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Morphostructure of the Egyptian continental margin: Insights from swath bathymetry surveys

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Abstract

In the Eastern Mediterranean, offshore Egypt, the Nile continental margin is characterized by a large deep water turbiditic system known as the Nile Deep Sea Fan. This post-Miocene terrigenous construction covers an approximately 10 km-thick sedimentary pile, including 1–3 km of Messinian salt layers. Systematically collected swath bathymetric data proved to be the most powerful tool to discover, describe and study many sea floor features of this sedimentary construction which reflects competition between active tectonic, sedimentary, and geochemical processes. Gravity tectonics, triggered by underlying mobile salt layers, construction of channel-levee systems, the passage of turbidite flows, sedimentary slope failures at various scales, massive mud expulsions and fluid seepages are all interfering to shape the Nile Deep Sea Fan seabed.

Introduction

The modern Nile Deep Sea Fan (Figure 1) is a fairly thick and quite recent sedimentary wedge which results from successive offshore growth of abundant terrigenous sediments delivered, chiefly since the uppermost late Miocene, by the Nile River (Salem, 1976; Ross and Uchupi, 1977; Dolson et al., 2000). The recent terrigenous cone drapes a segment of a much older passive margin whose total sedimentary thickness (including the post-Miocene terrigenous cone) is believed to reach in excess of 9–10 km (Aal et al., 2000; Mascle et al., 2003). Until the late 1990 the Nile Cone was almost unknown. In the past ten years the offshore and parts of the deep offshore Nile have been intensively investigated by oil/gas companies and the Nile margin is now a significant hydrocarbon production area (Dolson et al., 2000, 2005). In 2000 for example, 3.8 billion barrels oil equivalent, primarly gas and condensate, had already been discovered (Aal et al., 2000).

To better depict the overall structure and better understand the evolution of this margin segment, which is the major Neogene terrigenous accumulation in the Mediterranean Sea, Geoscience-Azur laboratory has successively since 1998 carried out five geophysical/geological surveys on the Nile Deep Sea Fan. These cruises include a recent expedition (Nautinil in Fall 2003) made in cooperation with several French, Dutch and German partners (Mediflux Euromargins ESF-supported project). Among these surveys the "Prismed II" and "Fanil" cruises, (Figure 2), respectively aboard the IFREMER research vessels "l'Atalante" and "Le Suroît" (in early 1998 and late 2000), provided continuous multibeam bathymetric and backscatter images of the Nile Deep Sea Fan, using Simrad EM12-Dual and EM300-Dual multibeam sounding systems. These swath data have considerably increased our knowledge of the different seafloor processes operating on this deep sea construction and have also served as backgrounds for scientific dives targets during the Nautinil

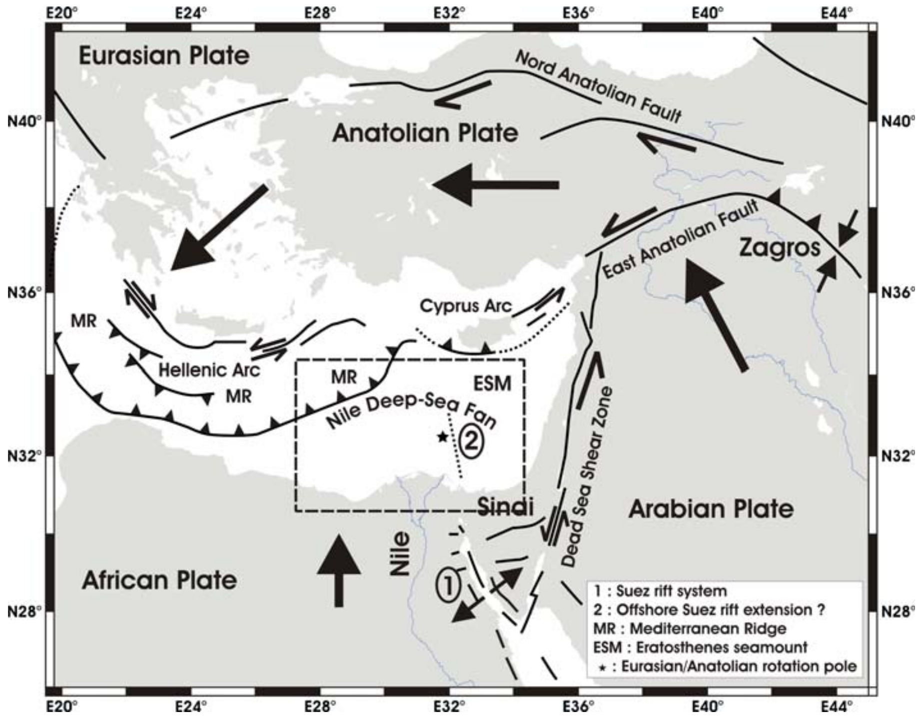

Figure 1. Geodynamic setting of the Eastern Mediterranean basin. The study area is indicated by the dotted box. Grey arrows indicate relative plate motions.

expedition. The Simrad EM12-Dual system operated on the RV L'Atalante recorded swaths of bathymetric and backscatter data about six times the water depth along tracks, while the Simrad EM300-Dual system, operated aboard the RV Le Suroit, allowed the recording of similar data but with a track-spacing about twice the water depth. Although the data recorded by the two systems have different resolutions (100–150 m precision for EM-12 data and around 30 m precision for EM-300 data), they have been merged and processed as a unique grid, with a pixel size of 50 m for bathymetric data and 25 m for simultaneous backscatter imagery records, using IFREMER Caraïbes software. A total of about 5000 km of continuous geophysical data (seismic reflection, gravity and magnetic data) also have been obtained over most of the Nile Deep Sea Fan during both surveys (see track-lines on Figure 2). In some areas of the Egyptian continental shelf this data set has been supplemented by coherency maps derived from 3D seismic surface data provided by BP-Egypt.

Integration of bathymetric, backscatter and seismic data sets has allowed us: (a) to better evaluate the deep sea fan's overall morphostructure and its recent tectonic evolution (Bellaiche et al., 1999, 2001; Mascle et al., 2000; Gaullier et al., 2000; Loncke, 2002), primarily controlled by the presence of underlying thick Messinian evaporites, which trigger regional gravity spreading and gliding processes; (b) to emphasize the importance and interconnections of various sedimentary processes, acting at different scales, and particularly the major effect of channel-levee systems, slumping, mass movements and debris flows on recent Nile Deep Sea Fan evolution (Loncke, 2002; Loncke et al., 2002); and (c), to identify important mud volcanism and cold seeps which occur on many areas of the seafloor of the Nile margin at various depths (Loncke and Mascle, 2004).

The chief aim of this paper is to present and comment on the swath bathymetry data and to document, using the derived images, the different sedimentary, geochemical, and tectonic seafloor processes which can be observed and addressed on the present sea bed of the Nile Deep Sea Fan.

Geological and geophysical framework of the Nile Deep Sea Fan

In the Eastern Mediterranean, the geodynamic of the Levantine Basin and surrounding areas results from

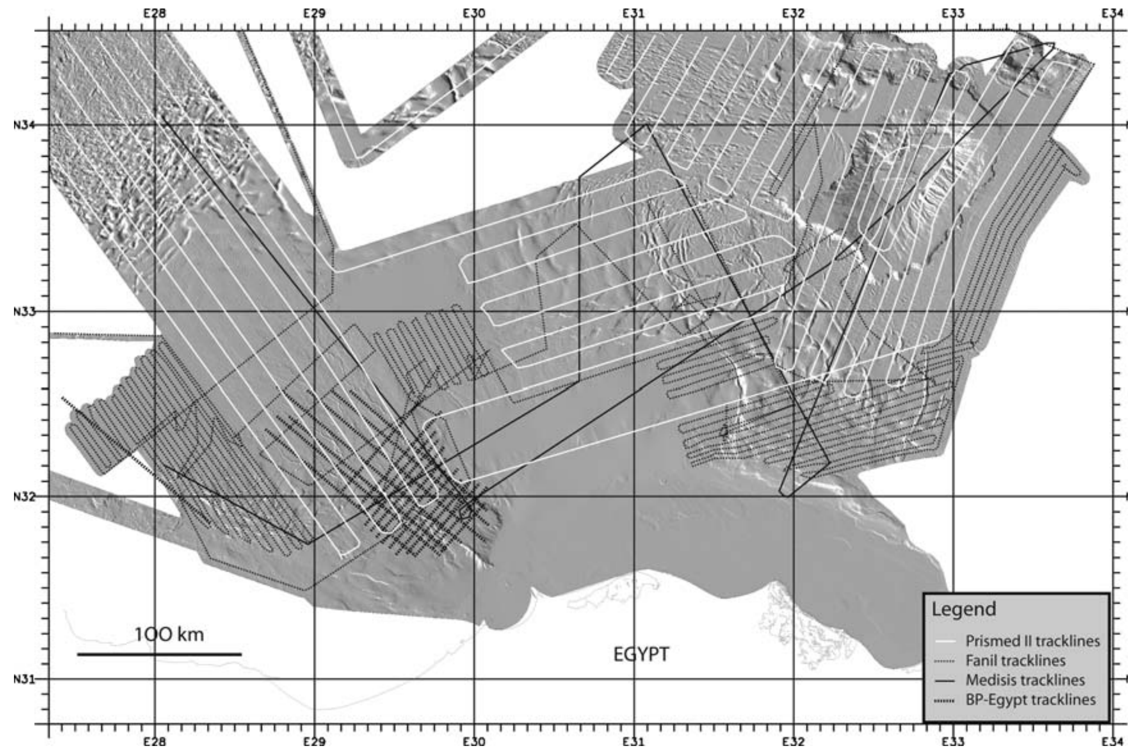

Figure 2. Tracklines of the different geophysical data available on the NDSF area. Prismed II survey (in 1998) tracklines are indicated in white, Fanil survey (in 2000) tracklines in dotted black lines. The platform area has been mainly imaged from BP-Egypt 3D seismic data first arrivals.

the interactions between the kinematics of various plates and micro-plates (Figure 1; McKenzie, 1972; Westaway, 1994; Le Pichon et al., 1995; McClusky et al., 2000; Kreemer and Chamot-Rooke, 2004). This has leaded to a complex geological pattern as the result of the combined effects of: (a) active subduction/collision (and associated southward growth of the Mediterranean Ridge) of Africa beneath Aegea-Anatolia along the eastern Hellenic and Cyprus arcs (Chaumillon, 1995; Huguen, 2001) (b) active deformation along two major transcurrent fault zones, the Dead Sea/Levant and East Anatolian Fault Zones (Neev, 1975; Girdler, 1990) resulting from the motion of the Arabian plate relative to Africa; and (c), to a less extent, the structures inherited from the very slow, almost aborted, Suez Rift (Courtillot et al., 1987). In addition to these active deformational domains lies the Egyptian passive continental margin to the south that is inferred to have initiated by rifting between Jurassic to Early Cretaceous times (Morelli, 1978; Guiraud and Bosworth, 1999; Dolson et al., 2000); this margin may have been partly re-activated during the middle to upper Miocene Gulf of Suez/Red Sea rifting (Mascle et al., 2000). The Nile deep turbiditic system, which drapes most of the Egyptian continental margin, consists of thick (up to 3 km), rapidly sedimented and unstable Pliocene to Quaternary sedimentary blanket emplaced on layers of evaporites or lateral equivalents (Loncke, 2002), whose thickness varies between 1 and 3 km (Camera et al., 2004). These evaporites were deposited during the Messinian dessication event (latest Miocene, 6.5–5.3 Ma) (Ryan and Hsü, 1973). Sedimentary loading on these ductile layers has triggered salt-related tectonic deformations (Gaullier et al., 2000; Loncke, 2002), similar to those commonly observed on other salt-bearing passive margins (see Vendeville and Jackson, 1992a, b). Gravity spreading of the salt and its overlying sedimentary pile has induced thin-skinned extension along the upper slope and distal contraction at the base of the continental slope. As a consequence of the salt-driven gravity tectonic activity, most of the Nile Deep Sea Fan Plio-Quaternary sedimentary cover is now destabilized and strongly tectonized. Moreover, overburden thicknesses are the cause of local overpressures on deeply buried sediments, explaining the observation of numerous fluid-related features (gas and under-compacted muds) (Loncke and Mascle, 2004).

Results

Today the sub-aerial Nile Delta shows two main fluvial/sedimentary paths: the Rosetta, or western branch, and the Damietta, or eastern branch (Figure 3). Offshore from the Rosetta branch the fluvial deltaic system extends across a wide and flat continental platform with an average width of 80 km. This platform is characterized, particularly in its eastern corner, by gentle undulations interpreted as hydraulic dunes created by a general east-directed longshore drift. At the foot of this wide platform lies the deep-sea fan itself, covering the entire continental slope and even parts of the adjacent abyssal plain to a depth of 3500 m.

Inspection of Figure 3 indicates that the overall morphology of this sedimentary construction is controlled by the combined interactions of various processes, whose effects are strongly imprinted on the seafloor. These include progressive downslope gliding of underlying Messinian evaporites, as well as various mechanisms of sediment dispersal, including turbiditic currents, giant slumps and debris flows, and fluid seepages (Gaullier et al., 2000; Loncke et al., 2002; Loncke and Mascle, 2004). On morphological grounds the Nile Deep Sea Fan can be subdivided from west to east into four distinct provinces, each of them imprinted by different prevailing seafloor shaping processes; they include:

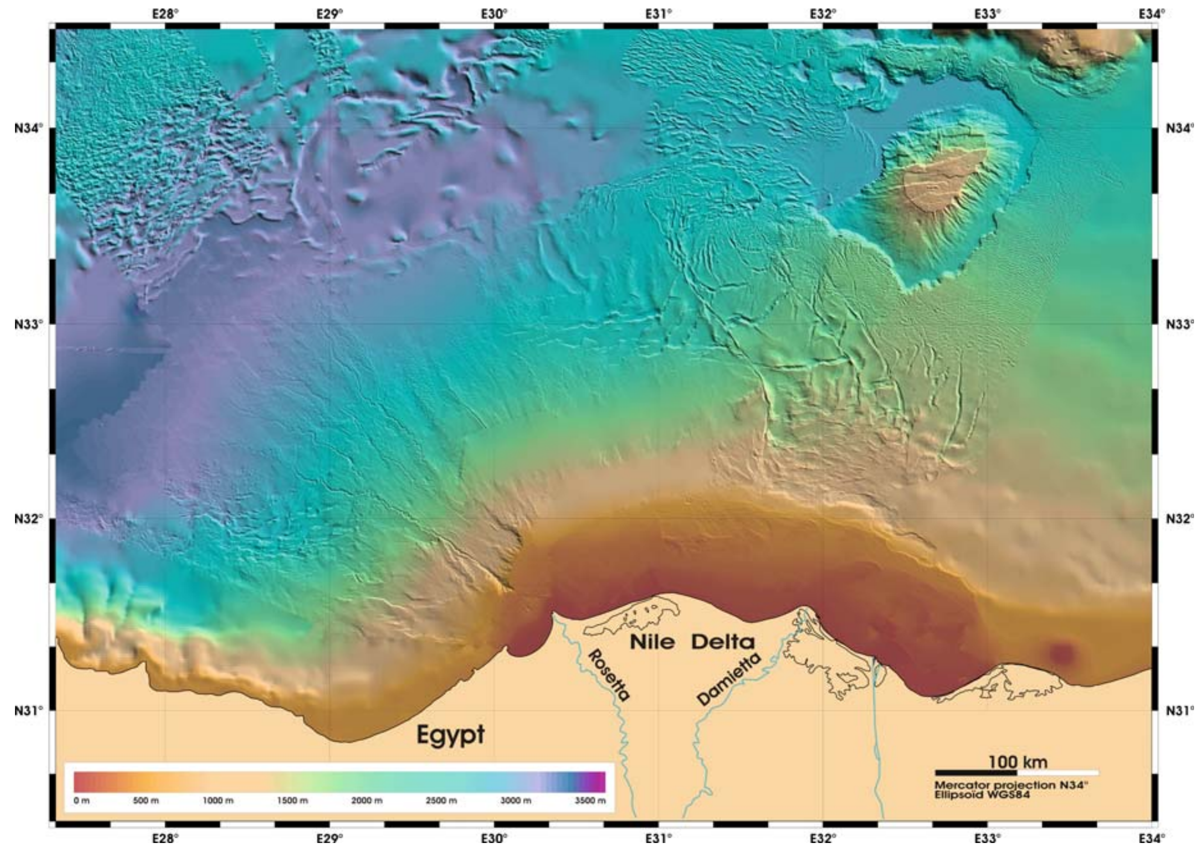

Figure 3. Color shaded bathymetry of the Nile Deep Sea Fan and Egyptian continental platform. On bathymetric grounds the Nile Deep Sea Fan continental slope can been divided into four different morphostructural domains: a western, central, eastern and Levantine provinces. To the northwest the Nile Deep Sea Fan and its bordering abyssal plain are bounded by the southern toe of Mediterranean Ridge; northeastwards the terrigenous cone is bounded by Eratosthenes Seamount.

A Western Province characterized by active turbiditic processes, salt-tectonics and fluid venting

Extending all along the slope, from the shelf off the Rosetta branch to the Heredotus Abyssal Plain to the north, the western province displays a morphology chiefly controlled by two dominant sedimentary and tectonic processes augmented by secondary seafloor shaping phenomena.

At first inspection the continental slope appears imprinted by a network of active and/or abandoned meandering and well-entrenched channel-levee systems through which turbiditic sediments have been, and still, are actively transported and delivered far offshore (nearly 300 km). The most recent of these channels is in direct connection with an important canyon head (Rosetta Canyon) cutting the upper continental slope and the shelf (up to 40–50 m); this system likely traps most of the sedimentary inputs from the western branch of the Nile River. Within the adjacent abyssal plain significant amounts of terrigenous sediments, which have bypassed most of the slope through the channels and their distributaries, have built a series of distal lobes that are particularly well imaged on backscatter records (Figure 4). As shown on the map the successive active channel systems have frequently been interrupted and have roughly migrated westwards through time (Figure 3). Giant upper slope failures and detachments, potentially controlled by sea level fluctuations (Loncke, 2002), and well imprinted on the morphology in the form of wide scars, are likely responsible for such frequent modifications.

The upper to middle continental slope of the area is also affected by a series of curved faults associated with elongated salt walls. This extensional pattern reflects the progressive downslope gliding of the Pliocene to Quaternary cover above the underlying Messinian evaporite décollement layers (Loncke, 2002). All along the middle to upper continental slope this fault belt constitutes the best marker to delineate the southern extent of Messinian evaporites (Loncke, 2002).

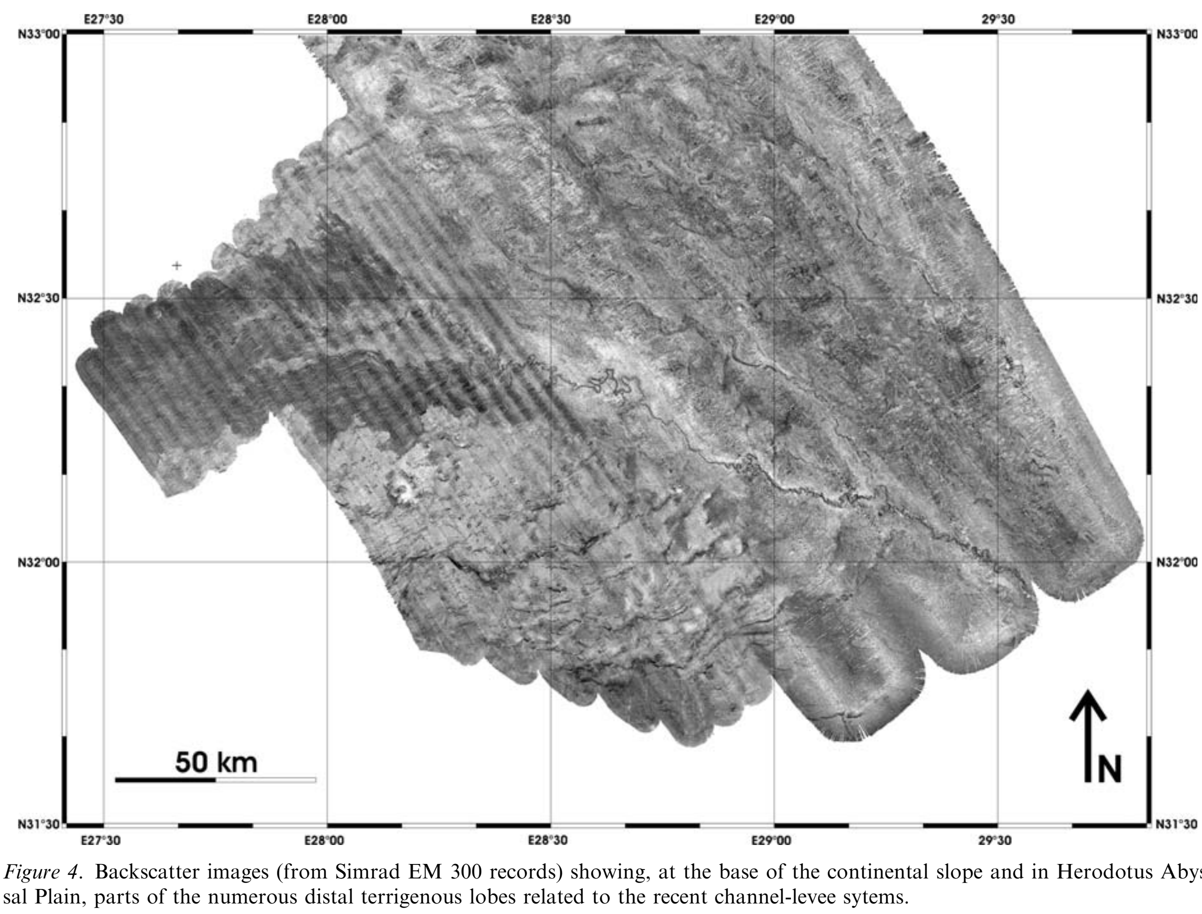

Figure 4. Backscatter images (from Simrad EM 300 records) showing, at the base of the continental slope and in Herodotus Abyssal Plain, parts of the numerous distal terrigenous lobes related to the recent channel-levee sytems.

In addition to these first order processes two others mechanisms have significantly impacted the overall morphology of this province: First, slope failures affect the shelf break upper-slope transition where numerous large scale sedimentary scars can be easely detected, particularly near the Rosetta Canyon. We suggest that giant upper slope failures, whose resulting mass flow deposits were detected on 3.5 kHz and high resolution seismic reflection profiles and which may reach several hundred meters thickness (Loncke, 2002; Loncke et al., 2002), are the cause of frequent ruptures and abandonment of channel-levee systems as well as of their progressive general westward migration (Figures 3 and 5).

Mud expulsions and associated fluid releasing features constitute another more localized but significant contribution to the diversity of the western Nile Deep Sea Fan sea floor morphology. Fluid escape features are of three main types; (i) almost circular, several kilometres in diameter, flat topped and a few tens meters high mud constructions seen chiefly on the upper slope, (ii) relatively small, but detectable cones (about few hundred meters in diameters and relief on order of 50–60 m), or (iii) large (up to 7 km in diameter), caldera-like subdued depressions (Figure 5). The first type corresponds to gas chimneys through which significant quantities of gas are released to

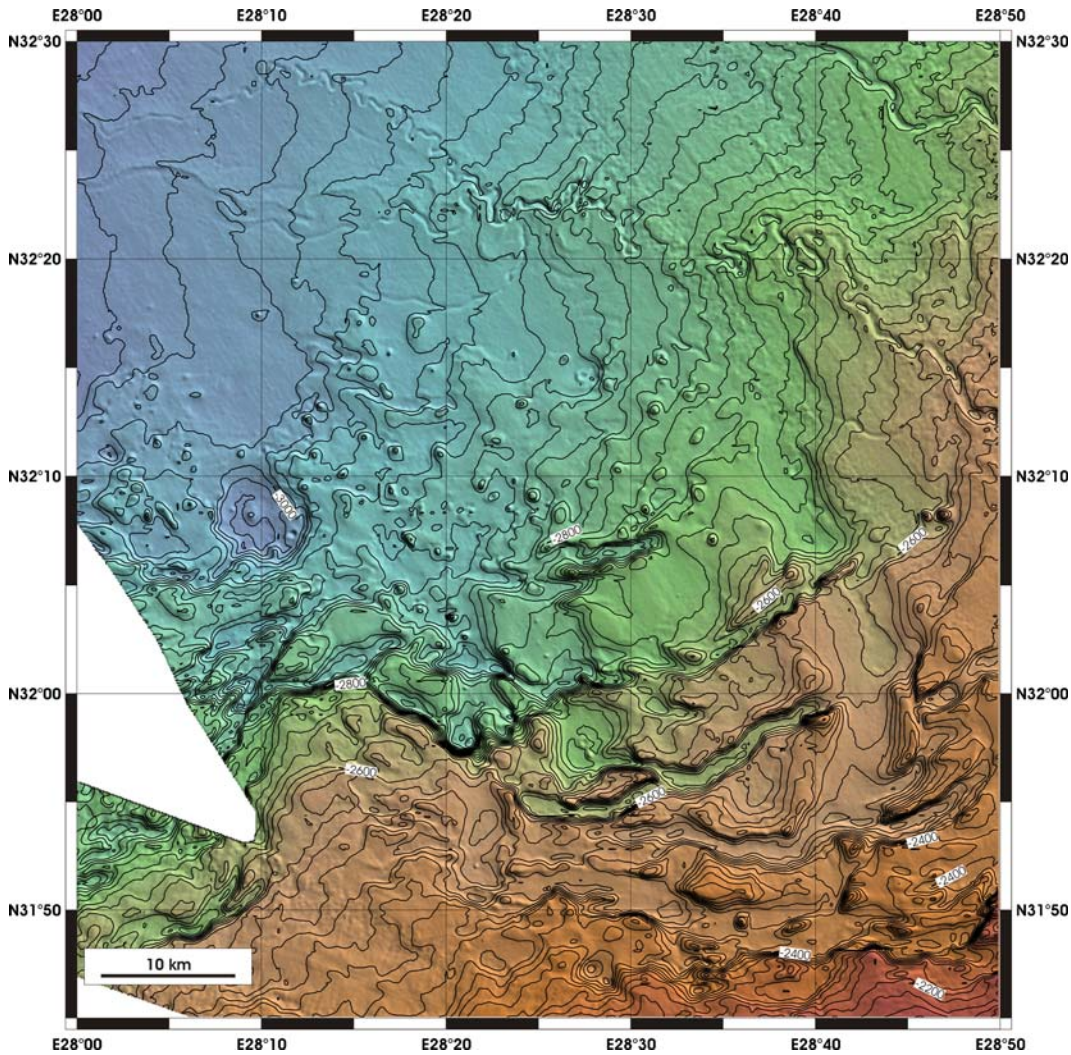

Figure 5. Contoured bathymetry in the western province, showing, at the foot of growth fault belt numerous sub circular small mud cones and a few bigger and circular caldera-like depressions.

the sea floor (see Loncke and Mascle, 2004 for discussion); types (ii) and (iii) are well imaged near the base of the continental slope at depths of 2300–3000 m, where they appear closely associated with the salt-related gravity fault network (Figure 5).

The Central Province an area of active destabilization and fluid related processes

Located between the Rosetta and Damietta Nile mouths the central province does not display a prominent canyon. Some disrupted quasi-linear channels, now likely inactive and associated with a very chaotic surface (Figure 3), shape the sea floor of the area. We interpret these features as morphological records of repeated sedimentary instabilities and slump generated massive debris flows and probable giant olistoliths (Figure 6) (Loncke et al., 2002). Repeated slope failures and subsequent debris flows deposition are believed to have been the main cause of the channel dislocations. According to Aal et al. (2000) this province of the Nile Deep Sea Fan was until late Piocene (1.7 Ma) an area of intense turbidite bypassing and therefore characterized by numerous now almost erased or buried channels that constitute apparently gas prolific reservoirs (Samuel et al., 2003). In this province, the evaporite-rooted growth faults, which correlate with the southern boundary of salt-rich Messinian sediments, are not all bathymetrically expressed, being sealed by massive debris flows. Eastwards, in areas where sedimentary destabilization seems to have been recently less active, a 150-km-long, and E–W trending belt of apparently still active growth faulting runs along the upper continental slope (Figure 3). At the base of the slope folds generated by salt tectonics are expressed by alternating gentle undulations and depressions. A few gas chimneys, identical to the ones detected in the western province and also located on the upper slope, can be observed from bathymetric data. Numerous pockmarks and mounds are seen in backscatter data as highly reflective patches (resolution of backscatter imagery being slightly better than bathymetry). As demonstrated by direct in situ observations made during the Nautinil survey (Bayon et al., 2004) these correlate more or less to a connected series of small depressions or mounds just several tens of meters in diameter and/or to fields of massive diagenetic carbonate crusts or small carbonates chimneys. A relationship between these degasing features and the hummocky morphologic pattern of this slope segment has been suspected but remains still to be investigated (Loncke, 2002; Loncke and Mascle, 2004).

The Eastern Province: a domain of intense salt-related tectonics

The Eastern Province offers a strong contrast with the two other regions and correlates with a NW-SE trending tectonic corridor that is more than 200 km long and almost 100 km wide and bounded on both sides by distinctive linear and narrow fault zones (Figures 3 and 7) (Mascle et al.,

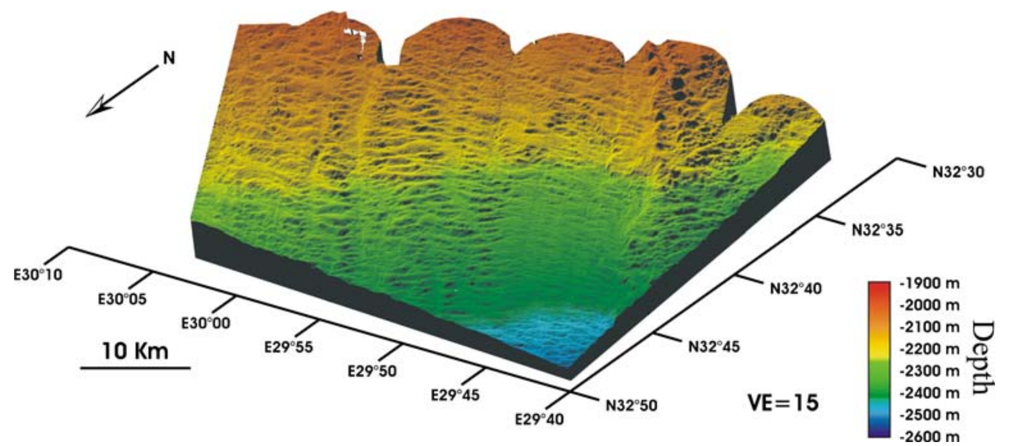

Figure 6. A 3D view of the central province showing its complex morphology due to sedimentary instabilities and mass wasting which have generated a very chaotic and ruguous seafloor. Pockmarks and mounds are prevailing fluid escapes features in this province.

2000). Within this corridor we observe upslope numerous small collapsed polygonal basins bounded by a set of linear fault scarps. Seismic data indicate that the basins are anchored within pre-Messinian sequences as a consequence of massive salt withdrawal and progressive downslope displacement of the salt/sediment system. Crestal grabens and associated salt ridges bounding non-collapsed depocenters cut across the middle slope. Downslope progressively stacked and thickened Messinian evaporites create curved salt ridges and an impressive wedge of folds and thrusts deforming the entire Pliocene and Quaternary sedimentary section (Loncke, 2002). Eastwards, this compressive system is expressed by a more than 400-m-high bathymetric salt-bearing scarp, quite similar the Sigsbee Scarp in the Gulf of Mexico (Diegel et al., 1995). This scarp faces the Eratosthenes Seamount (Figure 8). This last feature is interpreted as a continental horst resulting from Mesozoic rifting episods which created the margin (Robertson et al., 1995; Dolson et al. 2000, 2005). The seamount has been uplifted, possibly during middle Miocene margin reactivation as a consequence of the Red Sea/Gulf of Suez rifting (Mascle et al., 2000), and is probably still being uplifted now involved in progressive collision with the southern Cyprus margin (Robertson, 1998). Today the horst shows a very flat surface inherited from intense erosion when, in the Messinian regression, it was an island rising several hundred meters above the sea level. Today this continental block is progressively breaking apart as a consequence of its collision with Cyprus (Robertson et al., 1995). Several normal faults (with minor strike slip component) can be detected on its flattened top. Some of these faults, particularly along its northern slope, may have been

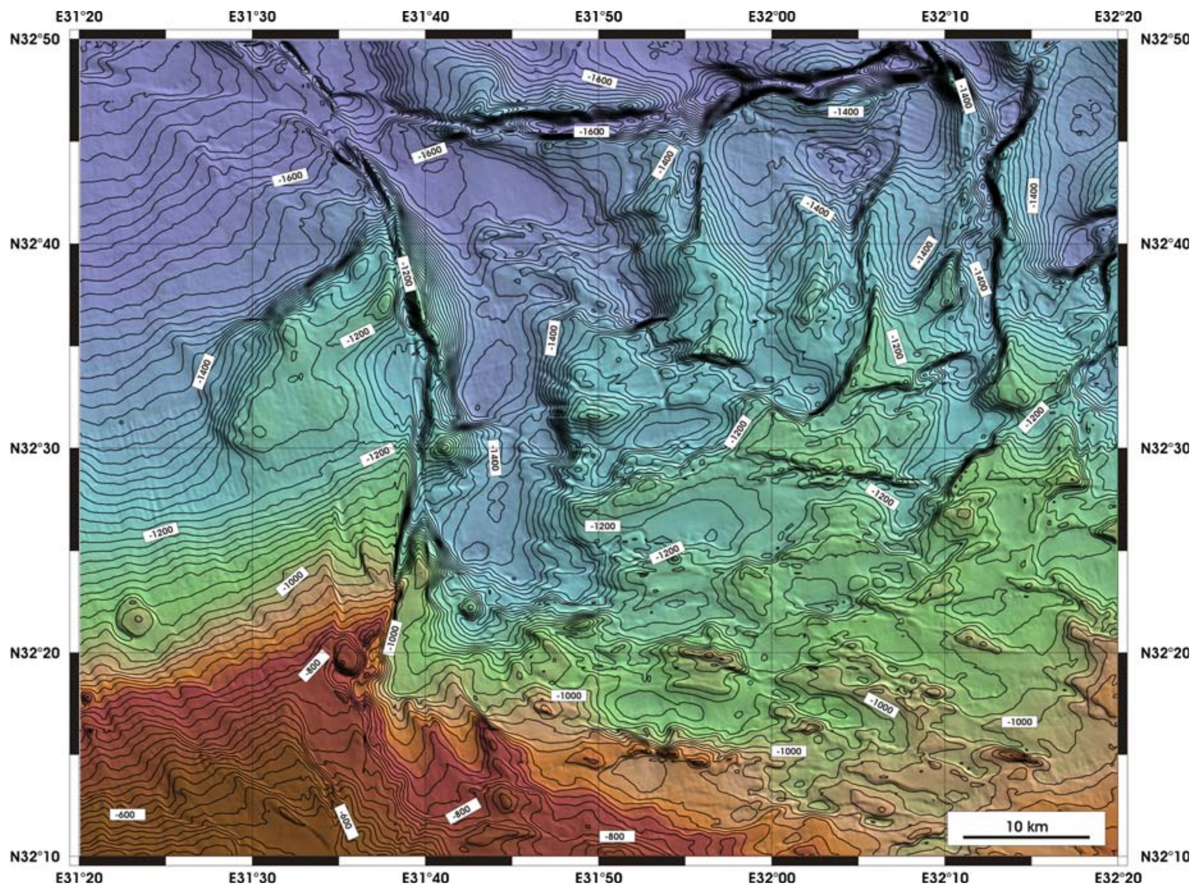

Figure 7. Contoured bathymetry of part of the eastern, tectonic, province showing the intense fracturing of the upper slope and the crestal grabens across the middle slope. Note also, on the upper slope, the presence of several circular and flat features which indicate active fluid ventings across so-called "gas chimneys".

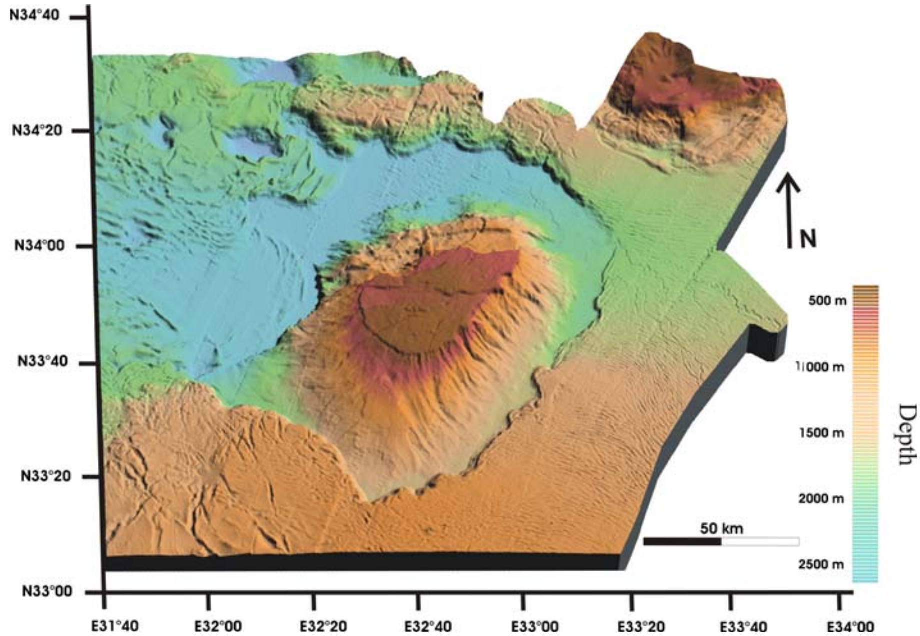

Figure 8. A 3D view of Eratosthenes Seamount; its eroded flat top is cut by a set of normal faults. To the south, the relief merges from a relict basin partly surrounded by salt scarps due to progressive salt gliding. To the east, short wave-length folding characterizes the Levantine province sea floor where a few channels originating from the Levantine and Egyptian margins are detected.

progressively re-activated as reverse faults (Robertson, 1998). In this tectonically active province and all along the Eastern Nile continental slope, disconnected meandering channels are detected (Figure 7). These deep channels are obviously not active, having been cut by intense tectonic activity, which constitutes the major mechanism controlling the shaping of the seafloor in the area. Finally, also closely linked to the fault system, several subcircular and flat mud constructions similar to the gas chimneys previously described, are found on the upper slope (Figure 7). Those features have used and still exploit the fault network as conduits for expelling overpressured muds and fluids to the seafloor. Numerous pockmarks and mounds are also detected on backscatter records in vicinity of the degassing chimneys.

The Levantine Province: a domain of salt-related folding

East and south-east of Eratosthenes Seamount, an eastermost (or Levantine) province is characterized by a gently folded seafloor (Figures 3 and 8). This undulating morphology results from progressive sediment compression on moving Messinian evaporites. As shown by seismic data (Loncke, 2002), salt-bearing sequences in the area are rather thin and only covered by a few hundred meters of Pliocene to Quaternary sediments. This province also displays a few channels, including a long meandering example originating from the Nile eastern slope. This channel and others apparently issue from the Levantine coast (Bellaiche et al., 2001) and act as conduits for turbidity flows participating to the sedimentary infilling of the small abyssal plain that still remains between Eratosthenes Seamount and the Cyprus margin.

Conclusions

All over the Nile Deep Sea Fan various deformational patterns typical of gravity spreading can be observed. Clearly salt tectonics is responsible for the creation of first order features that control the overall morphology of the turbidite cone. Important differences, however, can be observed from west to east along the margin. These differences have two origins: (a) the heritage of the Messinian dessication episode and (b) post-Messinian local variations in the relative importance of "second order" seafloor shaping processes.

During the Messinian period the area to the south of the Central Province consisted of a wide, elevated domain almost devoid of salt deposits, which has be interpreted as a Messinian shelf or a detrital cone on which the Plio-Quaternary pile is almost undeformed (Loncke, 2002). Around this Messinian surface the post-Miocene sediment cover is by contrast strongly affected by gravity spreading and/or gliding processes. The transition between these two, stable and unstable, domains is well defined by the presence of growth faults (Figure 3). The modern continental platform, emplaced above the Messinian stable domain, appears nearly undeformed. Only along its western corner is the margin destabilized, deformation potentially triggered by sea level fluctuations and gas hydrate dissociation, as suggested by the presence of numerous pockmarks and mounds (Loncke and Mascle, 2004).

Within the salt-bearing domain structural variations can be observed, for example, between the northwestern and the eastern provinces. This variation is probably due to interactions between salt tectonics and buried paleostructures acting as passive buttresses (Loncke, 2002). In both areas, associated fractures act as conduits for fluid migration and subsequent fluid and overpressured mud escapes directly on the seafloor.

In summary, the overall morphology of the Egyptian deep margin is chiefly the surface expression of active salt-driven gravity tectonic mechanisms preferentially interacting, depending of the area, with sedimentary instabilities (central province), terrigenous bypassing (western province), mud and fluid expulsions (all provinces except the Levantine). The morphology of Erathostenes Seamount, which bounds this margin towards the northeast, is the result from strong Messinian erosion and active fracturing due to its ongoing collision with Cyprus. The Messinian heritage, paleo-surface on the upperslope, salt-rich layers on the middle to lower slope, remains strongly imprinted on the modern Nile Deep Sea Fan.

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