are generally parallel to the coastline and separated by NW-SE fault trend that is the main structural element in the area. Other cross faults are perpendicular to the former trend. However, Said (1990) assumed that the Red Sea marginal homoclone dips gently eastward from the shore and is made up of many horsts and fault blocks. Uchupi and Ross (1986) used seismic reflection profiles to distinguish oblong low relief features (gently folded structures) in the northern Red Sea, which appear to have resulted because of the intrusion of the Miocene evaporites. They divided the rift of the northern Red Sea topographically into narrow shelves, which are less than −50 m bsl, marginal slopes with reliefs of about −600 m bsl and the main trough below −600 m depth. The central part of the main trough consists of northwest trending highs and lows truncated at the north by the Gulf of Aqaba trend.

Moreover, submarine terraces and canyons have been distinguished in several localities along the Red Sea Coast, e.g. Sharm El Sheikh, Gulf of Elat, Sudan, and Saudi Arabia (Emery, 1963; Gvirtzman et al., 1977; Fricke, 1983; Reaches et al., 1987). Embabi (2004) inferred from bathymetric lines on topographic maps, scale 1:1000000 small deltas along the Egyptian Red Sea Coast below the sea level in front of the main wadis. In the central continental shelf extends from Safaga to El Quseir, Moawad (2008) distinguished probable submarine terraces (−100, −50, and −20 bsl), submerged like-deltas and incised canyons of −500 m depth.

2. Study area

The Egyptian Red Sea Coast extends southwards from the southern limits of Gulf of Suez (27°43′N) to the Egyptian-Sudanese border (22°00′N), some 790 km (Fig. 1). It seems to be straight for the most parts due to the tectonic genesis of the Red Sea itself as a major part of the African Rift Valley. The transition zone between the Gulf of Suez and the northern Red Sea is avoided in this study, not to be confused with the Red Sea topography. The study area is a good example of a passive continental margin as no collision or subduction is taking place and tectonic activity is minimal. It is generally characterized by narrow continental shelves as there is a little sediment transport by the drainage system or redistribute by the longshore currents.

General oceanography reveals that capillary waves (≤0.6 m) are the most common throughout the year and the averaged wave height ranges from 0.6 to 1.5 m (Moawad, 2008). The wave occasionally exceeds 3 m whereas the wind speed increases above the normal average (6.15 and 4.5 m s⁻¹ in Hurghada and El Quseir, respectively, Climatological Normals of Egypt, 1975). It rarely exceeds 5 m during the gale wind as the wind speed is +17.49 m s⁻¹, which mostly occurs during winter and early spring (Edwards and Head, 1987).

In addition, the study area spans from the micro-tidal environments. Tide is semi-diurnal, has two high and two low waters per tidal day (Edwards and Head, 1987). Neap tide ranges from 0.83 to 0.6 m in Hurghada and Halaieb correspondingly. Tide amplitude is significantly low; varies between 0.46 and 0.48 m in winter and summer, respectively and the maximum amplitude is about 0.5 m owing to the seasonal changes during the winter months (Behairy et al., 1992). How-
ever, tidal water inundates the coastal low lands up to a few hundred meters (Moawad, 2008). As the longshore currents are mainly governed by the prevailing winds, they are generally very weak. The average velocity of the longshore currents is about 0.12 m s\(^{-1}\) (Edwards and Head, 1987). In other words, role of the coastal processes is mostly insignificant.

The main objectives of this study are to recognize the major submarine landforms that marked the continental shelf and its related slopes, their characteristics and evolution. The study may be helpful for further researches, as well to construct a general overview about the geomorphologic characteristics and evolution of the continental shelf and the Juxtaposition landmass.

3. Data and methods

The study depends on five data sets of topography and bathymetry, which have been integrated and/or overlaid for the purposes of data analysis. The data sets are the global bathymetry data set from Smith and Sandwell (1997), the SRTM DTED\(^2\), the Soviet Military topographic maps of scale 1:200,000, the US Army topographic maps of scale 1:250,000 and the ETM+ Landsat images.

The global bathymetry data set represents an estimation of seafloor topography. The data were obtained from shipboard depth soundings combined with gravity data derived from satellite altimetry. The final production is a gridded representation of seafloor topography for all ice-free ocean areas within ~72° latitude. The depth data were obtained by screening 6905 surveys from the NGDC (Marine Trackline Geophysics CD-ROM version 3.2), the Scripps Institution of Oceanography and Lamont-Doherty Earth Observatory databanks, and other data using quality control procedures based on those of Smith (Amante and Eakins, 2009). The data were obtained from the interactive database management system GEODAS (GEOphysical DAta System) developed by the National Geophysical Data Center (NGDC) (http://www.ngdc.noaa.gov/mgg/image/2minrelief.html). Data are available in ASCII raster grid format including arc header using spatial resolution 2 min along latitudes and longitudes (about 4 km at the equator and 2.6 km at 45° latitude).
SRTM DTED\textsuperscript{®} 2 is defined as a uniform grid of elevation values, spaced at three-arc second (approximately 90 m) intervals. Elevations are rounded to the nearest integer meter and are referenced to mean sea level defined by the WGS84 EGM96 (Earth Gravitational Model 1996) geoid. SRTM elevations represent the elevations of the reflective surface (e.g. tree canopy, building roof, bare ground) for the radar return beam and have not been reduced to bare Earth. Accuracy of the SRTM data is 16 m absolute vertical error (90% linear error, with respect to the reflective surface), 20 m absolute horizontal error (90% circular error) and 10 m relative vertical error (90% linear error) (NIMA, 2000). SRTM DTED\textsuperscript{®} 2 was preferred for many reasons, i.e. (i) the ability of identification, delineation, and elevation determination of water bodies that meet the minimum size criteria, (ii) coastlines and sea level are set to 0 m, (iii) double-line drains (rivers) greater than 183 m in width can be delineated, (iv) islands are delineated if greater than 300 m in length or, for smaller islands (down to14,400 m\textsuperscript{2}); if at least 10% of the island’s elevations are 15 m or more above the surrounding water. Odd points (spikes or wells) in the elevation data were removed and voided out if they exceeded the mean elevation of the surrounding (eight) neighboring elevation posts by 100 m or more.

Bathymetry lines were firstly digitized from thirteen topographic map sheets produced by the Soviet military of scale 1:200.000 and another eight topographic map sheets produced by the U.S. army of scale 1:250.000. Generally, contour interval varies from 10 m onshore and 100 m offshore. The lines were converted into points using ArcGIS v.10. Next, a raster surface was processed using ordinary kriging interpolation procedure. This procedure is preferred to determine error(s) of the global bathymetry data as the mean altitude varies greatly between the landmass and the surrounding continental margin. Therefore, the procedure attempts to have a mean residual error equal to or near zero and predict the semivariances multiplied by the ordinary kriging weights based on the variance of the vector data (Lloyd, 2007). This was carried out using 4518 control points derived from the topographic maps. Then, these points were input into the geostatistical analyst to create a spherical semivariogram. After that, a prediction surface was created and differences between the global bathymetry data and the DEM derived from the topographic maps were determined along some shared localities. The prediction surface from kriging was subtracted from the global bathymetry data to get a new DEM with the error removed.

The mean of the prediction error was estimated at −0.00453 and the RMSE (root-mean-square error) was estimated at 23.28. It is known that these values decrease as the number of nearest neighbors increase (Lloyd, 2007). Finally, bathymetry data (derived from topographic maps and the error removed DEM) were integrated together to create the final digital elevation model using spatial resolution 100 m. Golden Software Surfer 9.11 was preferred for better representation of the data in 3D perspective views.

However, major wadis were extracted from the SRTM DTED\textsuperscript{®} 2 to clarify their relation to other submerged landforms (e.g. submerged deltas and submarine canyons). This was done by determining the directions that water will flow out of each cell to its steepest down-slope neighbor (flow direction) relying on the 8D method (O’Callaghan and Mark, 1984). Flow accumulation function was applied to tabulate for each cell the number of cells that will flow to it (Chang, 2006) and cells of high flow accumulation were used to identify the main channels. ETM+ Landsat images were used to define accurately the pour points (outlets) of the main hydrographs and to visually verify the output streams. Stream network was derived from the flow accumulation layer by a threshold value of ≥150 cells, which was preferred as the resulting streams are likely corresponding to a network obtained from traditional methods using topographic maps of scale 1:50.000 (Tarboton et al., 1991; Moawad, 2008). Streams were extracted by assigning the flow accumulation layer to integer values ≥1 for a stream and no-data for background. Thereafter, streams were ordered according to Strahler (1957). For the purposes of data representation, major and trunk streams are only represented while the lower orders (i.e. orders 1st, 2nd and 3rd) were excluded.

4. Results of data interpretation

The submarine topography in the study area has been divided into six major divisions (Figs. 2 and 3). They are: (i) continental shelf and continental slope; (ii) subbasins; (iii) sea ridges and/or undulated seabed; (iv) sea mounts and knolls; (v) submarine canyons; (vi) submerged deltas. The following paragraphs shed light on their general characteristics.

4.1. Continental shelf and continental slope

The continental margin is the submerged outer edge of the continent. It is generally divided into two subdivisions: the continental shelf and the continental slope. The continental shelf starts from marks of the high water on the shore (littoral zone) and exhibit noticeable breaks in declivity from gentler slope near the shore to one that is much steeper (continental slope) beyond the shelf break. Along the Egyptian Red Sea Coast, depths of the shelf range from a very few meters (−1 m) down to ~120 m bsl. It is mostly covered by coral communities. Width of the shelf changes locally, varying from a few kilometers (5 km) to tens of kilometers (46 km). The widest part ranges from 24 to 46 km in the area that extends from Ras Benas to the southern tip of El Foul Bay (15 km long) (Fig. 4).

The continental shelf can be considered as tectonic and to a lesser degree depositional margin. Its accretion is constrained primarily by sediment supply since role of the coastal processes is mostly insignificant (Moawad, 2008). However, deposition is predominantly restricted to submerged deltas and some reef communities.

Topography of the continental shelf is not completely flat. The present-day platform slopes eastward gradually (2°–9°) between the mean low water to the further limit of the breaker zone toward the offshore. It is mostly covered by coral reefs that run parallel to the coastline (Unlimited Media, 2004). The breaker zone is defined by the outer limit of the fringing reefs as it acts as a line of breaker. Therefore, most of the waves are forced to be broken in the vicinity of the coastline between 50 and 400 m in average at depths 0.5–1.5 m bsl. The platform is often disturbed by inter-lagoons (pool-like) or mud flats (Fig. 5). These lagoons have generally oval or circular shapes (Moawad, 2008), and they are of few meters in depth (~2 m bsl).
Another interesting feature of the shelf is St. John’s cave at Mersa Alam that is reported by many divers in St. John’s reefs. The cave is a slightly misleading name it seems since scientifically it seems to be one of the many fissures that marked the continental shelf at depths of $-6$ to $-25$ m bsl. Such fissures are known by leader divers as tunnels or passages, of which many fissures have no direct access to the sea surface, although there are always small openings to allow light penetration.

The sea level dropped approximately 100 m below its present-day level during the last glacial maximum (LGM) ($\sim$23–18 ka bp, Gasse, 2000). It is assumed that a broad part of the shelf was exposed and subjected to subaerial erosion and resulted in the development of Karst forms beside shallow canyons and the present-day embayments (locally known as sharms) as the wadi system carved the continental shelf. This may explain the presence of the present-day coastal lagoons and some other small-scale sinkholes and submerged caverns. Nowadays, development of the modern reef communities led to shallow the shelf with numerous shoal reef areas that act as an extensive trapping of sediments.

Regional tectonic pattern of the continental shelf is mainly influenced by the surface faults extending eastward into the main Red Sea depression. Tewfik and Ayyad (1982) revealed that the Red Sea marginal homocline dips gently eastward from the shore and it is made up of many horsts and fault blocks. Further offshore, seismic reflection data indicate a relatively narrow NW trending zone of pre-middle Miocene horsts and tilted fault blocks. Ahmed (1972) revealed that in late Pliocene and Pleistocene times there was renewed block faulting accompanied by igneous intrusions. As a result, the Red Sea depression is characterized by rectilinear faults bordering blocks, which were rising or sinking concurrent with

![Figure 2](image-url)
the Neogene deposition. In many cases the structural axes are shifted laterally, probably as a result of E–W cross faults (Tewfik and Ayyad, 1982).

The continental slope starts from the edge of the continental shelf (shelf break) and declines progressively down to 500 and/or 700 m bsl. The slope is generally narrow (~1 km width) where it descends abruptly toward the deep seafloor and looks mostly like a fault-scarp. The form of the continental slope exposes normal faults trending NW–SE matching the main trend of the Red Sea trough with a fault plan of ~60° anticlockwise.

Figure 3 3D perspective views showing the main submarine topography along the Egyptian Red Sea Coast. (Locations shown in Fig. 1).
and steep slope (Fig. 4). Said (1990) cited that the major faults are attributed to the initial rifting of the Red Sea and they experienced tectonic events at the edge of the continental shelf (e.g. uplift, volcanic activity) in the later stage.

Sometimes width of the continental slope attains about 8 km as a result of the submarine deltaic deposits descending into the seafloor. No distinctive gently-sloping transition (continental rise) between the continental slope and the deep
seafloor was distinguished. This may be due to lack of thick accumulation of sediments from the neighboring landmass that is transported to the shelf and then down the continental slope. Generally, the continental slope has been interrupted by folding, faulting, and erosion with the present shelf configuration resulting from Pleistocene subaerial erosion with very little Holocene deposition (Said, 1990).

4.2. Subbasins

Based on gravity data Tewfik and Ayyad (1982) recognized many subbasins parallel to the coastline and separated by structural ridges. Using digital and visual image interpretations 12 subbasins were recognized from the digital elevation model. They vary in shape between longitudinal and semi-circular (Fig. 2). They run parallel to the continental shelf except the subbasin numbers seven and 11 that run from east to west. Generally, the subbasins are restricted to the lower tip of the continental slope from the east and to the sea ridges from the west with the exception of the subbasin number eight that lies on the continental shelf near El Foul Bay. Depth of the subbasins ranges generally between −196 m (subbasin number eight) and −853 (subbasin number nine). They vary as well in width from 12 to −40 km and the general physiographic settings reveal that the western limbs are generally higher than the eastern and southern limbs (Fig. 6). Some subbasins are separated by low ridges, which seem to be a part of regional undulated seabed strata of a wide extent (Fig. 2). Tewfik and Ayyad (1982) assumed that the subbasins seem to have been formed during the development of the regional arching and subsequent collapse of the Red Sea. They suggested that they are probably filled with middle Miocene evaporites and younger continental sediments.

4.3. Sea ridges

Ridges are common in the vicinity of the lower tip of the continental slope mostly without exceptions. Two types of ridges can be distinguished based on their altitudes. The first one is the low ridges that rise a few tens of meters above the surrounding seafloor (Figs. 3 and 4). They range in elevation from −400 to −600 m bsl. The second is the higher ridges that exceed +100 m above the surrounding seafloor (Fig. 4). Summits of the ridges are generally round and differ greatly in depth from −300 to −600 m bsl. The lower base of the ridges differs as well locally, ranging from −500 to −700 m bsl. Based on their symmetry, they might be inferred as a result of a regional fold system. In the vicinity of the continental slope, probable

Figure 6  Topographic cross sections of the subbasins. (Locations shown in Fig. 2).
normal faults separate the sea ridges from the continental slope with an estimated dip of a fault plane of $-60^\circ$. Investigation of the geological maps revealed that some offshore islands (e.g. Safaga, Sernaka Island, Mukawwa, Zabargad and the Rocky Island) are built up of the same rock formation(s) as the neighboring landmass. The islands constitute the small merged areas that are standing from the top of the sea ridges owing to the regional upward of the continental margin. Marginal upward might be a result of fault reactivations and major folding during the formation of the Red Sea trough. Jokela (1963) suggested that episodic compression occurred in the direction of the Red Sea axis in pre-Oligocene time and was expressed by folding of soft sediments along the Egyptian shelf and possibly by uplift of mountains in Turkey. Simultaneously, tension perpendicular to the sea axis formed fractures parallel to the axis, some of which served as volcanic and hydrothermal vents. Marshak et al., 1992 revealed that Zabargad Island was affected by the final phase of tectonism resulting in an array of high angle faults and associated folds. Together resemble palm structure typical of cross fracture zones in rift. The southwest corner of the island was subjected to large recumbent folds. It appears to be an uplifted fragment of sub Red Sea lithosphere and it is essentially the result of upward motion of mantle derived ultramafic bodies (Bonatti et al., 1983).

Seamounts are other distinctive features within the large structurally complex segment of the Red Sea. Twelve seamounts were recognized, which rise surprisingly from the seafloor and peaking below sea level (not reaching to the water’s surface). They range in elevation between $-100$ and $-800$ m bsl and have mostly circular shapes, which seem to be a result of small volcanic cones. Seamount numbers one and two shown in Fig. 2 in specific are distinguished as independent features since they exhibit typically conical topography with very steep sides. They rise abruptly from the sea floor of $-600$ and $-800$ m depth, respectively up to $-350$ and $-450$ bsl in the same order, and seem to be extinct volcanoes with round peaks (Fig. 7). Other minor features could be distinguished as sea knoll (seamounts with flat top) as they rise gradually from the undulated seafloor, mostly due to the regional folding system and upthrust faulting. These knolls play an important role in exposing tips of some reef pillars as semiatoll or offshore islands such as Al Akhawein islands, which is situated 67 km offshore east of El Quseir. The two islands are likely the exposed tips of two massive reef pillars that rise from the sea. The pillars cover the pinnacles of two undersea knolls rising from about $-300$ m bsl (Moawad, 2008).

Figure 7 3D perspective views showing the sea mounts. (Locations shown in Fig. 2).
Figure 8  Examples of the deep incised Messinian submarine canyons.
Alignment of the seamounts with the major axis of the continental shelf suggests relative synchronicity of volcanic eruption with the fault and fold systems influencing the continental edge. Although an absolute date is not yet available, assumption of synchronicity suggests the seamount as pre- and/or middle Miocene features. Said (1962) assumed that volcanism occurred in the compression zones of Egypt during the pre-Oligocene period of activity, but appears to have ceased after the Mio-Pliocene relaxation of stress in this area (Jokela, 1963). Coleman (1974) stated that during the Miocene time, volcanic activity continued in Afar Depression (Eritrea, Djibouti and the entire Afar Region of Ethiopia) and in western Saudi Arabia. However, he cited as well that during the formation of the axial rift (trench) in the Red Sea in the early Pliocene (~5 Ma); numerous submarine volcanoes contributed pyroclastic rocks and lava. As a result, many alkaline olivine basalt eruptive centers developed along the hinge line of the

4.5. Submarine canyons

The submarine canyons are the most conspicuous erosional forms marking the outer continental margin along the Egyptian Red Sea Coast. They carve the deep fissures along the continental slope, which are probably produced by an ancestor drainage system. Shepard and Dill (1966) argued that such canyons appear to have had several origins and producing distinctive types. They can be distinguished within the study area on the basis of their morphology as follows:

Figure 9  The close relationship between the present-day Red Sea drainage system and the submarine canyons. (Extracted from the DEM, boxed areas approximately show locations of Fig. 11).
4.5.1. Deep incised canyons
(Messinian canyons!!)

Deep incised canyons are the most common features that significantly break the continental slope. They reach ~500 m below the present-day sea level and distinguished by remarkable steep walls that seem to have been cut in the bedrock (Fig. 8). In some cases, head of the canyons may be traced to the upper part of the continental slope at depths ~100 and ~150 m bsl. Longitudinal profiles of the canyons are generally concave and sloping strongly seaward from the head of the canyons to the deep sea. Although, the incised canyons sometimes follow the major structural features seaward from the adjacent land as shown in Fig. 3, they seem to be the result of a great geological event that influenced the continental margin since they are common along the Egyptian Red Sea Coast mostly
without exceptions. Moawad (2008) showed some incision canyons spreading along the coastal area extending between Safaga and El Quseir. Siroko (2008, personal communication) believed that they are a result of the late-Miocene Messinian salinity crises (Messinian Event!!) owing to the sudden disconnection of water supply between the Atlantic Ocean and the Mediterranean sea. The Mediterranean water level dropped down to 1500 m below its present-day level, entailed a considerable increase of salinity and intense erosion of all Mediterranean rivers such as the Rhone and Nile canyons. The erosive phase is supposed to have occurred between 5.59 and 5.50 Ma and followed by deposition of non-marine sediments between 5.50 and 5.33 Ma (Krigsman et al., 1999). Stoffers and Ross (1974) argued that there was a large relief differences between the Red Sea depression and the surrounding land during Miocene time. Therefore, the Red Sea depression received marginal clastic sediments (2-3 km thick) interfingered with evaporites (3-4 km thick) and the Red Sea depression continued to subside (Ahmed, 1972; Coleman, 1974). In context, Gillmann (1968) inferred rapid erosion at the Yemen-Hail and Ethiopian arches during Miocene. It can be deduced that an old drainage system was the major carrier of such sediments, especially during middle-Miocene time as the climate was warm humid (Khedr, 1984). As a result, a great bulk of the Tertiary sedimentary rocks was swept out from the Miocene highlands in the Eastern Desert of Egypt. Sedimentologic evidences obtained from Jabal El Rusas (25°11′–34°46′E) clarified that the lower unit unconformably overlies the basement rocks. The unit consists of 2–3 m orthoconglomerate with angular and round clastic, which range from large boulders to granular. Khedr (1984) assumed that sedimentation of this unit begun in middle Miocene. Small pockets of the Tertiary sedimentary rocks are still preserved in the morphotectonic depressions in the Central Eastern Desert of Egypt such as Jabal Duwi (26°11′N–34°E) (Moawad, 2008).

Although, role of the recent fluvial process is insignificant, Fricke (1983) denoted that flash floods often of catastrophic nature, which influence the Red Sea region, carry large amounts of sediments into the sea. Accordingly, he suggested that occasionally gravity flows fed initially by sediments from aligned wadis are a major agent in cutting the deep submarine canyons into steep edges of the narrow Red Sea shelves. Fig. 9 shows a close relationship between the present-day drainage networks and the bathymetry. It is notable, as an example, that many wadis were debouching into El Foul Bay. The wadis are located some 25 km westward of the head of El Foul Canyon. The major trend of the streams and their tributaries is of W-E orientation. The main wadis range from 100 to +200 km long and their heads are incised in the basement rocks. Another evidence obtained from Jabal Abu Shaar (27°22′N–33°35′E) and Jabal El Rusas (25°11′N–34°46′E) revealed that the present-day drainage system is typically superimposed (overprinted) on the basement rocks. Therefore, the present-day wadi system is mostly inherited from an older one that may be back to pre-middle Miocene as the climate was shifted in Oligocene toward a Sudano-Guinean type of savannah (Le Houérou, 1997).

4.5.2. Submerged shallow canyons

The submerged lower water courses of the wadis exhibit sometimes small-scale canyon-like shapes, which marked mainly the continental shelf and, to a lesser extent, the continental slope. The canyons are relatively shallow as the depth varies from a few meters to tens of meters (~2 to ~70 m bsl). They are characterized by more or less symmetrical winding V-shaped and/or U-shaped (Fig. 10). Some smaller-scale tributaries, which have been identified from the hydrological model, are entering the canyons from both sides. The resemblance of submarine canyons to river-cut canyons on land and the juxtaposition of many land and sea canyons has always provided a strong argument that at least the heads of the submarine canyons were originally cut by rivers (Shepard and Dill, 1966). Morphology of such shallow canyons reveals that they are probably developed during the Pleistocene lower sea level some 90–130 m below the present sea level (Reaches et al., 1987). As a low raised beach borders the present-day coastline (~1.5 m), it can be inferred that an episode(s) of cut and fill related to the sea level changes influenced the shallow canyons. Role of subaerial erosion as well was proposed by Gvirtzman et al. (1977). He assumed that the lowest erosional base level was ~120 m bsl in the Red Sea during the last glacial maximum (LGM).

In general, position and configuration of the submarine canyons are controlled by multiple factors, including structural fabric, tectonism, sea-level variations, and sediment supply (Laursen and Normark, 2002). However, idea of marine origin of the canyons as supposed by Shepard (1972) is improbable in the Red Sea as no large active marine erosion has been found throughout the geological evolution of the Red Sea. Even the idea of turbidity currents that suggested by Daly (1936) is unlikely since there is no powerful current in the Red Sea, as far as known to date. It is believed that the role of marine erosion might have been restricted to some form modifications.

4.6. Submerged deltas

The general configurations of the bathymetric lines reveal submerged fan-like shapes of different sizes either partly of fully extended as a part of the continental shelf. The fan-like shapes are located seaward of the present-day drainage system. By following some criteria of the alluvial fan definitions (e.g. morphology of the bathymetric lines, location at topographic breaks), Embabi (2004) and Moawad (2008) assumed that they represent submerged deltas of an ancestor Red Sea drainage system in the Eastern Desert of Egypt. Toes of the deltas are plunging down into the deep sea for ~500 m below the present-day sea level. Individual deltas are bounded laterally by incised canyons, troughs, channels, and therefore the bathymetric lines became more crenulated. The canyons carving the submerged deltas play a significant role in sediment transport mostly during catastrophic flash floods. Sometimes, the lateral boundaries are less distinctive between the adjacent deltas as in the case of delta wadi El Ambagi that seems to be a result of some coalescing deltas (Fig. 11a).

Correlation between individual wadis is not fully conformable, as the present-day drainage system might have been subjected to meandering, shifting during the Pleistocene lower sea-level and/or tectonic events. However, some prolonged channels have been traced in the shallower part of the shelf.
such as wadi Queih (Fig. 11a) that seems to have cut the continental shelf during the maximum low stand of sea-level. The landward side of the delta is found just beyond the point where the recent trunk stream of wadi Queih is debouching into the Red Sea.

Generally, the submerged deltas seem to be constructed from consolidated alluvial deposits, as processes of diagenesis that resulting in compaction, cementation, and lithification require millions of years to transform the sediment into sedimentary rocks (National Research Council, 1996). Stow et al. (1985) and Kolla and Macurda (1988) determined the factors controlling the development of such submarine system into two groups. The first group includes the primary controls i.e. type of continental margin, relief and tectonic setting of the hinterland, continental shelf-slope relief, nature of basinal areas and basin size, distance from the source region, width and gradients of the shelf-slope, and type and amount of sediment supplied. The second group includes the secondary controls, i.e. climatic nature and vegetation of the source area, and high rainfalls during sea-level changes.

Marine terraces are one of the most important recognized features that marked the submerged deltas as flat surfaces of different extents. During Pleistocene and Holocene, the Red Sea experienced dramatic eustatic changes resulting in a sequence of raised coral terraces and alluvial terraces. Moawad (2008) distinguished three submarine terraces at −20, −50,
Detection of the submerged topography along the Egyptian Red Sea Coast using bathymetry

and ~100 m bsl, which are mostly a result of the last glacial maximum (LGM) low sea-level (~100–120 m bsl). It was assumed in this study that the terraces are in agreement with the generalized curve of sea level rise, which has been proposed by Gornitz (2007), since the last ice age. Based on the analysis of bathymetric data, notable submarine terraces were found in different locations and levels along the coast as shown in Table 1 (Fig. 12). They constitute mostly flat narrow surfaces and differ locally in depth and width. In comparison with the generalized curve of sea level rise since the LGM (~23–18 ka bp), it can be inferred that the terrace 100–120 m bsl may be in correspondence to the last glacial maximum (LGM) in the age range of melt-water pulse (MWP) 1A0 and 1A (~19–16 ka bp). The sea level rose rapidly about 10–15 m in less than 500 years during the MWP-1A0 and followed by another increase about 16–24 m during the MWP-1A. Terrace 50–75 m bsl is probably in accordance with the melt-water pulse 1B (11.5–11 ka bp) when the sea-level may have jumped by 28 m. Terrace 20–25 m bsl is mostly formed during the fourth melt-water pulse (MWP) 1C (8.2–7.6 ka bp) that is in accordance with the Flandrian Transgression. It is believed that the shallow submarine canyons were probably formed during the LGM and the present-day embayments were submerged during the Flandrian Transgression.

The submarine terraces in the study area are in accordance with the submarine terraces recorded in southern Sinai at 120, 60, and 20 m bsl (Gvirtzman, 1994). Terraces 100–120 and 50–75 m bsl are in agreement with terraces 90 and 60 m bsl in Sharm El Sheikh and Ras Burka (Fricke, 1983; Reiss and Hottinger, 1984) and terraces of Elat (90–50 m bsl) (Reaches et al., 1987). Terraces of Elat have likely developed between 70–50 ka bp, when the sea-level was 100 to 60 m below the present sea-level (Reaches et al., 1987).

Evidences obtained from the neighboring landmass clarified that the wadis cut through the present-day alluvial fans exhibiting several pairs of alluvial terraces that are in correspondence with the global Pleistocene eustatic sea-level changes (Table 2). It is worth mentioning that the peripheral parts of

<table>
<thead>
<tr>
<th>Location</th>
<th>Coordinates</th>
<th>Terraces (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharm El Arab</td>
<td>26°58′26″N–33°55′20″E</td>
<td>20</td>
</tr>
<tr>
<td>W. Naqarah</td>
<td>26°41′1″N–34°00′9″E</td>
<td>20–25</td>
</tr>
<tr>
<td>W. Safaga</td>
<td>26°38′27″N–33°59′40″E</td>
<td>20, 50, 100</td>
</tr>
<tr>
<td>W. Queih</td>
<td>26°21′15″N–34°09′57″E</td>
<td>50–75, 100–120</td>
</tr>
<tr>
<td>W. Abu Hamra</td>
<td>26°17′7″N–34°12′14″E</td>
<td>20</td>
</tr>
<tr>
<td>Um Gheig</td>
<td>25°43′57″N–34°33′26″E</td>
<td>20–25</td>
</tr>
</tbody>
</table>

Table 1 Locations of some submarine terraces below sea-level.

<table>
<thead>
<tr>
<th>Location</th>
<th>Coordinates</th>
<th>Heights (meters above the wadi floor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W. Queih</td>
<td>26°36′18″N–33°56′43″E</td>
<td>2.5–3, 6–7</td>
</tr>
<tr>
<td>W. Um Gheig</td>
<td>26°16′19″N–34°10′1″E</td>
<td>6–8, 15</td>
</tr>
<tr>
<td>W. Abu Dahab</td>
<td>26°14′42″N–34°10′38″E</td>
<td>5–6, 13–15</td>
</tr>
<tr>
<td>Hamraween</td>
<td>26°21′5″N–34°06′44″E</td>
<td>10–12, 15–16</td>
</tr>
<tr>
<td>Queih</td>
<td>26°09′12″N–34°14′36″E</td>
<td>5–6</td>
</tr>
<tr>
<td>El Quseir El Qadim</td>
<td>26°08′29″N–34°08′26″E</td>
<td>1–1.5</td>
</tr>
<tr>
<td>An-Nakahel</td>
<td>26°06′24″N–34°14′25″E</td>
<td>1–1.5, 4.5–5, 10–12; 12–21; 30–40; 60</td>
</tr>
<tr>
<td>El Ambagi</td>
<td>25°3′48″N–34°50′″E</td>
<td>1–2, 6–7, 12–14</td>
</tr>
<tr>
<td>Um Khariga</td>
<td>25°5′5″N–34°31′38″E</td>
<td>2–3; 4; 6, 10</td>
</tr>
<tr>
<td>Mubaraka</td>
<td>25°30′32″N–34°38′48″E</td>
<td>1–2, 8–14; 20–30</td>
</tr>
<tr>
<td>Um Gheig</td>
<td>25°43′16″N–34°32′24″E</td>
<td>1–2, 5–8; 13; 20–30</td>
</tr>
</tbody>
</table>

Table 2 Altitudes of the fluvial terraces along the Egyptian Red Sea Coast.

Source: Arvidson et al., 1994 and field work.
the NW Red Sea rift were inactive during the last 150–120 ka bp (Hoang and Taviani, 1991; Arvidson et al., 1994; El Moursi et al., 1994; Plaziat et al., 1995; Orszag-Sperber et al., 2001) and the coast attained its present-day shape mostly after the Flandrian transgression during the last 8–6 ka bp (Goudie, 2004).

5. Discussion and conclusions

A long time ago the Red Sea was only known by small-scale bathymetric, magnetic anomaly maps and a few seismic reflection or refraction profiles. Therefore, detection of the major submerged coastal features was unattainable. In this study submerged features along the Egyptian Red Sea Coast from latitude 27°43′N to the Egyptian-Sudanese border at latitude 22°00′N were identified based primarily on the global bathymetry data set from Smith and Sandwell (1997), bathymetry obtained from topographic maps of scale 1:200,000 and the US army topographic maps of scale 1:250,000. The Surface created from the topographic maps has many gaps owing to lack of detailed bathymetric lines. Therefore, the global bathymetry data were integrated to overcome the problem of lack of information. Spatial resolution of the global bathymetry data is about 2 min along latitudes and longitudes. Linear regression analysis reveals that the spatial accuracy ranges in the study area from 3.3 km at latitude 22° N to 3.1 km at latitude 28° N. That means the data are only adequate for recognizing features that have an extent of ≥ 3.1 km. Although Kriging interpolation procedure was used to create a smooth surface of cell size 100 m, the procedure does not increase accuracy of the foot print of the original data. However, valuable information has been obtained that manifest the main characteristics of the major submarine forms. Extracting smaller-scale features (e.g. estuaries, coral reefs, and submerged shallow water-courses) may need another data source (e.g. detailed multi-beam or echo-sounding survey) or enhanced digital image processing techniques that can be applied to high-resolution satellite images (e.g. ASTER, Quickbird, Orbview-2). The latter field is open for more innovative approaches to estimate bathymetry from optical remote sensing data on the basis of numerical models and algorithms. The Egyptian Red Sea Coast in specific deserves further researches to manifest the characteristics of the micro-submerged coastal landforms.

The major objective of this study is to clarify the general characteristics of the major submerged features. In that context, it is obvious that the continental shelf is noticeably influenced by the surface fault system extending eastward into the main Red Sea depression, showing the continental edge mostly like a fault-scarp of ~60° anticlockwise fault plane of steep slope. Sea ridges and subbasins were distinguished at the lower toe of the continental slope, which seem to be a result of the regional tectonic system. It is believed that the main fault and fold system belongs to the initial arching and rifting of the Red Sea (Tewfik and Ayyad, 1982; Said, 1990). Two sea peaks specifically were identified as extinct volcanoes owing to their abrupt rising from the sea floor and ideal conical shape with very steep sides. They are possibly attributed to the westward migration of the Red Sea asthenosphere during middle Miocene.

The study deduced as well that the submarine canyons are the most widespread features that break the continental edge. Two types of submarine canyons were recognized as deep incised canyons and shallow canyons. The deep incised canyons carve the continental edge with remarkable steep walls that seem to have been cut in the bedrock down to depth ~500 m bsl. They might be formed as a result of the Messinian event (~5.59 Ma) owing to the sudden disconnection between the Atlantic Ocean and the Mediterranean during late Miocene times. Additionally, it is estimated that the shallow canyons are mostly developed during the Pleistocene lower sea level (some 90–130 m bsl) where the major wadis cut their water courses through the continental shelf. Some individual submerged deltas were identified based on the configuration of the bathymetric lines and their location at the topographic breaks. A close relationship has been found between the present-day drainage system and the deltas. It is inferred that the present-day drainage system is mostly a successor to an ancestor drainage system that was mostly developed during middle Miocene as the climate was turned toward warm humid (Khe- dr, 1984) or pre-middle Miocene as the climate was shifted toward a Sudano-Guinean type of savannah since the Oligocene (Le Houérou, 1997).

During Pleistocene and Holocene times the Red Sea experienced dramatic eustatic changes resulting in a sequence of raised coral terraces and alluvial terraces. Three main submarine terraces were identified at depths 20–25, 50–75, and 100–120 m bsl. Generally, they are in agreement with the generalized curve of sea level rise since the LGM (~23–18 ka bp). Hence, it is deduced that terrace 100–120 m bsl is equivalent to LGM, terrace 50–75 m bsl ranges in age between 11.5 and 11 ka bp and terrace 20–25 m bsl is mostly formed during the Flandrian Transgression (8.2–7.6 ka bp). The Red Sea attained its present-day level mostly during the last 5–4 ka bp and the formation of the present-day estuaries may also be in accordance with this period. It is expected that results of this study will be helpful for shedding light on the geomorphologic evolution of the continental shelf and its surrounding landmass.

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References


