CENOZOIC EVOLUTION OF THE PROTO-NILE DELTA
WITH SPECIAL REFERENCE TO THE
MESSINIAN SALINITY CRISIS

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To Isis and Osiris of Ancient Egypt who, in the star of Sirius and the constellation of Orion, know the way to the one source, which like the Nile, gives rebirth to all who let the river flow in peace and tranquility.
ABSTRACT

From detailed borehole and integrated seismic facies analysis the Cenozoic succession of the Nile Delta region can be subdivided into two lithostratigraphic groups. The lower group is composed of Early to Middle Eocene carbonate shelf facies which rest unconformably on truncated Mesozoic carbonates. These rocks grade into the upper group of Late Eocene to Holocene fluvio-deltaic sediments which originated from an ancestral Nile River system. The overall offlap nature of the upper terrigeneous sequence is interrupted by two well-marked hiata. The first was caused by an extrusive fissure eruption at the end of the Oligocene. The second and most pronounced was caused by the Late Miocene (Messinian) salinity crisis when the proto-Nile Delta was severely eroded as a consequence of evaporitic drawdown and dessication of the Mediterranean Sea.

Seismic-stratigraphic evidence for the development of an extensive subaerial drainage system is outlined and supported by the presence of related fluvio-deltaic sediments deposited from the entrenched proto-Nile River. These sediments were deposited at depths of 2.5–4.0 km below present sea level and are sandwiched between units containing hemipelagic fauna. By seismic-stratigraphic facies analyses, the Messinian age fluvio-deltaic sediments can be divided into fluvio-deltaic, evaporitic, and post-evaporitic brackish water facies. Although chronostratigraphic relationships are not easy to determine due to a lack of faunal control, these facies types can be readily correlated with equivalent Messinian evaporite suites of Sicily and the Israeli continental margin.
Tectonic events were largely responsible for the initiation of the proto-Nile and its subsequent progressive increase in catchment area to the present day. This was caused by isostatic uplift of the African landmass throughout the Cenozoic Era aided by pre-rift crustal doming and rifting of the Red Sea. Middle Miocene normal faulting parallel to the Red Sea rift shifted the proto-Nile from its former location in the southern Western Desert to its present course. Only during the succeeding Late Miocene to Pliocene period has sediment loading contributed to overall crustal subsidence in the Nile Delta region.

Palaeogeographic observations in the Nile Delta confirm the existence of a deep Eastern Mediterranean Basin prior to the Messinian salinity crisis. The existence of subaerial erosion surfaces and related fluvio-deltaic sediments are in support of a deep dessicated basin setting for the Messinian evaporites in the Mediterranean Basins.
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I. INTRODUCTION

1. Purpose of Research

Prior to the advent of hydrocarbon exploratory drilling in the mid-1960's, the subsurface geology of the Nile Delta was completely unknown. Although a considerable amount of research had been completed on the Nile Quaternary sediments (Ball, 1910; Shukri and Azer, 1952; Attia, 1954; Soliman and Faris, 1963), there was little or no pre-existing information on the stratigraphy and facies relationships of the ancient Nile Delta.

By 1980, however, this situation had dramatically changed. More than forty boreholes had been drilled, the deepest of which, the Bilgas-1 penetrated to a total depth of -4,564 m, terminating in sediments of Late Miocene (Tortonian) age. Thanks to the generosity and cooperation of the various exploration companies, much proprietary data has been released for the purposes of this study. This work outlines a geologic model for the Cenozoic evolution of the Nile Delta with particular attention to seismic-stratigraphic analysis of Messinian age sediments beneath the contemporary delta. The findings presented here are based upon information derived from thirty-eight petroleum exploration boreholes, integrated with over 9,250 km of seismic reflection profiling. Most of these data are derived from hydrocarbon exploration programmes conducted during the late 1960's and early 1970's by two separate consortia led by Phillips Petroleum Company and the International Egyptian Oil Company (I.E.O.C.).

Early seismic reflection profiling revealed the presence of a profound unconformity throughout the Nile Delta region. This is now known to
correspond to the evaporitic drawdown and subsequent dessication of the Mediterranean Sea during the Messinian stage at the end of the Late Miocene. This catastrophic event is popularly known as the Messinian salinity crisis, after the pioneering work by Hsu et al., (1973) during DSDP Leg 13, where the intermittent dessication of deep oceanic basins was proposed to explain the presence of salts and evaporites beneath the floor of the Mediterranean Sea. One of the major aims of this research project has been to determine the effect of the Messinian salinity crisis on the Proto-Nile Delta and to see if any correlation exists with published results from other Eastern Mediterranean basins.

Aside from the Po Valley of Northern Italy (Rizzini and Dondi, 1979) the Nile Delta is unique in that it is one of the few regions around the Mediterranean Sea periphery where a relatively undisturbed Messinian sedimentary sequence is within reach of the drill. It is also unusual in that it is a site of both Messinian subaerial erosion and deposition. In most other peri-Mediterranean basins, the Messinian succession is either absent through non-deposition and erosion, or it has been displaced, deformed and uplifted by Pliocene-Quaternary Alpine orogenic events. Notable examples are the Gessoso-solfifera evaporites in Sicily (Decima and Wesel, 1973; Schreiber et al., 1976, 1977), the Appenines (Vai and Ricci-Lucchi, 1977) and the Late Miocene basins of southeast Spain (Dronkert, 1976; Esteban, 1979). Elsewhere, autochthonous Messinian sediments are only preserved in the deep Mediterranean basins, usually well beyond present capabilities of most commercial and academic drilling programmes.
It is hoped that this work will form a useful basis for more detailed studies, especially for correlation purposes with other Eastern Mediterranean basins. In this context, it forms an integral part of the IGCP Project No. 96 'Messinian Correlation' and some of the results have already been published in the interests of the scientific community (Barber 1980, 1981, 1982; and Barber, in preparation: Appendices I, II and III).

2. Area, physiography and geomorphology

The United Arab Republic of Egypt (Figure 1) lies between latitudes 22° and 32° north and is situated in the temperate climate belt, forming part of the great Sahara Desert that sweeps across the whole of North Africa, from the Atlantic towards the shores of the Red Sea, and beyond into Arabia. Summer air temperatures average 40°C during the day time, rarely falling to beyond 0°C at night, even during winter. Maximum rainfall of 20 cm a year occurs along the Mediterranean littoral, rapidly diminishing inland to an average yearly precipitation of 1 cm per year (Said, 1962).

Most of Egypt, therefore, comprises of a barren and desolate desert, broken only by the green swathe of the Nile River Valley. Like most large rivers, it is the climatic influence of the source area, some 2,500 km distance in the East African Highlands which controls the channel regime, rather than the local climate prevailing in the flood plain (Collinson, 1978). Although the headwaters of the Nile originate in a dry sub-tropical climate that only receives an average of 8.7 cm of rain a year, there is a catchment area of over 2.7 million
Figure 1: General geographical features and area of study
sq. km, ensuring a regular and voluminous supply of water (Coleman, 1976).

The existence of abundant shells, bones and flints in the Nile alluvium dating back to the Late Paleolithic Age (150,000 B.P.) indicates that man has sought refuge in the fertile Nile Valley from time immemorial. The rise of the powerful ancient Egyptian Kingdoms in 3,100 B.C. can be attributed to the introduction of irrigation of the alluvial terraces for cultivation, heralding a change from nomadic subsistence farming to sedentary settlement along this great trade route. An ancient Arab proverb states that 'the Nile is Egypt', so that even today, the Nile flows midway through the country, dividing it in such a fashion that nowhere in Egypt is further than 800 km from the river.

Despite intensive contemporary irrigation and water management, only 3% of the total area of Egypt is cultivated, either along the banks of the Nile River itself, in the delta province, or in the Fayum Depression. These fertile areas support a concentrated population with a present density of more than 1,000 persons per square kilometre (El Shazly et al., 1975) compared with one inhabitant per seven square kilometres in the vast desert areas.

It is not surprising that the Nile Delta is dissected by numerous man-made drainage channels supporting traditional crops such as maize, wheat, barley and jute. Most of the delta is low-lying, not more than 20 m above sea level and is covered by Pleistocene-Recent alluvial sands, silts and gravels. About 20 km north of Cairo, the Nile divides into two branches, the Rosetta Branch in the west which meets
the Mediterranean Sea near Alexandria and the Damietta Branch to the east, emerging just east of the Suez Canal at the Bay of Tineh. At one time, there were three main channels, but the third distributary, known as the Pelusiac Branch became silted up in the twelfth century B.C., causing abandonment of a major Middle Kingdom Egyptian port called Avaris (Magnusson, 1977) that once served as a major arterial route for commerce. The Nile Delta covers an area of over 22,000 sq. km and measures 175 km from its apex near Cairo to the coast, and extends for 200 km along the coast (Soliman and Faris, 1963). It is bounded to the west and southwest, and to the east and southeast by the Western and Eastern Deserts respectively. Its remarkable triangular pattern, accentuated by the contrast between the fertile delta and the peripheral arid deserts, led to the descriptive 'delta' acronym by the Greek historian Herodotus in 450 B.C.

Drastic changes in the Nile Delta hydrological regime, and maybe even the Mediterranean Sea water budget have been caused by the gradual damming of the Nile River, culminating with the completion of the Aswan High Dam in 1964. The flow of Nile water and sediment load into the Mediterranean has been almost reduced to nothing. In the past, the Nile River carried as much as 140 million tons of sediment per year. Prior to 1902 when the first barrage was constructed at Aswan, discharge was as high as 100 billion cubic metres per year, but since 1964, it is now about 35 billion cubic metres per year (Ross & Uchupi, 1979). Today, very little fresh water reaches the Mediterranean which has a considerable detrimental effect on offshore fisheries, coastal erosion and Egyptian agriculture. Prior to completion of the Aswan High Dam, Nile waters could be detected up to 80 km directly off the
coast and along the Israeli and Lebanese coasts (Venkatarathnan et al., 1972).

The arcuate shape of the contemporary Nile Delta front is a classic example of a moderately high-destructive delta of the wave dominated variety, produced by a predominance of wave action over fluvial energy and discharge. This process is exacerbated today by the negligible sediment load carried by the Nile River, a situation which is clearly demonstrated by the fact that the location of Ptolemy's Lighthouse, one of the ancient seven wonders of the world, is now several kilometres offshore. The city of Alexandria is strategically located on a series of lithified Pleistocene oolitic carbonate dunes (Hassouba, 1980). Due to regressive erosion, the western extension of these dunes now exists as isolated islands, several hundred metres offshore. Large-scale redistribution of delta front sands during the Holocene-Quaternary epoch developed an arcuate string of substantial beach-barrier bars along the entire Nile Delta coastline. Several large lagoons are trapped behind these barrier bars. Some, such as Lake Burullus still maintain narrow outlets to the Mediterranean; while others, notably Lakes Manzala, Idku and Maryut, are brackish water domains, being completely sealed from any marine influences (El Shazly et al., 1975).

The physiography of the offshore delta has been surveyed and documented by several academic groups (Allan and Morelli, 1971; Finetti and Morelli, 1973; Morelli, 1975; Ross and Uchupi, 1977, 1979; Summerhayes et al., 1977, 1978). The continental shelf is at its widest (48-64 km) between the Rosetta Branch of the Nile and the Bardawil Lagoon. West of Alexandria, it narrows to less than 20 km.
The continental slope is deeply entrenched by gullies causing a very irregular topography. A major feature is the Alexandria Canyon which extends from the edge of the shelf to the upper rise. The Nile Cone, on the continental rise, is over 230 km wide and extends as far north as the Mediterranean Ridge.

3. Regional Geologic Setting

(i) Plate tectonic setting

The evolution of the Nile Delta is intimately related to the capacity of the Eastern Mediterranean basin as a receiving basin. The development of the Eastern Mediterranean basin is an integral function of the converging Mesozoic plate motions of the Afro-Arabian and Eurasian landmasses (Figure 2). Numerous authors have used plate tectonic concepts to describe the evolution of the Mediterranean Sea basins (notably Smith, 1971; Dewey et al., 1973) while others have described variations on a theme of oceanization (Van Bemmelen, 1969; Laubscher, 1975). Recently, several papers have been published which advocate a combination of both processes (Bosellini and Hsu, 1973; Laubscher & Bernoulli, 1979; Biju-Duval et al., 1978). Hsu and Bernoulli (1978) have gone so far as to state that both processes are deeply interrelated and that the implied differences could be merely a question of semantics.

Despite the diverse views on the crustal genesis of the Mediterranean Sea, there is a consensus of opinion that the deep Mediterranean basins were mostly in existence prior to the Messinian salinity crisis (Bernoulli & Jenkyns, 1974; Ryan, 1976; Hsu, 1979). In particular, the recovery of deep-water hemipelagic marls directly above and below
Figure 2: Mediterranean Sea: geological synopsis and tectonic setting
the Messinian evaporites during DSDP Leg 42A confirms the view that the Mediterranean Basins were pre-Late Miocene creations. The Eastern Mediterranean differs greatly from its western counterpart which are Oligocene-Miocene episutural and intra-continental marginal basins formed during the climactic Alpine orogenic episode (Biju-Duval et al., 1978; Hsu & Bernoulli, 1978). In contrast, the Eastern Mediterranean Basin is a remnant of a much larger and older Mesozoic basin, now mostly consumed along the Hellinides-Dinarides-Taurides active margin.

Geophysical interpretations on the basis of gravimetric reflection and refraction data show that the deep abyssal plains of the Eastern Mediterranean are located on top of a thick sedimentary cover which is over 10 km thick, probably including not only the Cenozoic but also a thick Mesozoic series (Mulder, 1973; Finetti and Morelli, 1973; Morelli, 1975; Biju-Duval et al., 1974, 1978, 1979). Despite earlier claims for a rather thin continental crust or even oceanic crust between 19-25 km thick (Payo, 1967; Papazachos, 1969; Woodside, 1978), recent work (Cloetingh et al., 1980) suggests that the Eastern Mediterranean crust is between 35-40 km. In addition, the absence of magnetic anomalies suggests that the Eastern Mediterranean Basin south of the Mediterranean Ridge is a subsided northern extension of the African continental plate. Evidence points to the existence of a deep Eastern Mediterranean Basin by at least Cretaceous time. Indeed, correlation work (Hsu et al., 1978b; Mulder et al., 1975) with the Troodos Ophiolite suite on Cyprus (Moores & Vine, 1971) suggests that the northern extremity of the Eastern Mediterranean Basin is perhaps covered by thick pelagic and hemipelagic sequences above a deformed oceanic crust of Late Mesozoic age. The very old age of the basin is
manifested geothermally by extremely low heat flow values (Erickson, and Von Herzen, 1978). Field and subsurface borehole studies in Libya and Northern Egypt show that the Cretaceous sequences thicken northward with an increasing marine influence indicating an early origin for a deep Eastern Mediterranean Basin. Outcrop work along the Levant littoral indicates that the present Israel coastline was already a margin by Late Cretaceous times and in fact may have originated in the Triassic (Ginzburg et al., 1975; Neev, 1976).

The entire North East African coastline from Tunisia to the Levantine coast is marked by Cenozoic vertical tectonics and interrelated prograding sedimentary systems implying progressive subsidence of the Eastern Mediterranean. The most pronounced accretionary sedimentary package in the area is the Nile Delta. Deposition of the delta began in the El Badr Depression (southern Western Desert) during Late Eocene time, migrating to its present position in the Middle Miocene (Barber, 1976; Salem, 1976).

The Cenozoic history of the Eastern Mediterranean is largely governed by active plate subduction along the Hellinides-Taurides Trench (Biju-Duval et al., 1978), so that today, subsided African crust lying beneath the Eastern Mediterranean Sea is virtually in contact with the Hellenic Trench. Most of the basins in the Mediterranean, however, had assumed their present physiography and size when the Messinian salinity crisis started. This is well documented by numerous sub-aerial erosion surfaces which extend to several kilometres depth around the entire Mediterranean periphery (Ryan & Cita, 1978).
There have been some distinct changes in palaeogeography during the ensuing Pliocene-Quaternary era. With continuing northward African plate movement, marginal areas of several deep basins were severely deformed and the evaporite basins of Sicily, Calabria, Apennines, Tellian Atlas, Ionian Islands, Crete and Cyprus were uplifted and elevated above sea level. Of all the peri-Mediterranean margins, only the non-Alpine coasts of Catalonia in Spain, the Po Valley, the Levant margin, and the Cyrenaican Shelf of Libya and Egypt escaped deformation. Finally, there was widespread isostatic subsidence in response to drowning of the previously dessicated deep basins (op. cit.).

(ii) Tectonic Trends

The contemporary Nile Delta (Figure 3) lies at the intersection of two major extensional trends on the northeast margin of the African continental plate where east-west epicontinental subsidence along the Cyrenaican-Egyptian Shelf intersects the aulacogenic trends of the Gulf of Suez and the Red Sea rift (Coleman, 1974). From careful study of structural lineaments on Landsat images, El Shazly et al. (1975) and Bentz (1976) identified several linear trends, specifically related to either the Syrian Arc epeirogenic episode at the Mesozoic-Cenozoic boundary (Said 1962, Salem 1976), or to extensional tectonics caused by Oligo-Miocene rifting in the Red Sea and the Gulf of Suez (Figure 4). Similar lineaments were interpreted from Bouguer gravity data by Riad (1977).

The Syrian Arc episode is represented by normal faults trending N75E - N85E approximately parallel to the present day Egyptian Mediterranean coastline along the northern Sinai Peninsula. In addition,
Figure 3: Nile Delta and environs: index map illustrating surface geology and boreholes used in study.
Figure 4: Nile Delta: key structural elements from Landsat data
there are large folds striking N70E, of which the Abu Rhoash anticline near the Giza Pyramids is the most famous. The mechanism by which the Syrian Arc folding occurred is unclear, but is almost certainly related to dextral megacontinental shearing as Europe moved eastward relative to Africa in response to sea floor spreading of the North Atlantic during Late Cretaceous and Early Cenozoic times (Hsu & Bernoulli 1978). Moreover, active elimination by subduction of the northernmost edge of the North African plate beneath the Hellinides-Dinarides-Taurides active margin would have led to rapid sinking of the Eastern Mediterranean basin, promulgating active east-west normal faulting of the proto-Egyptian coastline.

Two new extensional trends occurred during the onset of rifting in the Gulf of Suez, one trending N35W and the other N50W. The N35W direction is largely confined to the rift itself, whilst the N50W trend is very prominent over the Eastern Desert and the northeastern sector of the Western Desert where it borders the Nile Delta. The parallelism of the Nile River to the Red Sea and the Gulf of Suez (see Figure 1) was noticed as early as 1904 by Suess and commented upon later by Lawson (1927). The absence of river terraces implying a fault-line controlled fluvial system, suggest a common genetic tectonic origin for the Gulf of Suez and the Nile River (Said, 1962).

The N50W trend appears to be related to rejuvenation of Precambrian shears in the basement. Bentz (1976) suggested that some right-lateral wrench motion may have also been reactivated on these ancient shears during the Gulf of Suez extensional regime. Indeed, the earlier N85E faults are severely cut by the later N50W lineaments.
The shape of the Nile Delta periphery is governed by the influence of these two fault systems. The southwestern flank borders onto the Wadi El Natrun depression, which is axially cut by a prominent N50W striking fault (Figure 4). This particular lineament separates the well-defined Miocene and Pliocene geologic units exposed on the southwestern side of the depression, from the Pliocene and Pleistocene sedimentary sequences on its northeastern flank (El Shazly et al., 1975). Eastward of the delta apex near Cairo, the southeastern boundary of the delta trends N85E along a marked normal fault system which separates Late Cretaceous-Oligocene sediments to the south from Quaternary deltaic alluvium to the north.

Neev (1975, 1977) advocated the existence of a major trans-continental sinistral shear zone extending in a NE-SW direction from the Niger Delta across Central Africa to the Mediterranean coast of Israel (Figures 5 & 6). He called it the Pelusium Line and suggested that it passed through the Nile Delta. A similar sinistral parallel fault zone was proposed through the Erathosthenes Seamount towards the Qattara Depression in the Western Desert of Egypt (Figure 6). Whilst strong Cenozoic wrench tectonics have indeed been documented along the trace of the suggested Pelusium Line, especially in the Benue Trough (Nagy et al., 1976) and central Chad (List and Peter, 1969), evidence in the Nile Delta is less apparent. Seismic interpretation from this study does indeed indicate the possible existence of NE-SW trending wrench faults through the subsurface of the western Nile Delta, but they are rather modern, geologically speaking, and could even be of Pleistocene age.
Figure 5: Delineation of the suggested Pelusium Line, a transcontinental shear zone extending from the S.E. Mediterranean through Africa to the equatorial fracture zones (from Neev, 1977)

Figure 6: Simple Bouguer gravity anomaly map of the Eastern Mediterranean illustrating contemporary shear zones (according to Neev, 1977)
Said (1962) presented the first major synthesis of the geological evolution of northern Egypt with extensive revisions being made in Salem's (1976) discussion of Eocene to Miocene sedimentation patterns. From subsurface biostratigraphic and lithological control, Rizzini and his co-workers (1978) were able to reconstruct three sedimentary cycles in the Nile Delta province, varying in age from Early/Middle Miocene to the Holocene, one of which included a Messinian regressive sequence.

The sedimentary succession (Figure 7) in the vicinity of the Nile Delta is characterised by a sequence of Mesozoic and Lower-Middle
Eocene shelf carbonates overlain by a northward thickening Upper Eocene to Holocene prograding fluvi-deltaic complex. The Mesozoic sequence was mildly folded, elevated and eroded during the Syrian Arc epeirogenic episode at the Mesozoic—Cenozoic boundary (Said, 1962; Salem, 1976).

Extensional subsidence of the ensuing synclinoriums allowed a very gentle major transgression to advance over the peneplained Mesozoic carbonates, with deposition of an unconformable layer of Lower Eocene shelf carbonates. By Late Eocene time, terrigenous clastics began to replace the earlier carbonates, heralding a change to clastic shelf progradation. This change is a precursor of the contemporary Nile, albeit on a much smaller scale than present. In response to the gradual megacontinental uplift of Africa throughout the Cenozoic, and associated rifting of the Gulf of Suez, the proto-Nile gradually increased its sediment load, building out a successively larger delta system through time. Middle Miocene normal faulting parallel to the Red Sea rift helped to shift the proto-Nile fluvi-delta system from its earlier location in the southern Western Desert to approximately its present location (op. cit.). E-W to ESE-WNW directed normal faulting and subsidence of the northern Egyptian margin between Alexandria and the Suez Canal from sediment loading dates from this period. Because of this loading, the Oligocene and older rocks now dip rapidly northward from their contemporary outcrops near Cairo (Enclosure 1).

Two well marked unconformities and/or hiatuses occur within the Upper Eocene to Holocene fluvi-deltaic interval. The first occurred at the close of the Oligocene when extensive, tabular, fissure basalt flows erupted in the Cairo-Suez region (Said 1962). The second and most
dramatic was caused by the Messinian salinity crisis. During Tortonian time, the proto-Nile had established a substantial delta system which was in turn severely eroded during the evaporitic drawdown and subsequent dessication of the Mediterranean Sea (Ryan and Cita, 1978; Hsu et al., 1978d; Rizzini et al., 1978). A deep gorge known as the Nile Canyon was cut by the proto-Nile River. The basal Messinian unconformity, determined by seismic analysis and borehole correlation, extends from almost sea level in the southern delta area to depths of at least 5 km in the Nile Cone (Ross and Uchupi, 1977; Ryan 1978). The onlap of the contemporaneously deposited fluvio-deltaic clastics of the Qawasim Formation occurs at between 2.5-4.0 km below present base level (Rizzini et al., 1978). The latter represents sediments deposited by the proto-Nile at the foot of the former Tortonian delta slope during the Messinian event. The Qawasim Formation is separated from the overlying transgressive Lower Pliocene Kafr el Sheikh deep-water prodelta shales by the anhydrite of the Rosetta Formation and delta front sands of the Abu Madi Formation. The entire Messinian sedimentary sequence may be in excess of 2,000 m thick (Enclosure 1).

During the final and irrevocable flooding of the dessicated Mediterranean Sea in the early Pliocene, the sea transgressed the Nile Valley 1,200 km upstream to Wadi Halfa in the Sudan (Chumakov, 1973; Said, 1973). The Early Pliocene was a period of rapid restabilization of the bathymetric and environmental conditions which had governed sedimentation during the Miocene, prior to the advent of the Messinian salinity crisis. The coastline became re-established in a position not much further north than that occupied during Tortonian time. As subsidence became increasingly dominated by fast sedimentation rates, the pelitic outer shelf and slope deposits of the Kafr el Sheikh
Formation were replaced by fluvio-deltaic sands of the El Wastani and Mit Ghamr Formations. Following a slight interruption by a Pleistocene glacio-eustatic sea level fall, these units aggraded upward into the surficial Holocene lagoonal and coastal deposits of the Bilqas Formation (El Shazly et al., 1975; Rizzini et al., 1978).

4. Overview of the Messinian salinity crisis in the Mediterranean

A brief history of the Messinian episode in the Mediterranean Sea is outlined below. It will enable a corresponding sequence of events recorded in the subsurface of the Nile Delta to be placed in a regional context.

The geodynamic concept of the Messinian salinity crisis was originally proposed following the discovery during DSDP Leg 13 cruise of thick Messinian evaporite sequences in the central abyssal plains (Ryan et al., 1973). Subsequent mapping and detailed field studies from Messinian outcrops along the Mediterranean peripheral margin, in conjunction with additional deep-sea drilling and core data from DSDP Leg 42A led to considerable reappraisal and revision of the original simplistic salinity crisis model (Hsu et al., 1978a). The picture now beginning to emerge is one of a sequence of complex local dessication and flooding events within isolated basins (i.e. Balaeric and Eastern Mediterranean Basins) each with its own distinctive evolution within the overall Messinian salinity crisis (Hsu et al., 1978d), (Table 1).

Effective isolation of the Mediterranean Sea from the world ocean system began with the continental collision of the Afro-Arabian plate with the Eurasian landmass along the Zagros Front during the
<table>
<thead>
<tr>
<th>AGE</th>
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<th>CONSEQUENCES</th>
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<td>TRANSGRESSION AND RETURN TO NORMAL MARINE CONDITIONS</td>
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<tr>
<td>LATE MESSINIAN</td>
<td>INFLUX OF FRESH WATER FROM PARA-TETHYS</td>
<td>&quot;LAGO MARE&quot; CONDITIONS IN THE EASTERN MEDITERRANEAN</td>
</tr>
<tr>
<td>MESSINIAN : UPPER EVAPORITE</td>
<td>ALTERNATING CLOSURE, AND INFLUX OF ATLANTIC WATERS</td>
<td>CYCLIC SEDIMENTATION OF UPPER EVAPORITE</td>
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<tr>
<td>INTRA MESSINIAN</td>
<td>CUT-OFF OF ATLANTIC WATER</td>
<td>INTRA-MESSINIAN U/C, EROSION AND DEPOSITION OF RECYCLED SALTS (UPPER MAIN SALT)</td>
</tr>
<tr>
<td>MESSINIAN : LOWER EVAPORITE</td>
<td>CONTINUOUS INFLUX OF ATLANTIC WATER</td>
<td>MAIN SALT DEPOSITION</td>
</tr>
<tr>
<td>BEGINNING OF MESSINIAN</td>
<td>CLOSURE OF BETIC AND RIF STRAITS</td>
<td>LOSS OF CONNECTION TO ATLANTIC, EVAPORITIC DRAWDOWN OF MEDITERRANEAN SEA LEVEL : BASAL MESSINIAN UNCONFORMITY AND CALCARE DI BASE</td>
</tr>
</tbody>
</table>

Table 1: History of the Messinian salinity crisis
Burdigalian (Early Miocene). As suggested by microfaunal correlations, repeated eustatic sea level rises allowed occasional links to form between the Mediterranean and Indo-Pacific faunal systems (Rogl et al., 1978). Final severance of these two realms took place during the Serravallian (Gvirtzman and Buchbinder, 1978). The merging of Afro-Arabia and Eurasia began a gradual change in Mediterranean climate which became increasingly arid, as is typical of regions that are within low latitude zones on the western side of continental masses (Hsu et al., 1978d). Moreover, Van Gorsel and Troelstra (1981) have postulated from planktonic foraminiferal studies in Indonesia that the Messinian climate was a warm-dry phase, probably caused by an expansion of the tropical belt, thus bringing the Mediterranean under the influence of the extremely dry belt similar to that presently over North Africa.

Following the Middle Miocene orogeny in the Alps, the Paratethyan Seas were cut off from the Mediterranean (Gheorghian and Popescu, 1975; Rogl et al., 1978) and the fresh-water influx from Central Europe eliminated, placing a considerable strain on the Mediterranean water budget. Only exchange with Atlantic waters through the Betic and Rif Straits (Benson, 1978; Cita et al., 1978; Biju-Duval, 1978; and Hsu et al., 1978d) prevented evaporitic loss. Finally, the early Messinian collision between the African and European plates in the vicinity of the Iberian Peninsula completed the total isolation of the Mediterranean from the world oceans. With evaporation loss exceeding runoff, the Mediterranean sea level began to fall, leading to eventual supersaturation and precipitation of the Messinian evaporites. Even today, there is a net loss of Mediterranean waters through evaporation. Inflow by runoff is insufficient and it is only the influx of Atlantic
waters that prevents a reoccurrence of this unique geologic event on such a magnitude.

Drastic changes occurred in faunal populations and species. Due to the hypersalinity there was massive extinction of normal marine species, with survival of only dwarfed oligotypic benthics such as brine shrimp and gastropods (Schreiber and Hsu, 1980). There was a massive diversity change in fish populations with a shift in faunas towards euryhaline taxa (Sorbini and Tirapelle-Rancan, 1979). The behaviour of Late Tortonian and Messinian reefs illustrates increasingly restrictive conditions in the Mediterranean as demonstrated in SE Spain where huge interlocking coral Porite and stromatolite banks were built up (Esteban, 1979). Esteban postulated that successive short hypersaline and mesohaline alternating conditions allowed re-introduction of corals under normal marine incursions. The corals were able to re-establish themselves very quickly in an environment with very few competitors who had been previously extinguished under hypersaline conditions. Stromalites reoccurred during times of increased salinity. With complete dessication of the Mediterranean Sea, land bridges enabled land mammals to migrate from North Africa into SW Europe (Azzaroli and Conazzone, 1979). Major effects of the Messinian salinity crisis are shown in Table 2.
1. SALINITY : NORMAL→HYPERSALINE CONDITIONS

2. GEOMORPHOLOGY : BASIN-WIDE DESSICATION
   : SUBAERIAL EROSION
   : KARSTIFICATION
   : LOWERING OF AQUIFERS
   : INCREASE IN SMECTITE CLAYS
     (INCREASING ARIDITY)

3. FAUNA : MASSIVE EXTINCTION OF NORMAL MARINE
   SPECIES
   : SURVIVAL OF DWARFED OLIGOTYPIC
     BENTHICS
   : GIANT STROMATOLITE-CORAL REEF BLOOM
   : MAMMAL MIGRATION VIA MESSINIAN LAND
     CONNECTION
   : SURVIVAL OF EURYHALINE ICHTHYOFANAUS
     (FISH)

4. SEDIMENTOLOGY : HEMIPELAGIC MARLS/NANNO-OOZE
   : SABKHA/SUBAQUEOUS EVAPORITES
   : REGRESSIVE CLASTIC SEQUENCES NEAR
     DELTAS

Table 2 : Effects of the Messinian salinity crisis
By careful integration of DSDP drilling data and seismic records with land sections, various authors (Finetti and Morelli, 1973; Ryan et al., 1973; Biju-Duval et al., 1974; Morelli, 1975; Hsu et al., 1978b; Montadert et al., 1978; Biju-Duval et al., 1979) were able to subdivide the Messinian sequences in the main Mediterranean Basin into two units: the Lower and Upper Evaporite Series (Table 1). The ubiquitous Main Salt Formation, prevalent throughout the Mediterranean Basin occurs within the Lower Evaporite Series which outcrops extensively in the Cattolica Basin of central Sicily.

The land record in this region is a classic type section (Decima and Wezel, 1973) for the Messinian stage and indicates a very sudden change from deep, open marine conditions to environments of shallow water carbonate-evaporite deposition associated with subaerial diagenesis. In this area, the basal Messinian Tripoli Formation (Figure 8)

**Figure 8** : Basal Messinian sequence in the central Sicilian Basin illustrating the original nature of the Tripoli and Calcare di Base Formations prior to calcitization and dolomitization (after McKenzie et al., 1979).
contains varved diatomites cyclically interbedded with dolomitic claystones. The claystones were shown by McKenzie et al., (1979) to have been diagenetically reduced from aragonitic-gypsiferous clays. Thus they concluded that the Tripoli marked periodic restrictions in the early Messinian Sea prior to the onset of the salinity crisis. Prolonged evaporation began with the overlying Calcare di Base Formation, a calcitized gypsiferous-carbonate sequence in which dessication features have been described (Schreiber and Friedman, 1974). The Calcare di Base Formation and the overlying Cattolica gypsum beds and massive halite correspond to the Main Salt sequences of the deeper basinal environment.

The Main Salt is over 1.5 km thick in the basinal depressions and is frequently diapiric (Montadert et al., 1978). Such a thickness could have only been precipitated by an intermittent feeding of sea water from the Atlantic over a restricted sill (Hsu et al., 1978a, 1978d) leading to a "bull's eye" pattern of saline zonation without any refluxing of brines (Figure 9).

Figure 9: Theoretical evaporitic facies distribution in a dessicating basin (from Hsu et al., 1978d).
A major cut-off of intermittent Atlantic waters caused an intra-Messinian unconformity, followed by erosion and deposition of recycled salts to produce the Upper Main Salt unit of the Lower Evaporite Series. This was overlain by the Upper Evaporite Series which are much more extensive and overlap the Main Salt onto the marginal areas. The Upper Evaporite Series are over 500-600 m thick (Montadert et al., 1978), and are composed of cyclically deposited gypsum, muds, marls and salts which represent an alternating influx and termination of marine water flow from the Atlantic (Hsu et al., 1978b). Isotopic evidence suggests that there was a considerable influx of waters from the continents into the dessicated Mediterranean basins (McKenzie and Ricchiuto, 1978; Cita et al., 1979). In addition, the presence of algae stromatolites indicates the development of coastal sabkhas around the peripheral margins (Garrison et al., 1978; Awramik, 1978).

Towards the end of Upper Evaporitic Series time, the Eastern Mediterranean Basin began to evolve separately from its western counterpart which remained a dessicated desert salt lake environment. Capture of high-standing fresh or brackish water lakes of the Paratethys region (the Pannonian-Black Sea basins), possibly by headwater erosion of rivers draining into the main dessicated Eastern Mediterranean Basin, has been suggested as the cause of desalinification of the late Messinian Seas in the Eastern Mediterranean. This led to the development of low-standing lakes of reduced salinity collectively known as the "Lago Mare" (Cita et al., 1978; Hsu et al., 1978d), (Figure 10). The euryhaline Ammonia becarrii-Cyprides fauna of the Lago Mare is comparable to Paratethyan faunas and is the principal evidence for the origin of the Lago Mare in the Eastern Mediterranean (Benson, 1978; Cita et al., 1978). Lago Mare sediments are mainly muds and marls,
Figure 10: Final stages in the dessication, flooding and oceanic episodes in the Mediterranean toward the close of the Messinian (from Cita and Ryan, 1973)
some of which were diagenetically altered to dolomite (Bernoulli and Melieres, 1978). Stagnant conditions are indicated by the presence of occasional sapropelic sediments.

The Western Mediterranean probably remained dessicated until Atlantic water began to spill over the western portal. This led to the Pliocene submergence of all the Mediterranean basins under deep and open marine waters. The basins were further deepened by Pliocene-Quaternary subsidence with normal marine circulation prevailing ever since the Pliocene deluge.
II. ACQUISITION AND COORDINATION OF SUBSURFACE DATA

1. Seismic stratigraphy

Seismic-stratigraphic modelling utilizing seismic and integrated borehole data constitutes a recognised technique within the petroleum industry for elucidation of subsurface facies and lithology in poorly explored areas. The ancient sedimentary environments deduced are indeed interpretations, but are considered reliable, based upon previous industrial experience in areas at a mature phase of hydrocarbon exploration; viz: The Fort Worth-Midland Basins of the U.S.A. (Brown, 1969; Fisher et al., 1969; Brown & Fisher, 1977), the North Sea (Woodland, 1975; Parry et al., 1981; Rochow, 1981), the Niger Delta (Weber, 1971; Ancel et al., 1974) and the Persian Gulf (Dunnington, 1958, 1967; Aubert et al., 1975).

One of the most useful concepts in seismic stratigraphy is that of "depositional systems" originally proposed by Fisher and McGowen (1967). A depositional system is defined as a three-dimensional assemblage of lithofacies, genetically linked by active (modern) or inferred (ancient) processes and environments (op. cit.). The lithofacies unit can be deduced from an interpretation of sedimentary structures, textural variations, bedforms, biological activity etc. used in association with adjacent facies. This approach requires a good understanding of various depositional processes in order that a good prediction of component facies can be made, even with limited data. Seismic reflection characteristics reflect the style of each depositional system, which as an interpretative aid can be initially classified into seismic stratigraphic units. Seismic stratigraphic units are bound by isochronous seismic reflectors representing the
boundary of each depositional system, and as such have therefore been
given a geometric (as opposed to genetic) classification by Sangree
and Widmier., (1976); Mitchum (1977); Mitchum et al., (1977); and
Vail et al., (1977). However, by combining seismic reflection
characteristics and depositional processes, a genetic facies inter-
pretation is possible. This technique was successfully used by Fisher
and Brown (1977) in their work on seismic-stratigraphic interpretation
of the Brazilian margins, and is similar to that used in understanding
ancient depositional analogues in the Nile Delta. Part of the termin-
ology used by Mitchum and his coworkers (1977) is appropriate in this
study, and the types of seismic- stratigraphic reflection terminations
within an idealised seismic sequence are therefore illustrated in
Figure 11.

Figure 11: Hypothetical seismic reflection terminations within an
idealized seismic sequence (from Mitchum et al., 1977)

As outlined by Brown and Fisher (1977), several consecutive steps are
involved in seismic-stratigraphic analysis:

(i) Recognition of regional (and sometimes minor) seismic
reflections or reflection discontinuities, subdividing the
basin into seismic-stratigraphic units;
(ii) Integration and interpretation of seismic signatures in the seismic-stratigraphic units with borehole data;

(iii) Regional and local palaeontological control for chronostratigraphic correlation;

(iv) Isochron and isopach mapping of both regional and local seismic-stratigraphic units;

(v) Synthesis of a depositional model for each seismic-stratigraphic unit.

In developing a 3-D synthesis of the Cenozoic evolution of the Nile Delta, the Messinian sequence is discussed in detail, whilst the remainder of the Cenozoic is briefly outlined for completeness in developing the regional picture.

2. Borehole data

Altogether, a total of thirty-eight boreholes were used in the study (Enc. 2). Composite logs* with palaeontological zone boundaries were available from all the wells and were backed by twenty-five sonic velocity logs for integration with seismic data. Additional correlation of borehole logs to seismic picks were facilitated by well velocity surveys from wells, backed by six velocity profiles. Dipmeter logs, wherever available, helped to define sedimentary breaks, especially from the coarse grained fluvio-deltaic Messinian clastics to the Lower Pliocene prodelta shale sequences. Despite the cutting of several cores in pre-Messinian sediments by the exploration companies, many were destroyed by commercial sampling. However, excellent cores were available in a good state of preservation.

*Note: All depths mentioned in this report are subsea (i.e. -2,427 m) unless otherwise stated.
from the Qawasim-1 borehole (Rizzini et al., 1978), which constitutes
the type section for the Messinian sequence in the Nile Delta
(Appendix IV). It is a key well for examining Messinian lithofacies
in detail with nine cores, totalling 52 m which were cut over a
1,013 m interval of Messinian section. A further two cores totalling
13.1 m were cut in the overlying Lower Pliocene section. Six metres
of core were available from the Messinian of Abu Qir-I, while brief
mention is made of previously complete (before destruction) Messinian
cores sampled from the Kafr el Sheikh-1 and Abu Madi-2 and -5 wells in
the discussion by Rizzini and his co-workers (1978) of Miocene-
Pliocene sedimentary cycles.

Faunal zonations by AGIP Oil Company of Italy on nineteen I.E.O.C.
wells from the central Nile Delta, and five detailed biostratigraphic
Phillips company well reports in the eastern delta area provide the
main faunal control. Modified zonations and range charts for the
Upper Neogene of the Nile Delta by Rizzini et al., (1978) provide
additional control (Tables 3 & 4).

3. Seismic data and interpretation (Table 5)
Extensive seismic exploration in the Nile Delta region, both onshore
and offshore, began in the mid-1960's. Most of the 9,260 km of
proprietary multichannel seismic reflection data used in this study is
derived from surveys by Phillips Petroleum Company and the Inter-
national Egyptian Oil Company (I.E.O.C.). Limited additional lines
were available from LVO International and Santa Fe Exploration Company
As shown in Table 5, quality ranges from early six-fold to the later,
<table>
<thead>
<tr>
<th>W.H. BLOW (1969)</th>
<th>MEDITERRANEAN SEA</th>
<th>NILE DELTA Rizzini et al. (1978)</th>
<th>AGE</th>
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<td>N. 22</td>
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<td>N. 21</td>
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<td>U. PLIOCENE</td>
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<td>N. 20 (N. 19)</td>
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<td>Globorotalia crassaformis</td>
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<td>L. PLIOCENE</td>
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<td>Sphaeroidinellopsis sp.</td>
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<td>N. 16</td>
<td>Globorotalia dottrei/ Globorotalia humerosa</td>
<td>Oligotypical fauna (Ostracode/Benthic fauna)</td>
<td>MESSINIAN</td>
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<td>N. 15</td>
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<td>N. 9</td>
<td>Praeorbulina glomerosa</td>
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Table 3: Biostratigraphic zonation for the Nile Delta and Mediterranean mainly based on planktonic foraminifera (from Rizzini et al., 1978)
Table 4: Range chart of the main planktonic foraminifera for the Neogene of the Nile Delta, based on the Qawasim-1 well (from Rizzini et al., 1978)
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<th>Energy Source</th>
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<td>I.E.O.C.:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>1967-68</td>
<td>Ben 2, Ben 2C</td>
<td>107.5</td>
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<tr>
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<td>L.V.O.:</td>
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<tr>
<td>Onshore</td>
<td>1975</td>
<td>90-95, 122-123, 131,141,148,153, 155,157,161,163</td>
<td>297.5</td>
<td>Vibroseis</td>
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<td>SANTA FE:</td>
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Table 5: Nile Delta study: seismic data sources
more sophisticated twenty-four fold coverage (see also Figure 12 & Enclosure 3).

Figure 12: Nile Delta: trace of seismic profiles and borehole locations

Five key high-amplitude seismic reflectors can be traced and mapped on a regional scale throughout the delta area. By correlation with borehole data, these reflectors correspond to the following colour-coded marker horizons:

(i) Base Cenozoic unconformity (blue)
(ii) Top Eocene carbonates (brown)
(iii) Top Oligocene basalt (red)
(iv) Base Messinian unconformity  
(v) Top Messinian anhydrite or equivalent

It should be understood that, although time boundaries are given for each mapped seismic-stratigraphic unit, they may not be exactly correct. The mapped unit does fall within the ages noted, but its base and/or top may well be diachronous because of transgressive and regressive episodes. Thus the maps in this study are essentially of litho-stratigraphic units, augmented wherever possible by chronostratigraphic considerations based on palaeontological restraints. The interpretations are consistent with all known regional data and quite reasonable in the light of current stratigraphic, sedimentological and tectonic knowledge of the Eastern Mediterranean periphery.

Compilation of all seismic-stratigraphic units into a diagrammatic lithostratigraphic framework (Figure 13) demonstrates progressive

![Figure 13: N-S lithostratigraphic cross-section through the Nile Delta illustrating offlap and onlap sequences](image)

progradation of the Nile Delta since its initial inception during the Upper Eocene. Only the Messinian section, occurring in an anomalously
low onlap situation disturbs the overall offlap sequence. The gradual change from localised basinal infill during deposition of the Lower Eocene Thebes Formation, to the initial offlap by the Upper Eocene Maadi Formation can be clearly delineated. Blanket progradation began with the Oligocene Qatrani Formation and has essentially continued to the present day, except for the aforementioned Messinian regressive phase.

Interval velocities (as determined from seismic stacking velocities, borehole sonic logs and velocity surveys), indicate a great diversity of acoustic characteristics, depending upon rock type and depth of burial (Table 6). It should be noted that these are average regional values for the main seismic-stratigraphic units in the delta area. In the southern delta region, the older sediments such as the Eocene carbonates outcrop at the surface and relatively low values are recorded due to insufficient compaction drape, thus raising the acoustic impedance. Towards the north, the Miocene and younger rocks thicken drastically and hence have a corresponding increase in velocity values. Generally speaking, the sediment type is reflected in its corresponding velocity characteristic.

For example, Lower Pliocene shales have average velocities in the order of 1,800-2,400 m/sec, occasionally rising to 2,700 m/sec in the extremely deep areas, whilst the underlying Messinian coarse clastics have velocities in the range of 3,000-4,000 m/sec. On the other hand, Tortonian shales, beneath the Messinian sequences, have slower velocities of 2,400-2,800 m/sec, as would be expected.
<table>
<thead>
<tr>
<th>MAJOR SEISMIC - STRATIGRAPHY UNIT</th>
<th>AVERAGE INTERVAL VELOCITY RANGE (M/SEC)</th>
<th>MARKER HORIZON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pliocene - Quaternary prodelta sediments</td>
<td>1800 - 2400</td>
<td>Orange</td>
</tr>
<tr>
<td>Messinian clastics</td>
<td>3000 - 4000</td>
<td>Green</td>
</tr>
<tr>
<td>Miocene clastics</td>
<td>2400 - 2800</td>
<td>Red</td>
</tr>
<tr>
<td>Oligocene Basalt</td>
<td>3850 - 4600</td>
<td></td>
</tr>
<tr>
<td>Upper Eocene - Oligocene clastics</td>
<td>2400 - 2800</td>
<td>Brown</td>
</tr>
<tr>
<td>Lower/Middle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eocene carbonates</td>
<td>3200 - 4680</td>
<td>Blue</td>
</tr>
<tr>
<td>Mesozoic carbonates</td>
<td>4000 - 4760</td>
<td></td>
</tr>
</tbody>
</table>

**Table 6**: Nile Delta study: major seismic-stratigraphic units and average interval velocities
4. Lithofacies analogue modelling

To enable a diagnosis of ancient sedimentary environments in the Messinian of the Nile Delta, seven depositional models have been assembled using subsurface borehole data (Enclosure 4). These models have been constructed using the similar ancient and modern analogues (especially the Mississippi) described in the classic works by Coleman and Wright (1975), Brown and Fisher (1977). Wherever possible, facies criteria such as character of bedding, bed boundaries, sorting, grain size, mineral constituents etc. are derived from cores in the Qawasim-1 and Abu Qir-1 wells. Electric logs (Induction-Electrical Survey: IES) are excellent for making facies interpretations in deltaic sequences and have been used where there is insufficient core data.

The major depositional types illustrated on Enclosure 4 are:

(i) Braided stream facies
(ii) Fluvial-upper delta plain facies
(iii) Lower delta plain facies
(iv) Distributary mouth bar facies
(v) Reworked deltaic sand facies
(vi) Interbedded carbonate-sabkha and clastic shoreline facies
(vii) Subaqueous evaporite facies.

Detailed criteria for each of these facies types are developed in Chapter 5 under the heading of "Messinian lithofacies" (p.98).
III. PRE-MESSINIAN CENOZOIC STRATIGRAPHY OF THE NILE DELTA

1. The basal Cenozoic regional unconformity

This unconformity is easily recognised within the Nile Delta subsurface. On seismic profiles it is marked by blue colour coding and occurs as a high amplitude reflector separating seismically-opaque reflectors of the Cenozoic series from the underlying subparallel Mesozoic carbonate sequences (seismic lines D3, D4, D39 and Tan 9: Enc. 5). The unconformity truncates the underlying Mesozoic with some slight irregularity. On a regional scale, this truncation appears to cut progressively older beds towards the south. As shown by Said (1962) and further demonstrated by Salem (1976), the Mesozoic continues into the Palaeocene without a break in central and southern Egypt. In the latter, the Upper Cretaceous Chalk Formation grades up into the Palaeocene Esna Shale (cf. at Aswan, Luxor and at the oases of Dakhla, Kharga, Farafra and Baharia). Because the influence of the Syrian Arc epeirogenic episode was stronger, in northern Egypt the Palaeocene is only preserved in synclinal depressions immediately south of Cairo and in the Western Desert.

Seismic-stratigraphic correlations indicate the complete absence of the Palaeocene throughout the Nile Delta, with sediments of Eocene and Oligocene age resting directly on the truncated Upper Cretaceous surface. Biostratigraphic information from Kafr el Dawar-1 well (Ayyad, 1980) shows that truncated northern reaches of the Chalk Formation were not overlapped until Oligocene time (see also Fig. 13). Only in the extreme southwest of the study area in Zebeida-1, have Palaeocene-age sediments been reported, but they are not included in this discussion since this region lies outside of the Nile Delta.
geologic province. The Upper Cretaceous has been penetrated by 17 wells in the Nile Delta region (Enc. 2) and is characterised by tan-chalky white limestone with scattered brown to milky-white chert nodules. The presence of Globotruncana sp. within the Chalk Formation in all the wells makes it readily identifiable. Faunal indications (Omar and El Gendi, 1970) indicate an outer shelf to bathyal depositional setting.

Seismic energy absorption contrasts, due to fast velocities within the Chalk Formation carbonate (4,000-4,760 m/sec), in comparison to the slower velocities in the overlying Eocene limestones and clastics (3,200-4,680 and 2,400-2,800 m/sec respectively) give rise to the characteristically strong basal Cenozoic unconformity markers on seismic profiles.

The unconformity has been mapped throughout the delta area (Enc. 6).* From the surface exposures at the Abu Rhoash Anticline, it dips progressively deeper northwards beneath the Cenozoic cover. 125 km north at the Damanhour South-1 well, the unconformity is at a depth of -2,560 m, representing the deepest point at which it has been penetrated by the drill. The generally smooth northward gradient of the basal Cenozoic unconformity is only interrupted by the channelling effect of the northward trending Messinian Nile Canyon. In fact, the canyon has cut through the overlying Cenozoic cover into the Cretaceous Chalk Formation (Fig. 14 & Enc. 6). In the extreme north of the

*Note: In this study, the term 'isochron' used in Enc. 6 and subsequent diagrams refers to a line joining all points of equal seismic reflection time (Sheriff, 1973). It does not refer to a similar term used to correlate synchronous stratigraphic rock units laid down at the same time.
Figure 14: Nile Delta: Basal Cenozoic unconformity contour map
mapped area, the gradient of the basal Cenozoic unconformity reflector steepens rapidly and cannot be traced beyond 3.9 secs (2WT). This converts by velocity analysis to approximately 4,250-4,500 metres subsea. The cause of this cutoff in reflector continuity is due to the presence of a very prominent large-scale normal fault system that trends in a WNW-ESE direction across the entire northern delta area (Fig. 14 & Enc. 6). In petroleum exploration parlance this is known as the Cretaceous hinge line, since it indicates the abrupt disappearance of Cretaceous rocks northwards, beyond the fault trace. The Cretaceous probably lies at depths of 6000-8500 metres below an extremely thick Cenozoic cover, and may even extend northwards towards the Mediterranean Ridge which is thought to contain a thick Mesozoic sequence (Mulder et al., 1974). Seismic profiles in the Nile Delta area suggest that the Cretaceous hinge line was particularly active from Eocene time onward.

In the southern Delta province, gentle NE-SW trending flexures are noted on the Mesozoic surface, increasing in intensity towards the south. These flexures can be considered compressional entities caused by the Syrian Arc epeirogenic episode at the end of the Cretaceous. Uplift also occurred, exposing the Cretaceous sediments to subaerial erosion, causing the flat peneplained nature of the basal Cenozoic unconformity noted on seismic profiles. In addition, several small WNW-ESE trending normal faults, striking parallel to the contemporary Cyrenaican-Egyptian margin can be observed on the seismic. These trends are not prominent on the Landsat images, since they are confined mostly to the Upper Mesozoic-Lower Cenozoic subsurface levels. Most of these faults probably developed during the Early Cenozoic. A great many of the faults perpetuate upwards from the
Mesozoic, through the basal Cenozoic unconformity into the overlying Eo-Oligocene and occasionally, Miocene sediments. This suggests that the entire Nile Delta province was a positive area throughout the Late Cretaceous and Palaeocene period with active subsidence commencing during Late Eocene time in response to extensional tectonism. This coincided with the early development of the proto-Nile fluvio-deltaic regime. Indeed, there is no evidence on the seismic data examined in this study for Syrian Arc related thrust faulting of "Mesozoic sedimentary sequences against basement buttresses" as suggested by Salem (1976). Even though the area may have undergone slight compressional activity and subsequent uplift during the Syrian Arc episode, the Cenozoic Era was generally a period of normal faulting and continual subsidence, associated with progressive deepening of the Eastern Mediterranean basin. This provides some indication of the existence of a deep Mediterranean basinal environment prior to the Messinian salinity crisis.

2. Lower and Middle Eocene Limestone unit: Thebes and Mokattam Formations

The Lower and Middle Eocene Limestone unit forms the first major seismic-stratigraphic unit that can be mapped. It is bounded at its base by the basal Cenozoic unconformity, and at the top by a fairly strong high amplitude reflector, annotated by brown colour coding on seismic profiles. Two formations are included in this seismic-stratigraphic unit; namely, the Thebes and Mokattam Formations, of Lower and Middle Eocene age, respectively. The unit generally exhibits a characteristic reflection-free opaque seismic pattern (see seismic line Tan 3 on Eric. 5) with occasional hummocky reflections on some seismic profiles.
Both the Thebes and Mokattam Formations have been studied in detail from extensive exposures along the flanks of the Nile Valley. According to Said (1962), the Thebes Formation derives its name from the cliffs overlooking the Valley of the Kings at ancient Thebes near Luxor (Fig. 1). It is up to 210 m thick and is largely an Operculina-rich limestone with occasional marl interbeds containing chert nodules. At Farafra Oasis, 500 km to the northwest, it occurs as a pink Alveolinid limestone. The Thebes Formation conformably grades upward into the overlying Mokattam Formation which is well known for its nummulitic fauna. The Mokattam Formation can be subdivided into two units; a lower snow-white limestone unit containing Alveolina, and an upper yellowish to white, hard limestone with abundant Nummulites.

In its type section at Gebel el Mokattam, on which stands the El Citadel in eastern Cairo, the Mokattam Formation is 133 m thick and is used as a local building stone (Said, 1962).

Major changes in the early Cenozoic palaeogeography of Egypt began during the Early Eocene. Gradually, the uplifted areas of northern Egypt were peneplained and sank below the encroaching seas, whilst the vast sedimentary basins of southern Egypt were gradually infilled. Lower Eocene rocks, for example, occur as far south as 23°30'N, whereas by Middle Eocene times the seas had retreated to 27°N. Finally, by Late Eocene time, the overall northward retreat of coastline was being enhanced by a transition from carbonate to clastic sedimentation (Said, 1962). These changes were fairly gradual, hence terrigenous influences (marls and shales) are quite common in the upper part of the Mokattam Formation before the transition to sandy
limestones, calcareous shales and marls of the overlying Upper Eocene Maadi Formation.

The top of the Middle Eocene Mokattam Formation may therefore not exactly correspond to the top Eocene limestone seismic reflector noted on seismic profiles, due to a northward "shaling-out" of the limestone facies. Nevertheless, seismic boundaries of litho-stratigraphic units are generally isochronous in the sense of Vail et al., (1977) and reasonable accuracy is expected in the current interpretation.

Seismic mapping indicates that the Eocene limestone in the Nile Delta area is largely restricted to a narrow ENE-trending corridor, extending from Wadi el Natrun through to the location of the Mit Ghamr-1 well (Enc. 7). It is partially bounded on its southern flank by the Abu Rhoash Anticline, and to the north by the contemporaneously exposed Cretaceous subaerial erosion surface. A further area of Eocene limestone exists as a thin small local tongue just to the southwest of Alexandria.

Borehole data confirms this distribution of the Eocene limestone which has been penetrated by six wells in the main corridor and by two wells (Shaltut-1 and Bax-1) in the localised zone near Alexandria (Enc. 2). Total thicknesses range from 787 m in Zebeida-1 to 53 m in Bax-1. Isopaching (Fig. 15) indicates that the Thebes and Mokattam Formations did indeed originate within narrow depressions between peneplained Syrian Arc ridges. These subsurface elongated ridges and troughs extend into the northern part of the Western Desert and have been mapped in detail in this area by Salem (1976).
Figure 15: Nile Delta: Lower-Middle Eocene limestone unit isopach map
Except for the mitigating effects of the Abu Rhoash inlier and the Messinian Nile Canyon channel erosion, there is a general thickening of the Eocene limestone unit toward the south, into central Egypt. This is not only demonstrated on seismic lines Tan-3 and Tan-7 (Enc. 5), but also by incorporating Salem's (1976) isopaching of the Eocene limestone in the region immediately south and southeast of Cairo (Fig. 15).

Due to the overall northward-thickening of the Cenozoic sedimentary package in the Nile Delta, the seismically-mapped Eocene limestone stratigraphic unit dips towards the northeast from a depth of -1,022 m in Tahrir-1 to -1,864 m in Mit Ghamr-1. These depths are equivalent to 1.0 to 1.8 secs two-way travel time, respectively (Enc. 7). It cannot be mapped further north or east due to the poor quality and scarcity of seismic profiling. Nearer the outcrop margins, especially to the south near the Abu Rhoash inlier, multiples cause seismic correlation problems.

Where it has been penetrated in the subsurface of the Nile Delta, the Thebes Formation exhibits pelagic characteristics typical of a shallow carbonate platform. It is a chalky-white to white, occasionally argillaceous limestone grading to chalk, containing frequent chert nodules. It is often dolomitic towards the base. The Mokattam Formation, on the other hand, was probably deposited in a more open marine platform environment with increasing interbeds of grey-green marl and shale intercalated within the overall tan, dirty-grey to cream coloured limestone sequence. It is this increasing terrigeneous input that is responsible for the somewhat variable interval velocity characteristics within the Eocene limestone stratigraphic unit, with
values varying from 3,200 to 4,680 m/sec (Table 6). The slow subsidence of the entire delta region is demonstrated by the onlapping nature of the Mokattam Formation onto the peripheral ridges. For example, at Shaltut-1, Shiben el Kom-1 and Mit Ghamr-1, the Thebes is completely missing; instead, thick sequences of the Mokattam limestone rest unconformably on eroded Upper Cretaceous carbonates.

3. Upper Eocene to Oligocene clastic sequence: Maadi and Qatrani Formations

The onlapping, locally transgressive nature of the Mokattam Limestone continues into the Upper Eocene with the submergence of most of the Syrian Arc ridges beneath nearshore marine clastics of the Maadi Formation. Nevertheless, certain elevated areas were probably not completely inundated until Late Oligocene times. The Maadi Formation and the conformably overlying Qatrani Formation lie stratigraphically between strong seismic reflectors marking the top of the Eocene limestones and the Late Oligocene Haddadin Basalt, and therefore constitute a readily identifiable second seismic-stratigraphic unit. Unfortunately, the subcrop of the Haddadin Basalt occurs only in the southern part of the delta province and it is not possible to seismically map the top of the Maadi-Qatrani seismic-stratigraphic unit over the entire study area. This is primarily due to the lack of a good velocity contrast between the Qatrani and the overlying Sidi Salem Formation wherever the basalt is absent. Lithological similarities between the two formations are the major cause of this problem. Hence, mapping of this seismic-stratigraphic unit is restricted to isopach maps based upon well control (Fig. 16). Indeed, the grouping of Upper Eocene and Oligocene rocks into one unit is convenient from a sedimentological view-point, since they are both lithologically
Figure 16: Nile Delta: Upper Eocene-Oligocene deltaic sequence isopach map
similar and appear to represent a continuous series of prograding shelf clastics.

In the Western Desert, drilling by Phillips Petroleum (Barber, 1976) proved the existence of an extensive Oligocene section up to 1,250 m thick, composed primarily of terrigenous prodelta siltstone, shale and sand. To the south, at Baharia Oasis (Fig. 1) occur widespread outcrops of fluvio-deltaic gravel and cross-bedded sandstone up to 250 m thick (Salem, 1976). These beds mark the first evidence of a major drainage system in Egypt, which served as a precursor of the modern Nile. Progradation of the shoreline northwards saw the gradual upward replacement of prodelta material by estuarine muds and silts.

In the Nile Delta study area, however, rocks of the Maadi and Qatrani Formations crop out immediately east of Cairo and range up to 45 m and 60 m in thickness respectively. The Maadi is composed of nearshore sands and limestone containing abundant echinoid and oyster fragments (Said, 1962), which grade up into massive variegated sands and gravels of the Qatrani. This indicates a change to a continental and fluvial depositional setting. Westward, across the Nile, both formations thin out against the Abu Rhoash anticlinorium and may only be 25 m thick. North of the outcrop belt, they dip beneath the Oligocene basalt and Neogene cover and increase in thickness to between 400-600 m in the pre-existing ENE-trending Eocene trough. Further north, it thins to 26 m in the Damanhour South-1 well (Fig. 16).

Particularly in the southern half of the delta, isopach values have been widely affected by the late Oligocene and Messinian erosional episodes. At Tahrir-1 and Shiben el Kom-1, several tens of metres of
Oligocene clastics have been removed by Messinian subaerial erosion; hence the isopach map serves as a guide, rather than an exact indicator of true depositional thicknesses.

From its outcrop limits near Cairo the Qatrani Formation gradually deepens northward beneath a younger cover. At Khatatba-1, it lies immediately below the Haddadin Basalt at a depth of -55 m. 92 km to the north, at Damanhour South-1, it lies below Miocene clastics of the Sidi Salem Formation at a depth of -2,534 m (Enc. 1). Further north, beyond the Cretaceous hinge line fault zone, it has not been reached by the drill and apparently lies at great depth.

Lithologically most of the Upper Eocene (Maadi Formation) in the Nile subsurface represents a continuation of open marine platform conditions prevailing from Middle Eocene time, but with a much greater terrigenous input. It is only found in the synclinal regions, extending eastwards from Zebeida-1, through WNX-1 and Tahrir-1 towards Shiben el Kom-1 and Mit Ghamr-1 (Fig. 16). The Upper Eocene interval is mostly composed of light to dark grey shales, which become sandy near the depositional margins and contain shallow water agglutinating fauna such as Haplophragmoides sp. and Cyclammina sp. It can be recognised also by the presence of a Globogerapis semiinvoluta marker zone towards the base (Omar and El Gendi, 1971).

The greater areal extent of the overlying Oligocene Qatrani Formation suggests a major subsidence of the erosional remnants of the Syrian Arc highs at this time. At Damanhour South-1 for example, there was a rapid change from subaerial erosion to marine conditions. Upper Oligocene rocks rest directly on the eroded Cretaceous carbonates and
contain faunal species such as *Globigerina oligocaenica*, *Bulimina scillpitilus*, and *Goborotalia opima opima*. These fauna are indicative of an outer shelf or upper bathyal slope environment (Bayliss and Bagnall, 1971).

Lithologically, the Qatrani Formation is typically composed of greenish grey to dark grey shales grading occasionally to grey claystone. The shales are pyritic and glauconitic, and contain frequent phosphatic pellets. Occasional regressive phases are represented by bands of buff coloured dolomite and fine to very fine grained sands interbedded with sandy shale. The latter contain pelecypod and echinoid fragments along with some occasional arenaceous forams. This is particularly noticeable near the basin margins. At Khatatba-1 and Abu Hammad-1, the Qatrani is composed entirely of continental sands with reworked Eocene fauna, especially *Nummulites*. These sands are very poorly sorted in size and sphericity and contain locally derived orthoclase clasts.

The progressive northward thinning of the Late Eocene-Oligocene seismic-stratigraphic unit as observed on the isopach map (Fig. 16), can be easily demonstrated on seismic profiles. Seismic traces (seismic line D4 : Enc. 5) across the Late Eocene-Oligocene shelf-slope show characteristic prograding clinoforms. The distinctive shallow sigmoidal configuration suggests a distal sedimentary supply (outer shelf-upper bathyal environment as suggested by microfaunal indicators) and a relatively rapid basinal subsidence (Mitchum et al., 1977). The overall homogeneous nature of the Maadi-Qatrani seismic-stratigraphic unit is further demonstrated by its limited range of
seismic interval velocities, which vary from only 2400–2800 m/sec (Table 6).

4. The Upper Oligocene extrusive episode: Haddadin Basalt

A broad linear belt of basaltic outcrops runs from the northern side of the Fayum Depression towards the Nile at Cairo, and continues eastward. These basalts mark a mappable unit that represents the upper limit of the Oligocene in Egypt (Said, 1962). Northward, they dip gently beneath the unconformable Lower Miocene sedimentary cover (Enc. 1 & Fig. 17). In subcrop, they are readily identified by a very strong high amplitude seismic reflector, highlighted by red colour coding on seismic reflection profiles (Encs. 5 & 8). Enclosure 9 indicates the subsurface distribution of the basalt flows, which extend in a broad, WNW-ESE trending swathe across the southern delta area. Six wells (Abu Hammad-1, Khatatba-1, Mit Ghamr-1, NWD-343/1, Shaltut-1, and WNX-1) have penetrated this unit (Fig. 17), encountering the top of the basalt at depths ranging from -28 m in Khatatba-1 to -1,100 m in Mit Ghamr-1. Northward, beyond the limits of the basaltic subcrop, the Oligocene–Miocene boundary horizon can be traced to beyond -2,500 m. In fact, on the basinal palaeoslope, sedimentation probably continued without a break from Oligocene to Miocene times. Only in the upper reaches did subaerial erosion, synchronous with the extensive basalt episode, occur.

From velocity analysis, acoustic velocities through the basalt layers vary from 3,850–4,600 m/sec. This wide variation in velocity is probably a function of differential mineral composition, caused by two distinct phases of igneous activity (Said, 1962). The main phase of labradorite and augite-rich flood basalt extrusion was followed by a
Figure 17: Nile Delta: Top Oligocene Basalt contour map
second phase of intense hydrothermal activity. The latter caused alteration of pyroxenes and plagioclases into various secondary minerals such as chlorite, hematite and sausurite.

The vast extent of the basaltic extrusive episode is a function of early rifting in the Red Sea and the Gulf of Suez. N50W trending faults were activated across the northeast Egyptian margin, especially along a narrow zone through Cairo. These faults formed ideal conduits for basalt emanations and related hydrothermal fluids to reach the surface.

The basaltic sheets spread over the pre-existing Oligocene coastal plain, with a fairly uniform thickness of approximately 50 m (Enc. 2). Only toward the northeast, on the former Oligocene continental slope, is there any appreciable thickness; at Mit Ghamr-1, 328 m of basalt was penetrated by the drill. The tabular, plateau-like nature of the flood basalts formed a highly resistive subaerial platform during the Messinian erosional episode. It developed an extensive erosional front characterised by scarps, and isolated mesas as can be observed on seismic profiles. The serrated edges of the basaltic erosional front can be easily discerned in the subsurface (Fig. 17 & Enc. 9).

5. Lower Miocene to Upper Miocene (Tortonian) deltaic sequence: Sidi Salem Formation

This sequence includes the entire Miocene sedimentary sequence except for the Late Miocene Messinian stage. The top of this sequence is easily identifiable by the basal Messinian erosional surface (green marker) on seismic lines (Enc. 5 & 8). Conversely, the base is poorly defined, being for the most part gradational from Oligocene to
Miocene, especially in the northern and central delta areas. Only where the basal Miocene rests on the Haddadin Basalt, is the base easily discernible. Chronostratigraphically, this seismic-stratigraphic unit extends from Blow's (1969) N4 to N17 zone (Enc. 2).

The Miocene extends in outcrop over vast areas of the Western Desert and along the southern periphery of the delta province (Fig. 18). Generally speaking, Lower Miocene depositional conditions represent a continuation of the Oligocene fluvio-deltaic regime prevailing in the southern part of the Western Desert where the proto-Nile Delta had its early beginnings. Lower Miocene fluvio-deltaic strata is over 600 m thick in the Western Desert, thinning eastward toward the Nile region (Salem, 1976). This situation changed dramatically during Middle Miocene times. With the accelerated opening of the Red Sea and Gulf of Suez rifts, faulting caused the proto-Nile to change to its present course (see Chapter I) and thick sequences of carbonate shelf deposits known as the Marmarica Limestone, replaced the earlier clastics in the Western Desert (Said, 1962). Terrigenous deposits now began to prograde northwards over the early Miocene and Oligocene Basalt terrain near Cairo, with the resultant accumulation of huge quantities of fluvio-deltaic sandstone and shale, a situation which continued until the commencement of the Messinian salinity crisis.

Miocene sedimentary rocks have been reached in 23 Nile Delta wells (Fig. 18). None of the wells north of the Cretaceous hinge line penetrated the entire sequence due to its great depth and increase in thickness, although in the Abu Madi field area, wells did reach the Langhian (Enc. 2). Isopachs of the Miocene sequence are not feasible due to the large sedimentary thickness which has been stripped off by
NILE DELTA STUDY
DISTRIBUTION OF LOWER MIocene-Tortonian DELTAIC SEQUENCE

Figure 18: Nile Delta: Distribution of Lower Miocene-Tortonian deltaic sequence
Messianic subaerial erosion. Nevertheless, over 1,513 m was drilled (without penetrating the entire sequence) at Ras El Bar-1 in the northeast offshore. Tentative speculative estimates, based on deep seismic reflectors suggest that possibly over 2,500-3,000 m of pre-Messianic Miocene sediments may be preserved in the northern delta. Sigmoidal seismic clinoforms within the Miocene sedimentary sequences suggest fast sediment supply, either equal to or faster than basal subsidence (seismic lines D4 & D39 : Enc. 5).

Beyond the Cretaceous hinge line, continual rapid subsidence of the northern Egyptian epicontinental margin allowed maintenance of a steep delta slope, which encouraged a substantial sedimentary buildup at its base. Fast progradation of the delta to the northeast of Cairo led to contemporaneous growth faults, some of which were later reactivated as Messinian growth faults near the Kafr El Sheikh-1 and Sidi Salem-1 wells (Fig. 19 & seismic lines Tan 5 & Tan 9 : Enc. 5).

The Miocene succession in the Nile Delta exhibits sedimentary characteristics typical of delta progradation into a deep marine environment. Shallow-water to continental fluvio-deltaic sandstone occur at the outcrop near Cairo (Fig. 18), changing northward to deeper water prodelta shale and clays on the palaeoslope (Fig. 20). The entire seismic-stratigraphic package is known as the Sidi Salem' Formation after the formal name given to the upper type section penetrated by the Sidi Salem-1 well (as described by Rizzini et al., 1978). This well includes the middle-upper part of the Miocene, mainly Serravalian and Tortonian stages, based on a fauna typical of the Globorotalia gr. fohsi and Globorotalia menardii zones (Tables 3 & 4). In its type section and elsewhere north of the Cretaceous hinge line, the Sidi
Figure 19: Seismic line illustrating truncation of Tortonian rotated fault blocks by basal Messinian unconformity.
Figure 20: Nile Delta palaeogeography: Serravallian-Tortonian
Salem Formation is composed of grey-green, montmorillonite and kaolinitic shale and claystone with occasional thin distal turbidite sands. Faunal characteristics suggest an outer slope, bathyal environment. South of the hinge line, open shelf or upper slope conditions prevailed, as indicated by a *Globogerinoides* sp. and *Orbulina* sp. rich fauna. Occasional large foraminifera such as *Miogypsina* sp. suggest dispersal into the basinal environment from nearby shallow water areas as a result of current action. Updip, much of the Miocene shelf sequence is missing in the southern delta area due to Messinian erosion (Fig. 18). The small variation in seismic interval velocity through the Miocene sequence (2,400-2,800 m/sec), is indicative of its overall homogeneous lithology.

As the Miocene delta system prograded northward, by Tortonian (Late Miocene) time, flanking carbonate platforms developed on the delta margins (Fig. 20). Remnants of these limestones were drilled in the North Dilingat-1 well, where they formed an erosionally resistive cap on a mesa carved out of the Miocene bedrock during the Messinian erosional episode (seismic line D4 : Enc. 5). Stratigraphically, these limestones are a diachronous Tortonian equivalent to the Middle Miocene-age Marmarica Limestone sequences found in the Western Desert.
IV. THE MESSINIAN SALINITY CRISIS IN THE NILE DELTA

1. Concepts

In the absence of reliable diagnostic, faunal bathymetric indicators, considerable reliance has to be placed on lithostratigraphic information for recognition of Messinian depositional environments in the Nile Delta region. In this respect, determination of Messinian lithofacies is based upon idealised electric log responses for selected vertical sequences, using proven ancient and modern analogues (refer to discussion on seismic-stratigraphy p.46, and lithofacies analogue modelling p.57). By composing the idealised lithofacies types illustrated on Enclosure 4 with log responses, cores, and other subsurface data and integrating these into Fisher and Brown's (1977) concept of seismic depositional systems, it is possible to reconstruct the Messinian palaeogeography of the proto-Nile Delta. Seismic lithofacies modelling of this nature indicates that the Messinian sequences in the Nile Delta were most likely laid down by a fluvio-deltaic system, prograding and interfingering with an evaporitic shelf facies at least 2.5-4.0 km below present sea level (Fig. 21).

2. Biostratigraphic control and gross lithology

The main outlines of biostratigraphic control in the Neogene section of the Nile Delta have been described by Rizzini et al., (1978), which entailed some slight revisions to the well-defined faunal subdivisions of the Mediterranean Neogene (Bizon and Bizon, 1972; Cita, 1975). In the absence of suitable biostratigraphic criteria, as is common throughout Messinian sediments in the Mediterranean, the Messinian of the Nile Delta is defined as the lithostratigraphic sequence laid down between latest Tortonian and earliest Pliocene sediments of normal
Figure 21: Messinian proto-Nile Delta model
salinity containing authochthonous stenohaline fauna (Fig. 22, Table 3). Sediments of Messinian age (upper N. 17) rest unconformably on prodelta shales of the Sidi Salem Formation which ranges from the Globorotalia fohsi peripheroronda zone (N9/N10), through the Globorotalia menardii zone (N15) to the Globoratalia acostaensis zone (N16). The age in any one place depends upon the degree of subaerial erosion during the initial phase of evaporitic drawdown at the start of the Messinian stage. The top of the Messinian in the Nile Delta is defined by the presence of the Sphaeroidinellopsis acme-zone MPL1 (Cita, 1975; Ryan, 1978), within basal units of the overlying Pliocene prodelta shales of the Kafr el Sheikh Formation.

In common with the Messinian elsewhere in the Eastern Mediterranean, the entire Messinian sequence in the Nile Delta is devoid of normal stenohaline fauna. It is characterised by a dwarfed oligotypic fauna of benthics including Cibicides, Bolivina and Eponides, and the ostracod genus Cyprideis (Rizzini et al., 1978). These all are indicative of an abnormal environment of variable salinity, ranging from brackish-water, mesohaline (Cyprideis spp) to hypersaline and even sterile conditions. This is especially true for the several large Messinian clastic sequences in the Nile Delta which are devoid of fauna, although the latter may be also a function of non-marine depositional processes. It has been suggested that Cyprideis also has an ability to tolerate a euryhaline environment, and is therefore an important indicator of brackish water conditions (Cita et al., 1978; Rizzini and Dondi, 1979).

Despite such variable faunal environmental indicators, the Messinian succession in the Nile Delta has been tentatively subdivided by
<table>
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<th>AGE</th>
<th>FORMATION</th>
<th>BIOZONES</th>
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<th>STRATIGRAPHIC MODEL</th>
<th>GROSS LITHOLOGY</th>
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<td>LOWER PLIOCENE</td>
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<td>Globorotalia fohsi</td>
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Figure 22: Late Miocene-Early Pliocene chronostratigraphy
Rizzini and his coworkers (1978) into three units, namely the Qawasim, Rosetta, and Abu Madi Formations, which broadly represent three phases of sedimentological evolution (Figs. 22, 23 & 24). These are, respectively:

(i) a fluvio-deltaic phase characterised by a restricted marine environment, later followed by evaporitic conditions in the deeper Eastern Mediterranean basin; 
(ii) an evaporitic phase with deposition of gypsum-mudstone cycles; 
(iii) a post-evaporitic phase characterised by brackish and freshwater conditions.

Much of the sequence is comprised of the Qawasim Formation with a maximum recorded thickness of 1,447 metres in the Kafr el Sheikh-1 borehole (Enc. 1 & Fig. 25). Seismic control however, suggests that it may be in excess of 2,000 metres thick in the Abu Qir Bay area, 25 km to the northeast of Alexandria. Core data suggests the Qawasim Formation to be composed of fluvio-deltaic clastics. This conclusion was also reached by Rizzini et al., (1978) in their study of the Neogene of the Nile Delta. Calcareous intervals with some thin
Figure 24: Qawasim-1: well log profile through type section for Messinian sedimentary sequence.
Figure 25: Kafr el Sheikh-1: well log illustrating maximum recorded thickness of Messinian sediments in the Nile Delta.
evaporites are found near the base of the section and may indicate lagoonal-sabkha conditions.

These occur in sequences and/or palaeogeographic settings not affected by high energy fluvial activity of the proto-Nile river. There has been considerable reworking of earlier sediments, as shown by the occurrence of fauna from the underlying Globoratalia menardii (N15) zone of the Tortonian. In many instances, especially in the lower levels of the Qawasim Formation, reworked Eocene Nummulites are common, indicating active downcutting of the Nile Canyon through Eocene Mokattam Limestone which are exposed today on contemporary flanking scarps near Cairo (Said, 1962).

The Qawasim Formation is conformably overlain by the anhydrites of the Rosetta Formation. These range in thickness from 4 m to a recorded maximum of 50 m in the Rosetta-2 well, and are laterally very extensive, being found throughout the Upper Messinian section of the northern Nile Delta region, and indeed, throughout the entire Levant margin (Gvirtzman and Buchbinder, 1978). The anhydrite is characterised by a very distinctive high-amplitude double reflector on seismic profiles. It can be traced into the deeper parts of the Eastern Mediterranean where it marks the uppermost limits of the Messinian sequence (Ross and Uchupi, 1977; Hsu et al., 1978d; Ben-Avraham and Mart, 1981) and corresponds to the Horizon "M" of Ryan (1978) and Horizon "A" of Finetti and Morelli (1973).

Southward, and updip beyond the Messinian sedimentary onlap, Horizon "M" represents the subaerial erosion surface formed during the Messinian dessication of the Eastern Mediterranean basin. As outlined by Ryan (1978), Horizon "M" in the Nile Delta represents subaerial
exposure, erosion and resedimentation at the southeastern Mediterranean margin during the Messinian salinity crisis. Overlapping both the Rosetta Anhydrites and the Qawasim Formation are sands of the Abu Madi Formation which are in turn overlain by the Pliocene Kafr el Sheikh pro-delta shales. It has been long recognised in the Nile Delta, through petroleum exploration drilling programmes, that the basal Pliocene transgression following the Messinian salinity crisis is marked by the presence of the Sphaeroidinellopsis acme-zone MPL1 (Cita, 1975).

In this study, it is suggested that the Abu Madi clastic units lying between the Rosetta Anhydrites and/or the Qawasim Formation, and the Lower Pliocene Sphaeroidinellopsis acme-zone, are in fact, delta front sands laid down along the margins of a deepening fresh to brackish water lake. Conversely, Rizzini and his coworkers (1978) had placed the Abu Madi sands in the basal Lower Pliocene. However, these sands contain Ammonia becarrii and other euryhaline fauna such as Cypeideis spp, and thus correspond instead to uppermost Messinian "Lago mare" facies (Cita et al., 1978; Hsu et al., 1978d).

Economically, Messinian fluvio-deltaic clastics in the Nile Delta are important gas and gas-condensate reservoirs. To date, several large gas fields have been discovered, including the Abu Madi and Abu Qir gas fields with respectively 2.5 and 1.22 trillion feet of recoverable reserves. To the north of the Abu Qir Field, the Naf gas field has been recently discovered. It may ultimately contain over 4.0 trillion cubic feet of recoverable reserves (International Petroleum Encyclopedia, 1975; World Oil, 1980).
3. Recognition of the Messinian erosional surface

The basal Messinian unconformity appears as a pronounced, continuous high amplitude seismic reflector truncating numerous deeper horizons (Encs. 5 & 8). In the southern delta area, it is synonymous with Ryan's Horizon "M", while toward the north, it lies beneath the onlap of the Messinian sedimentary sequence, the top of which essentially forms the continuation of the "M" marker (Enc. 8). Seismic velocities as determined from borehole sonic logs and velocity surveys indicate that the overlying Lower Pliocene section is of an acoustically low-amplitude character with average velocities ranging from 1,800-2,400 m/sec. In contrast the seismic velocities below Horizon "M" are usually much faster, examples being 3,400-3,500 m/sec such as recorded in Messinian clastics at the Buseili-1 borehole and 2,400-2,800 m/sec through Tortonian shales at Damanhour South-1.

Based upon the close seismic grid control, a time contour map has been constructed (Enc. 10). By utilizing an average interval velocity contour map (Enc. 11) it is possible to formulate a computerized true depth map of the basal Messinian erosional surface (Enc. 12). This depicts the development of an incised drainage network superimposed into an extensive palaeoslope with a northward directed flow. The palaeoslope represents the former Tortonian proto-Nile delta slope which became an extensive linear erosional front during the Messinian era. This palaeo-relief can be traced from an elevation of -55 m at the Khatatba-1 borehole to approximately -2,500 m near Buseili-1. It is not only modified by the presence of drainage channels, but also by large mesas, buttes and escarpments (Enc. 8). The Nile Canyon, cut by entrenchment of the proto-Nile river, trends northward from beneath Cairo where it is approximately 12 kms wide and at least 1.5 kms deep.
(assuming faster velocities for the overlying Pliocene sediments may increase this figure even deeper, to 2 km). The canyon can be traced northward on the available seismic records to a depth of nearly 3,750 m, which is approximately equal to nearly 3 secs two-way travel time on seismic sections. By mapping strong seismic reflectors representing the tops of the underlying Mesozoic carbonates, Eocene carbonates, and Oligocene basalt or equivalent, it is possible to construct a subcrop map beneath the Messinian erosional surface (Enc. 13 & Fig. 26). From this map the control of lithofacies type on the Messinian drainage patterns can be more clearly discerned.

In subcrop, the Oligocene basalt forms an exposed plateau bounded by an eroded northern escarpment which extends along the entire southern and southwestern upper margin of the palaeoslope. Occasional basalt-capped mesas form outliers, although several mesas are characterised by a variety of erosionally resistant rock layers, as confirmed by drilling at the Mit Ghamr and North Dilingat boreholes. At Mit Ghamr (seismic line Tan 7 : Enc. 5), the mesa is composed of Lower Miocene clastics overlying Oligocene basalts, while the North Dilingat mesa (seismic line D4 : Enc. 5) is capped by Tortonian limestones resting conformably on deltaic shales. In most of the southern Nile Delta wells, haematite staining, thought to be the product of subaerial erosion, was observed in drill cuttings from immediately beneath the basal Messinian unconformity. Despite the ever deepening Messinian palaeoslope towards the north, rocks beneath the Messinian subcrop become progressively younger so that eventually, the unconformity truncates Tortonian prodelta shales before passing beneath the southern onlap of the Messinian Qawasim Formation further north (Encs. 1 & 5). This unconformity is the equivalent of the presalt discordance
Figure 26: Basal Messinian subcrop and Messinian drainage pattern
noticed by Ross and Uchupi (1977) on seismic profiles over the present day Nile Cone, and later confirmed by Ryan (1978).

Indirect evidence for Messinian excavation of the proto-Nile Delta is illustrated on Bouguer and residual gravity maps published by Sheerif (1972). These maps show a remarkable linear gravity low corresponding to the approximate position of the Messinian Nile Canyon. Sheerif, without the benefit of seismic data, was only able to suggest that the gravity low represented a sediment-filled, fault-bounded trough.

4. Geomorphology of the Messinian erosional surface

Rapid entrenchment of the proto-Nile River must have occurred for the main Nile River fluvial channel to erode a canyon 1,200 km upstream to Wadi Halfa in the Sudan (Chumakov, 1973), and to a depth of at least 1.5 kms near Cairo. Here the river downcuts through erosionally resistant Oligocene basalts into the underlying Mesozoic and Eocene carbonates. This could only have been initiated by a very pronounced drop in the Eastern Mediterranean sea level during Messinian time, causing the proto-Nile to re-grade upstream, and cut back into its former delta slope. The "V"-shaped nature of the resulting gorge cut by the Messinian proto-Nile channel in an attempt to regain equilibrium is clearly illustrated on seismic line A42 (Enc. 8) and on the contour gradients across the Nile Canyon near Cairo (Enc. 12). Three-dimensional computer models (Figs. 27 & 28) of the basal Messinian unconformity give a good visual illustration of the differential rates of erosion. The continually flowing proto-Nile fluvial channel has clearly cut down much faster than intermittent drainage systems, perched on the plateau rims.
Figure 27: Basal Messinian unconformity: computerized 3-D model viewed from an azimuth of 23 degrees with 30 degree viewing angle from the horizontal.

Figure 28: Basal Messinian unconformity: computerized 3-D model viewed from an azimuth of 45 degrees with 30 degree viewing angle from the horizontal.
The subcrop map (Enc. 13) demonstrates marked truncation of horizontally bedded Mesozoic and Eocene carbonates on the Nile Canyon walls. Northward, away from the Oligocene basalt escarpment, the palaeo-relief is less pronounced as the Mesozoic and Eocene carbonates dip beneath a less resistant, thickening section of Oligocene to Miocene fluvio-deltaic clastics. Consequently, the Nile Canyon widens out with entrenched meanders being common and the valley assumes a more open character in cross-profile (seismic lines Ben 2 & Ben 2C : Enc. 8). Paired and impaired rejuvenation terraces are clearly observed, suggesting a constant lowering of base level, with dramatic falls related to sudden changes in Messinian sea level. These are a result of drastic changes in the net Mediterranean water budget (Cita et al., 1978). Moreover, with the overall fall in Messinian sea base level, the strandline migrated northwards resulting in a series of WNW-ESE trending terraces parallel to the strike of the former Tortonian delta slope. This can be observed on the seismic section D39 (Enc. 5) at 1.7 secs (two-way travel time), converting to a depth of approximately 1,700-1,750 metres. A little further north, occurs the onlap of the Qawasim Formation, confirmed by the Mahmoudyah 1 borehole which penetrated 234 metres of Messinian clastics and sandy micritic limestones. Due to rather poor seismic data in the onshore northern delta area, it is difficult to seismically determine the actual onlap of the Qawasim Formation over the basal Messinian discordance.

Two drainage pattern types appeared to have developed further inland on the upper levels of Messinian subaerial erosion surface. These can be related both to bed rock type and the physiography of the late Tortonian delta complex (Fig. 26). To the west of the Nile Canyon, horizontally-bedded homogeneous rock suites have been cut by a trellis
drainage system originating from NE and NW-orientated megafracture patterns developed within the readily exposed Oligocene basalts. Due to extensive erosion, this drainage pattern became superimposed onto the underlying Oligocene clastics and older sediments. In contrast, east of Nile Canyon, there is not such a marked drainage pattern (this is, in part, due to the lack of detailed seismic control), as the basalt dips gently eastwards beneath a cover of Miocene deltaic sediments, upon which presumably developed a northward-directed consequent channel system.

Likewise, more basinward, the gradient of the former Tortonian delta slope, now a linear erosion front, also controlled the development of consequent fluvial channels fed by an elaborate upper slope network of dendritically-orientated minor streams. These streams rapidly cut back into the easily eroded Tortonian pro-delta shales and captured channels of the higher trellis drainage system. This led to the formation of mesas and buttes as erosional remnants. A number of the erosional highs have pronounced west and south-facing cliff scarps (seismic lines D18 & D26 : Enc. 8). This is in marked contrast to gentler northern slopes which were formed where the Messinian sub-aerial erosion surface cut along bedding planes in the underlying Tortonian delta-slope shales, often forming "hogback" erosional remnants (seismic line Tan 7 : Enc. 5).

In cross profile, the upper slope drainage channels have sharp box profiles typical of wadis in a desert badland environment (seismic line D31 : Enc. 8). Certainly, the arid climatic considerations of Van Gorsel and Troelstra (1981) have been supported by the work of Chamley and Robert (1979) who suggested that arid conditions existed
during the Messinian stage based upon the presence of fluvially reworked smectitic continental clays in Messinian deposits. The immature wadi profiles are in marked contrast to the "V" shaped valley profile of the continually flowing proto-Nile fluvial channel in the Nile Canyon. These wadis coalesce into piedmont fans that merge into the deltaic and braided stream deposits of the Qawasim Formation, deposited by the proto-Nile at the mouth of the Nile Canyon.

It has been difficult to recognise wadi deposits in the drainage channels particularly from seismic data, especially since most boreholes were drilled on topographic highs or to test deeper pre-Messinian structures. Nevertheless, discontinuous high amplitude reflectors, observed on some seismic profiles may indicate infilling of wadi channels. Only one well, the Itay El Barud-1 borehole, has been drilled into the flanks of such a channel (seismic line D31 : Enc. 8) where it penetrated a basal pebbly sand unit 29 m thick. Electric log characteristics and well cuttings indicate a very immature conglomeratic sand with a very high argillaceous shale content up to 30% by volume. Porosity values vary from 6% to 48% suggesting poor sorting and immaturity as would be expected from a wadi deposit. High amplitude reflectors on the seismic profile across the lower Nile Canyon (seismic line Ben 2 : Enc. 8) may indicate fluvial channel lag deposits, but without borehole correlation it is impossible to classify these features as fluvial sands of the Qawasim Formation, or conversely as deltaic or proximal turbidites of the Lower Pliocene.
5. Messinian lithofacies

(i) Major subdivisions

Although the Qawasim, Rosetta and Abu Madi Formations represent three phases of sedimentological evolution in the Messinian of the Nile Delta, lithofacies modelling from seismic and borehole data (See Chapter II) suggests that the Messinian seismic-stratigraphic unit can be conveniently subdivided into six major lithofacies groups:

- Delta front facies : Abu Madi Formation
- Subaqueous gypsum facies : Rosetta Formation
- Subaqueous debris flows
- Mud flows
- Fluvio-deltaic facies
- Basal high amplitude zone

Qawasim Formation

The heterogeneous nature of the great variety of lithofacies types deposited under such a palaeogeographic setting is reflected by the extremely varied acoustic velocities observed throughout the Messinian sections. For example, interpretation of sonic logs from the Rosetta-2 well indicate that the velocity range for Rosetta Anhydrite shelf facies can vary from 3,500-6,000 m/sec, depending upon the degree of contamination by indigenous argillaceous elements. Conversely, velocity values within the Qawasim fluvio-deltaic sequence are less variable, ranging from 3,000-4,000 m/sec.

(ii) Geometry

Altogether, a total of over 20 boreholes have been drilled into the Messinian sedimentary sequence in the northern Nile Delta, nearly all of which also penetrated through the basal Messinian unconformity into underlying prodelta shales of the Sidi Salem Formation.
Gross lithostratigraphic modelling from borehole data indicates that after the initial dessication, the delta plain began to build out from the mouth of the Nile Canyon over the basal Messinian discordance at average depths of 2.5 to 4 km below present sea level (Ross and Uchupi, 1977; Ryan, 1978). Isopachs of the Messinian sedimentary sequence (Fig. 29) geometrically conform to a highly lobate to occasionally elongate, fluvially-dominated delta pattern, generally indicative of a high outflow velocity for the proto-Nile River. Two consecutive major depocentres are noted. The first depocentre originated near the Kafr el Sheikh-1 borehole where the proto-Nile River emerged from the confines of the Nile Canyon. It is over 1,500 m thick. Fast rates of sedimentation caused syndepositional growth faulting (seismic line Tan 5 : Enc. 5) before the delta front prograded westward to form a second depocentre centred on Abu Qir Bay. Large east-west trending antithetic growth faults in this area (seismic lines 300130, 300430, 301330 : Enc. 14) permitted the accumulation of over 2,000 m of Messinian sediments. Rapid westward progradation of the delta front-slope system in the Abu Qir Bay area is clearly observed on east-west seismic lines (seismic lines 313130E, 312530E : Enc. 14), and has been confirmed by dip directions derived from dipmeter analysis on the Abu Qir-1 and -2 wells.

Apart from growth fault instability due to gravity loading of coarse Messinian clastics overlying incompetent Tortonian prodelta shales, gentle intra-Messinian westward crustal tilting is believed to have caused migration of the prograding delta system within the confines of the Abu Qir fault system, rather than towards the north as might be
Figure 29: Messinian sedimentary sequence: isopach map
expected. Indeed, seismic profiling in the northeastern offshore delta region indicate a general pinchout of Messinian clastics to the east, with the Rosetta Anhydrites (Horizon "M") resting directly on truncated pre-Messinian sediments (seismic lines WDN 143, WDN 145: Enc. 15). Moreover, gentle eastward onlap of the overlying transgressive Lower Pliocene Kafr el Sheikh Formation supports this contention (seismic line WDN 143: Enc. 15). In addition, slumping and minor erosion of delta plain facies (seismic line Tan 5: Enc. 5), as recorded by Rizzini et al. (1978), toward the top of the Messinian section in the southern Nile Delta area near the Kafr el Sheikh-1 location indicate that westward channelling of the proto-Nile stream channels through the Abu Qir Bay area was aided by a steep draw-down in Messinian sea level.

The Messinian salinity crisis effectively caused rejuvenation of the landscape without any interrelated vertical tectonic activity, thus inducing very rapid denudation and a subsequent proportional increase in sediment discharge by the proto-Nile. During the 1.1 million year Messinian stage, sediments were deposited in the Nile Delta region at a rate of approximately 1.82 cm/yr, over three times as fast as the 0.58 cm/yr rate established after the return to normal marine conditions in the following Pliocene-Quaternary period which lasted 5.2 million years.

(iii) Basal High Amplitude Zone (Lower Qawasim Formation)
Especially in the deeper, basinward parts of the Messinian sequence in the Abu Qir Bay area just above the basal Messinian discordance (which effectively forms acoustic basement) occur several high amplitude
reflectors (seismic lines 300130, 300430, 301330 : Enc. 14). These reflectors bound a common seismically-opaque zone between 0.1-0.2 secs (2WT) thick. High amplitude seismic reflection signatures and low frequency characteristics suggest the possibility of a carbonate-evaporitic layer which may correspond to the Horizon "P", noted in the deeper offshore seismic interpretations of the Nile Cone by Ross and Uchupi (1977). Although this zone has not been penetrated by any of the wells used in this study, the lower sequences of the Abu Qir-1, Buseili-1 and Abu Madi-2 wells can be interpreted from electric log analysis to contain lagoonal carbonate-sabkha and clastic shoreline facies (Enc. 16). Such sequences typically cause random, scattered low-velocity impulses as noted on seismic profiles above the basal high amplitude zone. It is suggested that the postulated basal carbonate-evaporite layer graded upward into these facies which developed within interdistributary lagoons away from the major stream channels which emanated from the proto-Nile fluvio-delta system.

(iv) Fluvio-deltaic facies (Qawasim Formation)

Despite periodic oscillations in Messinian sea base level, which caused alternate minor transgressions and regressions of the Messinian palaeo-shoreline, as indicated by discordances on seismic profiles within the Messinian interval, gradual infilling and progradation of deltaic facies occurred. This is shown by the overall vertical facies change in the Kafr el Sheikh-1 well (Enc. 17). Electric log interpretation suggests that there is an upward trend from delta front sands to an abundance of fluvial sands, particularly braided stream facies. In fact, one series of stacked braided stream sequences (3,027-3,283 m) is over 256 m thick. Due to its proximity to the Nile Canyon, the Kafr el Sheikh-1 well penetrated the thickest gross sand
section in the entire delta, with 750 m of sand within an overall Messinian section of 1,447 m, an overall sand-shale ratio of 1:2. Only 24 kms to the NW, at the Qawasim-1 well (Enc. 16) this ratio drops to 1:2.5, as delta margin and lagoonal facies became more prevalent. This change in environmental setting can be observed by comparing the Messinian sequences shown on two east-west correlation charts (Encs. 16 & 17). The basinward section, (Enc. 16) demonstrates a far greater number of "marine" and "non-marine" sequences as compared to the landward section which is predominantly composed of "non-marine" or fluvial sequences. Nevertheless, there is also a diachronous east to west change in facies within the basinward section (Enc. 16). Much of the thick Qawasim Formation drilled by the Sidi Salem-1 and Qawasim-1 wells probably accumulated prior to westward migration of the proto-Nile between the confines of the Abu Qir Bay antithetic faults. Thus, most of the thick Messinian sequence drilled by the Abu Qir-1 may well correspond to a "marine" sequence deposited whilst the earlier sequence was being eroded. This is diagramatically represented by an intra-Messinian unconformity which informally subdivides the Qawasim Formation into upper and lower intervals to the west and to the east respectively (Enc. 16). Indeed, the intra-Messinian unconformity, at -2,430 m in Buseili-1, is now probably downfaulted to a depth of approximately -3,250 m in Abu Qir-1.

Virtually all the usual facies typical of a fluvio-deltaic system as demonstrated on Enclosure 4 can be observed within the Qawasim Formation. Several of these facies have been described from study of requisite cores and cuttings integrated with electric log data, examples of which are discussed below:
Braided stream facies (Qawasim-1, core 10 : Appendix IV) are composed of poorly sorted, sands containing subangular to subrounded, medium to coarse grained quartz and feldspar grains with minor clays. Occasionally, gypsiferous cements occur, as a diagenetic byproduct from the migration of sulphate-rich fluids related to sabkha groundwater capillary processes (Shearman, 1966). Channel lag deposits at the base of the braided stream sequences frequently exhibit large scale cross-bedding with cobbles and mud pebbles. They are not only conglomeratic, but also gravelly, a function of long-distance transport by the proto-Nile with far-flung headwaters. The subaerial environment of deposition in a semi-arid climate (Chamley & Robert, 1979; Van Gorsel & Troelstra, 1981) is typified by the absence of both fauna (except reworked), and glauconite grains which are normally found in a marine environment (Selley, 1976). There is also a lack of carbonaceous matter along with frequent hematite staining. In some braided stream sequences, there are abundant scour surfaces caused by episodic flooding.

In most wells drilled in the northern part of the Nile Delta, electric log interpretation of the Qawasim Formation indicate a predominance of delta plain and delta front facies as exemplified by careful correlation of wells drilled throughout the Messinian section of the Abu Madi field (Enc. 18). Elsewhere in the northern delta area, delta plain point-bar sequences are common (Enc. 16). Some, particularly the coarse-grained type (McGowen & Garner, 1970) have multistorey stacking of several channel systems in which silts and fine grained sands of the flood plain and levee environment have been eroded away, giving typical blocky spontaneous potential log responses (eg. Kafr el Sheikh-1 well, 3,414 m to 3,565 m : Fig. 25). Large scale chute-bar
foresets are only common to the coarse grained point-bar sequences (Qawasim-1 core 6 : Appendix IV), in contrast to meandering stream point-bar sequences which include small trough sets and parallel laminae. These bedforms indicate a stream flow with a much lower bed-suspended load ratio. Particularly in the latter instance, there is occasional preservation of carbonaceous material (possibly mud drapes and levee banks) despite some oxidation in semi-arid climatic conditions. Again a subaerial environment of deposition is implied by the lack of any fauna or glauconite.

Lower delta plain and delta front facies are common furthest away from the confining influences of the Nile Canyon. With this facies change, a dwarfed benthonic fauna (molluscs, echinoids, etc.) and ostracods occurred with a corresponding lower sand/mud ratio, such as 1:4 as recorded in the Sidi Salem-1 well. Single sand units occur frequently, and are encased within thick interdistributary and delta front muds and silts (Qawasim-1, cores 5, 9 & 11 : Appendix IV). Delta front sands such as distributary mouth bars can be observed on electric logs which exhibit coarsening upward sand sequences (i.e. : Sidi Salem-1, 2,982-3,100 m : Enc. 16). In particular Core 8 from Qawasim-1 (Appendix IV) is a good example of an upward coarsening distributary mouth bar sand, overlain by channel bar sands containing accretionary pebble lag clasts. The lower distal bar is flaser-bedded, trending up into slump and roll structures which are common in the bar front. This is in turn, overlain by fine to medium grained sands with multi-directional planar and festoon cross beds. These finally grade into climbing ripple festoon cross-beds, common in the distributary channel bar.
(v) Subaqueous debris flows (Qawasim Formation)

During the latter half of the Messinian, the delta front migrated westward, between the confining Abu Qir antithetic faults (Fig. 29). The Abu Qir-1 well drilled over 1,037 m (from 2,447-3,484 m subsea) of the postulated 2,000 m of Messinian section in this area. Cuttings descriptions and electric log responses suggest that much of the Qawasim Formation cut by this well is composed of a mixed environment of delta front and delta slope sands interbedded with braided stream facies (as suggested by the presence of very immature sands and gravels). Core 1, taken from the interval 3,049-3,055 m in the Abu Qir-1 well reveals an extremely unstable environment of deposition with postulated slumping of pebbly sandstone into slumped ripple-bedded sand deposits laid down by traction currents (Appendix IV). The pebbly sandstone sequence exhibits scouring of individual grains into the underlying sequence and occasional fluidised injection tracts.

Since these sands are matrix supported and contain semi-lithified intraformational clasts it could be argued that they are slumps of subaqueous origin. Certainly, the Abu Qir Bay region marked an area of deltaic progradation into the restricted Messinian evaporitic sea, especially during the latter half of the Messinian stage. Most of the progradational units in the Messinian section at Abu Qir Bay however, occur to the west of the Abu Qir-1 location (Seismic line 312530E: Enc 14). Lack of diagnostic fauna indicators especially with regard to palaeobathymetry, prohibit definitive conclusions to be drawn about the environment of deposition in the Messinian of the Abu Qir-1 well. Core 1 seems to exhibit the characteristics of a subaqueous debris flow deposited in an upper slope submarine fan environment. However,
uncertainty about the environment of deposition suggests that the core could also possibly represent slumping of an alluvial fan deposit into a shallow marine embayment.

The depositional process was facilitated, nevertheless, by a rapid regressive phase which was eclipsed and preceded by a major intra-Messinian fall of sea level in conjunction with incipient movement along the Abu Qir syn-depositional fault system. Indeed, throughout many of the cores taken in the Messinian section of the Qawasim-1 well, numerous small scale faults can be observed which probably occurred just after early lithification. This suggests very rapid rates of deposition. Substantial basinward transport of a heavy suspended load debouched from the fluvio-deltaic channel was probably facilitated by the large density contrast between inflowing fresh waters of the Nile and the hypersaline waters of the dessicated Eastern Mediterranean basin. This would account for the poor sorting, instability, and slumping noticed in the core from this interval in Abu Qir-1.

(vi) Mud debris flows (Qawasim Formation)
Occasional flash floods from the elevated wadi drainage network perched on the erosional front dispersed sporadic mud debris flow deposits across the delta plain (Qawasim-1, core 7 : Appendix IV). Bedding in mud flow units is poor to non-existent, with extremely limited sorting of lithic clasts which are supported by a calcareous clay matrix. Pebbles are sporadically arranged without preferred orientation and are interspersed with armoured mud balls. Detrital elements exhibit a great variation in sphericity, ranging from well-rounded grains to clasts of extreme angularity, suggesting
intermixing of contemporaneous wind-blown sands with material derived from subaerial erosion of older water-lain deposits. The existence of iron-staining caused by oxidation in such an environment supports this contention. Wells drilled on the flanks of the erosional slope such as El·Tabia-1 and Mahmoudyah-1 show an abundance of poorly sorted detrital debris that can be interpreted as subaerial talus products.

(vii) Subaqueous gypsum facies (Rosetta Formation)

Borehole intercorrelation used in conjunction with seismic mapping of the ubiquitous Rosetta Anhydrite reflector indicates that the anhydrite units are laterally very extensive throughout the northern Nile Delta, particularly toward the north and northwest (Enc. 19). Depths to the top of the Rosetta Anhydrite range from -2,030 m in El Tabia-1 to -2,791 m in Qawasim-1. In all wells where it has been penetrated, the anhydrite is only associated with interbedded grey siltstones and marly shales, implying low energy conditions below wave base, and possibly below the photic zone as calcareous intercalations are rare. Glaucnontite and dwarfed benthic fauna are common. Despite being relatively thin (average thickness 3-4 m) by electric-log correlation standards, individual anhydrite bands can be traced from borehole to borehole (Fig. 30). This suggests that the anhydrite

Figure 30: Interpretative electric log correlation through Rosetta Anhydrite from Abu Qir-1 to Buseili-1
bands originated as subaqueous gypsum precipitates (Schreiber and Friedman, 1976), and could well be the lithological equivalent of gypsum-mudstone cycles noted in cores 16-20 at DSDP Site 374 (Garrison et al., 1978). It is unlikely that these are sabkha evaporite facies since the latter in the Nile Delta are frequently associated with interbedded coarse terrigenous clastics and lagoonal carbonates, and are restricted in areal extent. This association would be expected to give random chaotic seismic reflectors, in contrast to the widespread, thin Rosetta Anhydrite seismic marker.

The Rosetta Formation is a transgressive sequence, indicating a rising Messinian sea level. In the northeastern offshore near the Ras el Bar-1 borehole, it overlaps the Qawasim Formation to rest unconformably on the erosional surface (seismic line WDN 145 : Enc. 15). Towards the south, on the lower slopes of the linear erosional front, seismic continuity of the anhydrite reflector indicates that there is a facies change updip to nearshore paralic carbonates interbedded with calcareous sands and shales. These rocks were penetrated by the Mahmoudyah-1 borehole (Enc. 19) and pinchout very rapidly updip against the linear erosional front.

Anhydrite is conspicuously absent within high energy sandy facies due to penecontemporaneous scouring by submarine channels derived from the delta front (Fig. 31). Mapping of the Rosetta Anhydrite double seismic reflector clearly shows syndepositional scouring by large northwardflowing stream channels emanating from the receding delta front at the mouth of the Nile Canyon (Enc. 19). Seismic profiles across the uppermost Messinian prodelta front (seismic lines WDN 138, WDN 142, WDN 143 : Enc. 15) demonstrates extensive channel cut and
fill with synchronous precipitation of subaqueous gypsum on the intervening interdistributary highs.

(viii) Delta Front Facies (Abu Madi Formation)
Despite the presence of the characteristic Ammonia beccarii fauna, continual coarse clastic deposition by the proto-Nile renders difficult the recognition of the Abu Madi "Lago Mare" facies in the Nile Delta. Sedimentologically they occur between the aforementioned Rosetta Anhydrite and a deeper water sequence of distal deltaic sands and shales from the overlying Sphaeroidinellopsis acme-zone. The Abu Madi sands are over 50 metres thick in the northern delta wells and show delta-front characteristics: a distributary mouth bar sequence was observed in Qawasim-1 Core 3 (Appendix IV). The Abu Madi sands unconformably overlap clastics of the Qawasim Formation and demonstrate an overall fining upward signature on electric logs (Encs. 16
This is suggestive of a general rise in sea level at the end of the Messinian period with the return of quieter, deeper marine conditions.

6. The case against deep water sandstone facies

Although turbiditic sands do exist in several isolated and localised Messinian basins, for example, the Fusignano Formation described in the subsurface of the Po Valley by Rizzini and Dondi (1979), the preceding discussion of Messinian lithofacies in the Nile Delta indicates an overall fluvio-deltaic, shallow water environment of deposition. It should also be remembered that unlike the Messinian proto-Nile, there was no shelf environment in the partially dessicated Po Valley basin, hence sediments were deposited in this area by submarine fan processes into a large enclosed standing body of water (op. cit.).

Aside from the well-versed arguments for a deep-basin dessication model for the Messinian by Hsu and his coworkers (1973, 1978b) there is substantial evidence against a deep water origin for the Messinian clastics in the Nile Delta. In particular, the basal Messinian discordance in the Nile Delta can be correlated with analogous subaerial erosion surfaces around the peripheral margins of the Mediterranean. These erosional surfaces developed in response to evaporitic drawdown and dessication during the Messinian salinity crisis (Ryan and Cita, 1978; Hsu et al., 1978d).

It is interesting to note that the erosional topography found at the base of the Messinian in the Nile Delta does not occur in the underlying Miocene or overlying Pliocene sedimentary sequences. Indeed, as
is common elsewhere throughout the main Mediterranean Basin, the basal discordance separates the pre-Messinian Miocene from the overlying post-Messinian Pliocene sequences. On faunal evidence alone, both sequences were deposited under hemipelagic conditions, and are sometimes separated by neritic or continental deposits laid down during the Messinian salinity crisis (Ryan and Cita, 1978). There is no seismic or borehole evidence to suggest the existence of unconformities of this proportion in the Miocene and Pliocene sequences below or above the Messinian sedimentary package in the Nile Delta. This engenders submarine fan processes unlikely for the origin of the basal Messinian discordance.

On most deltaic margins where submarine fan processes occur, several interlapping discordances can be usually observed due to progressive fan lobe switching and abandonment (Normark, 1978; Walker, 1978). This is not the case in the Nile Delta. Moreover, feeder channels to submarine fan sequences are usually developed in a lower shelf to upper slope bathymetric environment, and generally will not be able to cut back a gorge deep into the cratonic hinterland such as occurred in the example of the Nile, which was entrenched to at least as far back as the Sudan (Chumakov, 1973). For this to occur, a drastic fall in Mediterranean sea level seems more likely, especially when geomorphological considerations such as the incision of a dendritic drainage pattern, entrenched meanders, and the development of an erosional surface typical of a badlands topography, as observed in the Nile Delta, are taken into account.

Messinian deposits in the Nile Delta do not geometrically conform to a submarine fan model. Seismic records do not show the characteristic
convex-upward depositional bulge typical of the submarine fan (Normark, 1978; Heritier, 1981). Except for localised sequences in the Abu Qir Bay area, there is no evidence of widespread foresetting suggestive of delta progradation into deep water such as observed in the Palaeocene of the North Sea (Parker, 1975; Rochow, 1981, Knox 1981). Well-defined prograding sequences can be clearly seen, however, in the underlying Miocene and overlying Pliocene hemipelagic sequences (seismic lines D3, D4, D39, Enc. 5) which occurred under normal marine conditions.

Lithological interpretation of electric logs does not show the overall upward-coarsening and thickening motifs characteristic of submarine fan progradation over basinal shales (Collinson 1969, Walker 1978). Both log motifs and cores indicate a marked absence of very parallel bedding with monotonous alternations of sand-shale sequences typical of lower submarine fan aprons. Also no Bouma sequences can be observed in the numerous cores.

The exception to the overall fluvially dominated sedimentary sequence in the Messinian of the Nile Delta occurs in the Abu Qir Bay area, where subaqueous debris flows (Walker, 1978) are thought to be present. This region is where the main Messinian protoNile fluvio-deltaic front prograded into a drastically lowered Mediterranean Sea, some 2.5-4.0 km below present sea level. With such extreme hypopycnal flow conditions it is not surprising that subaqueous debris flows could develop beyond the delta front. Slumping was further exacerbated by gross instability of the underlying Tortonian delta cone, due to the unwieldy overburden of thick, high-density, Messinian coarse clastics.
Turbiditic sequences are frequently noted for their intermixing of neritic and pelagic fauna (Selley, 1976). In the Messinian of the Nile Delta, there is a notable absence of deeper water fauna, unlike in both the preceding Miocene (Tortonian) and succeeding Lower Pliocene sediments. Although microfossils are by no means abundant, there is a predominance of shallow water benthic assemblages, such as Cibicides, Bolivina, and Eponides. Rizzini et al (1978) regarded these faunas as being characteristic of a restricted littoral and lagoonal environment with very little circulation.

In addition, a very sudden change in tectonic stability would be required to dramatically change the Nile Delta basinal setting from Tortonian hemipelagic prodelta shale to huge influxes of coarse clastics and occasional evaporites during the Messinian. From Late Cretaceous-Palaeocene times onward, the northern Egyptian margin has been relatively calm, tectonically speaking. Evaporitic drawdown and dessication of the Mediterranean Basin therefore remains the best model to explain the Messinian catastrophic event.
Seismic–stratigraphic integration of all seismic and borehole data in the Nile Delta allows several palaeogeographic reconstructions to be made. These models, with one or two exceptions confirm the salinity crisis model developed by Hsu et al. (1978d) (Table 1).

1. Serravalian-Tortonian prelude
Following the realignment of the proto-Nile River to its present course during the Middle Miocene, in Serravalian-Tortonian times a substantial delta had been built out into the Mediterranean Sea north of Cairo (Fig. 20). This delta system formed the morphological base onto which the Messinian subaerial erosional surface was incised. As previously stated, the Serravalian-Tortonian delta was characterised by a steep delta slope maintained by high fluvial discharge, leading to contemporaneous growth faults which later guided Messinian growth faults near the Kafr el Sheikh-1 and Sidi Salem-1 boreholes.

2. Basal Messinian initial drawdown
The onset of the Messinian salinity crisis introduced a gradual drawdown of the Eastern Mediterranean Sea to at least the levels of the pre-existing Tortonian prodelta floor (Fig. 32). There is substantial evidence to suggest that there may have been an almost complete dessication of the Eastern Mediterranean Sea at the start of the Messinian event. For example, Ryan (1978) mapped a basal discordance beneath the thick salt layer in the Eastern Mediterranean to depths of approximately 6.0 secs (two-way travel time). It is still uncertain how quickly this episode occurred, or for how long a period of time, but net Mediterranean water budget imbalances due to sporadic
Figure 32: Nile Delta palaeogeography: Basal Messinian initial drawdown of the Eastern Mediterranean Sea.
influx of Atlantic waters probably caused partial reflooding of the Mediterranean, perhaps several times shortly after the initial dessication (Cita et al. 1978; Cita 1979). As the Eastern Mediterranean sea level fell, a juvenile subaerial badlands topography began to develop on the former Tortonian delta slope, producing a linear frontal escarpment, and the proto-Nile became entrenched into a deeply-incised gorge, the Nile Canyon. Entrenched meanders developed where the proto-Nile river emerged from the confines of the Nile Canyon. The presence of both paired and unpaired rejuvenation terraces on seismic profiles suggest a constant lowering of base level with dramatic falls related to sudden change in Messinian sea level.

The basal discordance can be traced northward beneath the onlap of the Messinian sedimentary wedge, but high seismic energy absorption in the Messinian clastics does not facilitate contour mapping of the erosion surface in this region. Nevertheless, large northward-trending basal Messinian scour channels up to 15 km wide can be observed on several seismic profiles (seismic lines WDN 138, WDN 142, WDN 143 : Enc. 15).

Although Messinian sea level base was never in true equilibrium, it oscillated between approximately 2.5-4.0 km below present sea level datum. This was the level at which the Messinian proto-Nile Delta began to build out over the former Tortonian prodelta floor from the mouth of the entrenched Nile Canyon. Prior to massive progradation of the delta, a carbonate shelf environment may have existed on the flanks of the erosional surface, forming the basal high amplitude seismic zone of the Qawasim Formation. It is tentatively suggested that this may correlate with the Calcare di Base carbonates from the

3. Messinian Lower Evaporite Series equivalent

As the Messinian salinity crisis continued, rapid denudation caused disintegration of the linear erosional front, with the development of a well established dendritic and radial drainage pattern, isolating mesas and buttes as erosional remnants (Fig. 33). At the same time, the Messinian proto-Nile river began to form a substantial delta (lower part of the Qawasim Formation), eventually leading to syndepositional growth faulting due to differential loading of vertically stacked clastic units overlying incompetent Sidi Salem shales. Generally speaking, despite oscillations in Messinian sea base level, the delta prograded towards the north. Adjacent to the main high-energy fluvio-deltaic channels, fine suspended muds and silts settled within inter-distributary lagoons where carbonate-sabkha and clastic sequences developed from time to time. Intermittent flash floods washed over the fluvio-delta plain, periodically depositing alluvial fan and mud flow debris.

The Messinian sea level base was substantially depressed as recorded by non-deposition over the Rosetta-2 and Ras el Bar-1 erosional highs towards the northwest and east of the contemporary Messinian delta front. Despite a lack of faunal indicators and marker horizons, the lower part of the Qawasim Formation probably corresponds stratigraphically to the massive halites of the Lower Evaporite Series in Sicily (Decima and Wesel, 1973). The presence of a major basin-wide intra-Messinian unconformity overlying both sedimentary sequences supports this contention.
Figure 33: Nile Delta palaeogeography: Lower Evaporite Series equivalent
4. Intra-Messinian unconformity
A marked lowering of the Messinian sea level then followed. This led to regression and exposure of pre-existing Messinian sediments. Aided by possible aulacogenic movements in the Gulf of Suez and the Red Sea related to initial stages in the opening of the Gulf of Aden (Coleman 1974), the Nile Basin gently tilted on a regional scale towards the west, causing the proto-Nile Delta to be channelled westwards between the Abu Qir antithetic fault systems (Fig. 34). This, coupled with the steep basinwide drawdown in Messinian sea base level, caused normal faulting, slumping and minor subaerial erosion of the pre-existing Qawasim Formation delta plain.

5. Messinian Upper Evaporite Series equivalent
As the Messinian sea oscillated at a slightly lower base level than had previously existed, thicker fluvio-deltaic sediments of the upper part of the Qawasim Formation accumulated between the Abu Qir Bay faults (Fig. 34). This probably corresponds to the cyclically deposited salts, sands and marls of the Upper Evaporite Series on Sicily (Decima & Wesel, 1973).

6. Messinian Late Upper Evaporite Series equivalent
Subsequently, a gentle and final transgression at the close of the Messinian era caused shallow flooding of the Abu Qir channel system; and once more the proto-Nile was able to flow northward (Fig. 35). The Messinian sea, despite a rising sea level stand was still supersaturated in salts. Subaqueous gypsum (now diagenetically altered to the Rosetta Anhydrite) was precipitated in a low energy setting away from the turbid effects of submarine channels associated with the
Figure 34: Nile Delta palaeogeography: Intra-Messinian unconformity
Figure 35: Nile Delta palaeogeography: Late Upper Evaporite Series equivalent
receding delta front. As the Eastern Mediterranean Sea gradually deepened due to the freshwater influx from Paratethys (Cita et al., 1978; Hsu & Glovanoli, 1979), the Rosetta Anhydrite gave way to the brackish water "Lago Mare" facies of the Abu Madi Formation, heralding a change from mesohaline to oligohaline conditions. As the transgression progressed, normal marine conditions became re-established by the beginning of the Pliocene with the introduction of the deep water prodelta shales of the Kafr el Sheikh Formation.

7. Summary of events in the Messinian Nile Delta

From the ensuing palaeogeographic reconstructions at least seven stages of evolution can be recognised in the Messinian of the Nile Delta.

(i) Initial dessication of the Eastern Mediterranean Sea by evaporitic drawdown to at least the levels of the former Tortonian prodelta floor, with synchronous development of the Nile Canyon and possible isolated carbonate-evaporite shelf deposition (basal Qawasim Formation) on the flanks of the ensuing erosional surface.

(ii) Concommitant development of an extensive fluvial plain (Lower Qawasim Formation) with substantial modification throughout the Messinian by periodic oscillations in sea level, causing alternate downcutting and aggradation by fluvio-deltaic processes. Severe subaerial erosion and initiation of an extensive drainage network on the former Tortonian delta slope.

(iii) Large syndepositional, antithetic, east-west growth fault movements, especially in the Abu Qir Bay area.
(iv) Gentle westward epicontinental tilting of the Nile Delta region causing channelling of the proto-Nile fluvio-deltaic system between confining Abu Qir faults. This occurred synchronously with a major fall in Messinian sea base level (intra-Messinian unconformity and upper part of the Qawasim Formation).

(v) Final Messinian sea level rise causing shallow flooding of fluvio-deltaic channels, formation of open lagoons and precipitation of subaqueous gypsum (Rosetta Anhydrite).

(vi) Continuing rise in sea level caused by Paratethyan freshwater influx and replacement of evaporitic conditions by "Lago Mare" facies (Abu Madi Formation).

(vii) Basal Pliocene transgression and return to normal marine conditions.
1. Regional correlations

Several sub-basins (i.e. Sicily and Antalya) and peripheral margins (i.e. : Israel coast) contain sedimentary sequences that genetically form part of the main Eastern Mediterranean evaporite basin (Fig. 36).

They contain for the most part, calcareous and evaporitic sediments which persisted in the basinal environs away from sources of clastic supply such as the proto-Nile River and the peri-Adriatic orogenic belt. Nevertheless, despite the lack of faunal indicators and a
predominance of fluvio-deltaic facies, the Messinian of the Nile Delta can be correlated with carbonate-evaporite sequences of the same age in Sicily, the Messina Abyssal Plain (DSDP 374) and the Israel margin (Fig. 37), especially since all four localities are part of the overall Eastern Mediterranean Basin. In particular, as already mentioned (p.41), Sicily is a key type section for the Messinian stage and therefore forms the standard for any correlation work. Unfortunately, none of the DSDP boreholes in the Eastern Mediterranean reached the Main Salt horizon restricting correlation to the topmost Messinian levels.
The correlation of the Messinian deposits along the Israel coast and margin is of special interest because they are found in a similar geomorphological setting to the Nile Delta.

According to Gvirtman and Buchbinder (1978), the basal Messinian erosion surface can be traced from 518 m above sea level in the coastal foothills to nearly 2300 m subsea on the continental shelf. The erosion surface has the characteristics of a dessicated topography (Fig. 38), similar to that found in the Nile Delta, and truncates Cretaceous and older Cenozoic rocks. The overlying Messinian sedimentary sequence is composed of the Mavqiim and Afiq Formations, and varies in thickness from a few metres to 250 m. The basal Mavqiim Formation contains nodular anhydrite and algal stomatolites which are attributed to a sabkha environment, evolving on the flanks of a rapidly dessicating basin. The anhydrites were diachronously overlain by halite precipitates infilling the thalwegs of the erosion surface formed during the initial dessication of the Eastern Mediterranean Sea. Both the anhydrite and halite units can be correlated with the Cattolica Gypsum Beds and the Main Salt sequences respectively which outcrop on Sicily (Fig. 37).

Although not mentioned by Gvirtzman and Buchbinder (1978), the intra-Messinian unconformity documented throughout the Eastern Mediterranean must have effected the Israel margin. It is suggested that the unconformity occurs just prior to the final anhydrite sequence of the Mavqiim Formation (Fig. 39). The reason for this is based by analogy with the Rosetta Formation of the Nile Delta. In both the latter area and offshore Israel, uppermost Messinian anhydrites and inter-bedded
Figure 38: Location and trace of seismic profile, offshore Israel (from Gvirtzman and Buchbinder, 1978)
Figure 39: Representative Messinian sequence from Ashqelon-4 well offshore Israel (from Gvirtzman and Buchbinder, 1978)
marls are recorded seismically by a strong double amplitude reflector which occurs on a basinwide scale (Fig. 38). The upper Mavqim anhydrites forms a characteristic veneer on the erosional surface, on both the interfluves and canyon floors and is thus indicative of a subaqueous origin. Moreover, the overlying non-evaporitic Afiq Formation is probably a deltaic sequence, restricted to the channel thalwegs, and contains freshwater ostracods (Neev, 1979) which populated the "Lago Mare" sea toward the end of Messinian time. Therefore the Afiq Formation is the lateral equivalent of the Abu Madi Sands in the Nile Delta (Fig. 37).

In general, three distinct basinwide phases can be recognised within the Messinian sediments of the Eastern Mediterranean:

(i) increasing salinity leading to carbonate-evaporite deposition followed by precipitation of the Lower Evaporite Series including the Main Salt sequence;

(ii) the intra-Messinian unconformity followed by cyclic deposition of the Upper Evaporite Series; and

(iii) a post-evaporitic phase characterised by brackish and freshwater deposits of the "Lago Mare" Sea.

The Lower Evaporitic Series phase therefore comprises the lower part of the Qawasim Formation in the Nile Delta, with postulated carbonates in the basal high velocity zone being the lateral equivalent of the Cattolica Gypsum of Sicily and the basal nodular anhydrite of the Mavqiim Formation of Israel. The remainder of the Lower Qawasim Formation can be equated to the Main Salt deposits of the Lower Evaporite Series.
The second phase is heralded by the intra-Messinian unconformity which subdivides the Qawasim Formation into its lower and upper members. No evidence in the Eastern Mediterranean exists to suggest the presence of recycled salts (Upper Main Salt: Table 1) related to this unconformity as proposed by Hsu et al. (1978a). Whilst recycled salts may occur in the basinal deeps, their existence has not been confirmed in boreholes nor observed on seismic profiles. Indeed, the Upper Main Salt may be a phenomena peculiar to the Western Mediterranean evaporite basin alone and as such, has been documented on seismic records in this region by Montadert and his coworkers (1978). The Upper Evaporite Series constitute the return of evaporitic conditions to the Eastern Mediterranean basin after the Intra-Messinian Unconformity, and is represented in the Nile Delta by the Upper Qawasim Formation. On the elevated Israel margins it is probably absent due to non-deposition. The final vestiges of evaporitic sedimentation occurs with the subaqueous precipitation of the Rosetta Anhydrites in the Nile, the uppermost Mavqiim anhydrites in Israel, and the gypsum-mudstone cycles noted in Cores 16-20 at the bottom of DSDP Site 374 in the Messina Abyssal Plain (Garrison et al., 1978; Fig. 37).

The third phase, the "Lago Mare" Sea episode, is manifested by the presence of deltaic sands in both the Nile Delta (Abu Madi Formation) and the Israeli margin (Afiq Formation) containing brackish water ostracods. In the uppermost Messinian sequences cored in the basinal deeps at DSDP Sites 374, 375 and 376 occur dolomitic marls interbedded with very thin distal turbiditic arenites. These were deposited in an oligohaline, deep, standing body of water (Hsu et al., 1978d) and were probably derived from turbidity currents originating from unrestricted
Nile River waters, as normal marine conditions returned to the Eastern Mediterranean basin.

The Nile Delta Messinian section cannot, however, be readily correlated with various tectonically isolated sub-basins of the Eastern Mediterranean such as are found in the Aegean Sea and on Cyprus. These areas were already a series of sub-basins prior to the Messinian salinity crisis and each evolved its own desiccation history (Hsu et al., 1978d). Consequently, there is insufficient resolution between each sub-basin in these areas due to a profound facies variation. Correlations are impossible without detailed biostratigraphic zonation of the Messinian which is in turn hampered by lack of diagnostic fauna and species. On Cyprus, for example, there are lateral changes from basinal to marginal evaporites and reefal elements indicating that deposition occurred in a number of different environments and tectonic settings at the same time (Pantazis, 1978; Baroz et al., 1978).

Some correlation may be possible however, between the main Eastern Mediterranean Basin and both the Piedmont and Po Valley of Italy, and of course by inference, the Nile Delta. Sturani (1978) subdivided the Messinian of the Piedmont Basin into three episodes, which may be compared to the three phases described for the main Eastern Mediterranean basin:

(i) a pre-evaporitic clastic phase in which the sea progressively increased in salinity;
(ii) a minor evaporitic phase leading to some restrictions in areal extent of the basin. No major evaporitic drawdown and dessication effects are noted, as occurred in the Eastern Mediterranean;

(iii) a post-evaporitic phase with alluvial, marsh, and lacustral facies deposited during "Lago Mare" conditions.

A similar succession of events has been described in the Po Valley by Rizzini and Dondi (1979). Whilst the Po Valley and the Piedmont do show indications of dessication and occasional evaporites, they have a sedimentary history more in common with the Paratethys Basins than the main Eastern Mediterranean Basin due to overwhelming freshwater influences (Rizzini and Dondi, 1979). It is possible that, in addition, a tectonic sill may have separated the Eastern Mediterranean from the peri-Adriatic basins, allowing freshwater influxes to maintain a substantial body of water for longer periods of time.

It seems, however, that there is one episode of the Messinian salinity crisis which all major basins and sub-basins of the Eastern Mediterranean region have in common. This is the final post-evaporitic stage during which the "Lago Mare" developed, flooding the pre-existing palaeogeography of each individual isolated evaporite basin. For example, marls and silts from the "Lago Mare" of the main Eastern Mediterranean Basin (DSDP sites 129A, 375, 376) are strikingly similar to those of the same age found in the peri-Adriatic region, where they occur as olive-grey marls overlying the topmost evaporitic sequences (Cita et al., 1978).
2. Geodynamic considerations

Despite general acceptance of a repeated evaporitic drawdown and dissection model for the evolution of the Messinian evaporites (Ryan and Cita, 1978; Hsu et al., 1978d) there is not total agreement that such a model is valid. Currently, there are two schools of thought implying either an eustatic or isostatic model of origin.

The eustatic model (Hsu et al., 1978) implies relative tectonic stability of the Mediterranean basins during Messinian times to allow repeated dessication and infilling of marine water. Hsu and his coworkers (1978) calculated that the total volume of over one million cubic km of Messinian evaporite would have been precipitated from a volume of sea water estimated to be 30 times that contained in the present day basin. This model does not call for contemporaneous sinking of the basin floor since space for the thick sequences of evaporites would have been provided by the pre-existing deep basin.

The isostatic model (Drooger, 1975; Fabricius et al., 1978; Gvirtzman & Buchbinder, 1978) suggests, on the other hand, that the Mediterranean Basins were relatively shallow prior to the Messinian salinity crisis. Thick sequences of evaporites were able to accumulate by continual subsidence of the basin floor. Within this shallow basinal setting Fabricius and his coworkers (1978) have suggested that the influx of brines from the Atlantic was never completely terminated. They postulate that distribution of the Messinian evaporites can be explained by Schumtz's (1970) tear-drop model of evaporite precipitation. Rapid post-Messinian foundering during the Pliocene-Quaternary
would have then occurred, submerging the Messinian sequences beneath the abyssal plains of the Mediterranean basin floor.

Geodynamically, the evolution of the proto-Nile Delta during the Messinian salinity crisis confirms the eustatic model proposed by Hsu et al. (1978).

The erosional discordance at the base of the Messinian in the Nile Delta can be traced northwards on seismic profiles to depths of 2.5 to 3.0 km before any major Pliocene faulting is observed. As demonstrated on diagrammatic cross sections (Enc. 1), much of this faulting originated during Messinian time, and has continued to the present day in response to isostatic loading of Pliocene overburden. The same unconformity extends northwards beneath the Nile Cone to depths of 3.0 and 5.0 sec two-way time (Ross & Uchupi, 1977; Ryan, 1978). The dessication of the Mediterranean by evaporitic drawdown can be demonstrated by the existence of the Nile Canyon over 2.5 km deep, cut by the proto-Nile fluvial channel, and by the development of dendritic and trellis drainage systems on the former Tortonian delta slope. A gradual drop in Messinian sea base level with occasional rapid falls and quiescent episodes is implied by the presence of both rejuvenation terraces on the flanks of the lower Nile Canyons, and raised strandline platforms left behind by the northward receding shoreline. While the Messinian sea base level may have initially dropped to below 5.0 sec (two-way travel time), the average base level probably oscillated at between 3-4 km below present. This contention is supported by the great thickness (2000 m +) of fluvial-deltaic sediments and minor evaporites within Messinian sediments, sandwiched between deep water
Late Miocene (Tortonian) and Lower Pliocene prodelta shales at this stratigraphic level.

There is therefore no evidence to support the hypothesis that the Eastern Mediterranean hosted a shelf-sea before it floundered in the Pliocene-Quaternary (Gvirtman & Buchbinder, 1978). As stated by Hsu et al. (1978) there is even less evidence for the corollary hypothesis by the same authors that the African and Arabian platforms were elevated thousands of metres above global sea level to account for deep erosion of the Nile and other rivers draining into the dessicated Eastern Mediterranean basin.

Reiteration of proof for large scale drawdown in the Mediterranean area is indicated by incision of the subaerial drainage system around the entire Mediterranean Basin (Clauzon, 1979; Rizzini & Dondi, 1979; Ryan & Cita, 1978); by shallow water terrigeneously-derived facies patterns (Rizzini & Dondi, 1979); and by deposition of shallow water stromatolites, sabkha and shallow-water subaqueous evaporites in the basinal deeps (Wright & Cita, 1979). In addition, cyclic bulls-eye zoning of evaporites in the Upper Evaporite series of the Eastern Mediterranean (Hsu et al., 1978b) emphatically refutes the postulated tear-drop model proposed by Fabricius et al. (1978).

Finally, it is worth mentioning that the initiation of the Messinian salinity crisis was caused by tectonic closure of the marine strait between Iberia and North Africa, and not by glacio-eustatic changes in sea level. As explained by Cita and Ryan (1979) it was rather the opposite: the salinity crisis was probably the cause, not the effect of the Late Miocene glacial expansion in Antarctica due to lowering of
the world ocean salinity by 6%. This decrease in salinity had far-reaching climatic repercussions such as raising the freezing point of sea water, allowing expansion of the ice caps, increasing the albedo effect, culminating in climatic deterioration (Ryan et al., 1974). The resultant glacio-eustatic rises and falls (50m) would be a mechanism by which the Mediterranean could be periodically isolated from Atlantic waters (Ryan, 1973). The extent of intra-Messinian drawdown would have been a function of local hydrological regimes. For example, a continual influx of freshwater via the proto-Nile River with headwaters as far back as East Africa would account for the reason why the Eastern Mediterranean may not have been completely dessicated for long periods, unlike its western counterpart.
The uppermost seismic-stratigraphic unit recognised in the subsurface of the Nile Delta is the Pliocene to Holocene sedimentary sequence. It is defined at its base by the Horizon "M" marker unit. In the southern delta area, the basal Pliocene rests unconformably on the Messinian subaerial erosion surface. Basinward, the basal Pliocene is not easily recognised, since Horizon "M" corresponds to the top of the Rosetta Anhydrite, and not the true Mio-Pliocene boundary which lies at the top of the Abu Madi Formation. It is, however, extremely difficult on seismic profiles to distinguish the gradational contact between the Abu Madi and the overlying Lower Pliocene Kafr el Sheikh Formations. Hence, for practical purposes in seismic mapping, the Pliocene-Recent unit does indeed include the uppermost Messinian Abu Madi Formation which is only approximately 50 m in maximum thickness.

The approximate thickness of the Pliocene-Recent seismic-stratigraphic unit can be determined by converting the time-contour map of the Top Messinian (Rosetta Anhydrite : Enc. 19) into a depth-contour map (Enc. 20) incorporating an average velocity gradient map for the Pliocene-Recent section (Enc. 21). Velocity values range from 1800-2400 m/sec. with average depths ranging from 2000-3000 metres.

With increased overburden throughout the Pliocene-Recent, continued growth faulting occurred along the Abu Qir antithetic fault system (Enc. 14) and other Messinian faults. The Cretaceous hinge line had presumably become dormant, as no evidence can be observed for upward perpetuation of this fault zone into the Pliocene and younger section.
A new fault pattern trending NE-SW can be traced throughout the northern delta area (Enc. 20) and may even cut the earlier Messinian growth faults. A fault interference zone can be observed just off-shore near the Rosetta Branch of the Nile River, where a major NE-SW fault merges into the E-W trending Abu Qir antithetic fault system. These NE-SW faults may indeed be wrench faults related to Neev's (1977) Pelusium Line. They do show some evidence for strike-slip motion, particularly as a number of very gentle anticlines or swells of Pliocene-Recent age can be seen in close proximity to the fault traces and could therefore be of a wrench-induced origin. Rosetta-2 was drilled on such a feature. The lack of a dense seismic control prohibits further analysis beyond this speculative suggestion.

As defined by Rizzini et al. (1978) the Pliocene to Recent sedimentary sequence can be subdivided into four formational divisions as follows:

- Holocene: Bilqas Formation
- Late Plio-Pleistocene: Mit Ghamr Formation
- Late Pliocene: El Wastani Formation
- Early-Middle Pliocene: Kafr el Sheikh Formation

These divisions document the infilling of the Messinian erosional terrain and subsequent progradation of the Nile Delta to its present day configuration. On many seismic lines in the delta province, progradation of the Nile Delta did not begin in earnest until well into the Middle Pliocene stage (Enc. 8). There is evidence of delayed progradation, since the Lower Pliocene (Lower Kafr el Sheikh Formation) sequence infills the dessicated Messinian surface (Encs. 5 & 8) in a horizontal fashion.
This can be attributed to Messinian over-incision of the Nile River into its channel as far back as the Sudan (Chumakov, 1973). With the subsequent drowning of the Messinian Nile Valley, volumetrically significant out-building of the Nile Delta could not be expected to continue until the valley had been filled in. Thus, there was sedimentary onlap infill within the Nile Delta region until equilibrium was restored by delta front progradation, once the Nile Valley had been restored to its former grade. This is probably also a function of a rapidly increasing discharge and corresponding bedload capacity in the Nile River. Zaghloul and his coworkers (1980) noticed an upward increase in unstable minerals (epidote, amphibole and pyroxene) within the Kafr el Sheikh Formation. They concluded that these minerals were derived from basement rocks of the Eastern Desert which were being uplifted and denuded in response to continual rifting along the Red Sea margins. The Nile not only captured river systems in the Eastern Desert, but by Pleistocene time had captured Abyssinian tributaries. This is suggested by the occurrence in the Mit Ghamr and Bilqas Formations of pollen from Podocarpus trees which grew in the Ethiopian Highlands at a height of 3200 m (op. cit.).

The Kafr el Sheikh, Wastani and Mit Ghamr Formations are, in reality, different facies within the overall Plio-Pleistocene progradational sequence, and are in this sense, diachronous. Prodelta facies are represented by the upper part of the Kafr el Sheikh Formation; delta front facies by the El Wastani Formation; and delta plain facies by the Mit Ghamr Formation. The Holocene Bilqas Formation is merely a facies continuation of the underlying Mit Ghamr Formation, having been separated from the latter by a small unconformity which was caused by
a Pleistocene glacio-eustatic sea level change. The overall shape of the Pliocene progradational sequence observed on seismic traces (i.e. seismic lines D3 & D39 : Enc. 5) is a combination of oblique and sigmoidal configurations. This indicates an increasing sediment supply over basinal subsidence allowing upbuilding and later depositional bypass of topset units over obliquely bedded offlap units.

Except for a Recent sedimentary veneer, the Plio-Quaternary sediments of the Nile Delta only occur in the subsurface, and as such have only been recognised as a consequence of petroleum exploratory drilling:

1. Kafr el Sheikh Formation

The type section is found in the Kafr el Sheikh-1 well from -1269 to -2727 m (Rizzini et al., 1978). The base is indicated by the presence of the ubiquitous Sphaeroidinellopsis sp. zone. This formation is largely composed of soft clays, siltstone and shales with occasional sandy interbeds which are probably turbiditic in origin. In the lower part of the formation, clastics deposited in a postulated submarine suprafan lobe environment have been cored in the Qawasim-1 well (Qawasim-1, Core 2 : Appendix IV). In the southern delta area, the Kafr el Sheikh Formation infills the Messinian erosional topography, whilst to the north it is gradational upward from the sands of the Abu Madi Formation. Evidence for the Lower Pliocene flooding of the Mediterranean Sea by normal marine waters is indicated by a rapid change from a benthic oligotypic fauna in the Abu Madi Formation to an outer shelf-slope neritic fauna in the lower Kafr el Sheikh Formation.

Particularly in the deeper east and northeastern delta province, the basal units of the Kafr el Sheikh Formation progressively onlap over
the erosional surface towards the east, indicating that westward tilting of the delta region occurred during Late Messinian time (seismic lines WDN 143, WDN 145 : Enc. 15). Indeed, westward tilting probably continued along the Israel continental margin throughout Pliocene time (Neve, 1977; Gvirtzman & Buchbinder, 1978) and may be indicative of a wider tectonic event related to isostatic subsidence of the Eastern Mediterranean crust.

The upper part of the Kafr el Sheikh Formation is indicated by the lowermost offlap and downlap prograding sequences on seismic profiles (Enc. 8).

2. El Wastani Formation
The type section is found in the El Wastani-1 well from -1004 to -1127 m (Rizzini et al., 1978). It is composed of alternating sands and shales with an upward increasing sand content as prodelta shales of the Kafr el Sheikh Formation were succeeded by delta front sands of the El Wastani Formation. The latter forms the uppermost offlap and toplap sequences on the prograding seismic sequences (Enc. 8).

3. Mit Ghamr and Bilqas Formations
These form the seismic toplap sequences noted in the Pliocene of the Nile Delta. The type section is from the Mit Ghamr-1 well between -20 and -483 m (Rizzini et al. (1978). It consists of thick fluvial sands and gravels with clay interbeds towards the base. It is gradational into the underlying El Wastani Formation. Lagoonal deposits originated from time to time as indicated by the presence of coquina and bivalve fragments.
The overlying Bilqas Formation type section occurs from 0-25 m in the Bilqas-1 well and consists of a medium-fine grained moderately well sorted sand. It is probably restricted to the outer margins of the Nile Delta, being the last stage of deltaic progradation prior to the present day. Occasional peat horizons ascertain to brackish lagoonal episodes which presumably developed behind a barrier complex. These dunes probably formed as a consequence of the Pleistocene glacio-eustatic sea-level fall. As sea level rose afterwards, the ensuing marine ingression reworked the pre-existing delta front into an arcuate beach barrier system which still exists today (El Shazly et al., 1975).
The Cenozoic history of the Nile Delta is not a simple vista of deltaic progradation over a subsiding continental margin. The location of the Nile River along the northeastern margin of the African continent engenders a unique evolution, both from a tectonic and sedimentological viewpoint. The Nile Delta lies at a crossroads, where the African and Arabian plates meet, and where the aulocogenic trends of the Gulf of Suez intersect the Eastern Mediterranean, which itself has an active orogenic northern margin.

The history of the Nile Delta region is therefore a function of both compressional and extensional tectonic events, related to the gradual closure and subsidence of the Eastern Mediterranean Basin between the converging African and Eurasian landmasses.

The main compressional event in the Nile Delta region was the Syrian Arc orogenic episode which occurred at Mesozoic-Cenozoic boundary time. This coincided with the period of overthrusting and large nappé development along the northern margin of the Eastern Mediterranean Basin especially in Turkey and Cyprus (Biju-Duval et al., 1978). Only mild folding occurred in the Nile Delta, creating gentle ENE-WSW trending ridges and troughs, that were later transgressed by shallow carbonate seas during the Lower Eocene. It was not until Oligocene times that the peneplained remnant high axes were finally submerged and covered by terrigeneous sediments.

The embryo Nile Delta, per se, began to form in the southern Western Desert during Middle Eocene times, coinciding with both a combined
isostatic gradual uplift of the African continent and a renewed subsidence of the Eastern Mediterranean sea floor. These extensional processes are still not understood, but are probably related to pre-rift (Red Sea) doming of African continental crust, attenuated by lithospheric cooling and post-orogenic subsidence of the Eastern Mediterranean floor.

The origin of the proto-Nile Delta is a product of tectonic processes rather than by sedimentary loading of the lithosphere. As shown by Watts and Ryan (1976), an initial oceanic realm at least 5 km deep is required before subsequent sedimentary overburden can generate crustal subsidence by loading alone. This is contrary to palaeogeographic modelling of the proto-Nile Delta which was essentially covered by shallow seas until early Miocene time. Since this period, however, it seems that proto-Nile Delta sediments infilling the depression caused by the driving tectonic mechanism responsible for subsidence of the Eastern Mediterranean floor, may indeed have contributed to further local subsidence. This is demonstrated by antithetic faulting in the Abu Qir Bay area during the Late Miocene (Messinian) with further renewed subsidence in the succeeding Pliocene-Quaternary. Quantitive estimates of the degree of crustal subsidence in the Nile Delta cannot be resolved until deep seismic refraction work is done in the area to determine the nature and depth to basement.

Extensional tectonics played a dominant role in the construction of the proto-Nile Delta, not only in changing the course of the Nile to its present position from its predecessor in the Western Desert, but also by rapid subsidence of the northern Egyptian margin during Miocene-Pliocene times. This allowed a large delta to accumulate
north of Cairo. Successive phases of deltaic development of the
proto-Nile are illustrated on Figure 40 which demonstrates the gradual
increase in volume of the water carried by the proto-Nile River,
especially from the mid-Miocene onwards, as the Nile captured addi-
tional tributaries. Zaghloul et al., (1980) noted a gradual vertical
change in sediments relatively rich in stable minerals to younger
sediments (Pliocene-Recent) containing abundant unstable minerals. Most
likely this was caused by progressive denudation and unroofing of
tectonically active provinces containing igneous and metamorphic rocks
such as occur in the Eastern Desert and the Ethiopian Highlands.
Older sediments (Miocene and Pre-Miocene) contain a predominance of
stable minerals implying reworking of locally derived Palaeozoic and
Mesozoic sedimentary rocks.

The only reversal to the gradual progradational offlap of the proto-
Nile Delta occurred with the evaporitic drawdown and subsequent
dessication of the Eastern Mediterranean basin during the Late Miocene
(Messinian) salinity crisis. Evidence for the fall in Messinian sea
base level to depths of at least 2.5-4 km below present is confirmed
by detailed seismic mapping of the ensuing erosion surface in the Nile
Delta region.

The basal Messinian unconformity, determined by seismic analysis and
borehole correlation, extends from almost sea level in the southern
delta area to depths of at least 5 km in the Nile Cone. Over
1000-2000 m of fluvio-deltaic clastics were deposited at the foot of
the pre-existing Tortonian delta slope. These clastics prograded into
a restricted carbonate-evaporitic environment which was common over
most of the dessicated Eastern Mediterranean Basin at this time.
Figure 40: Successive stages in the development of the proto-Nile Delta
Gradual initial drawdown of the Mediterranean Sea with occasional sudden sporadic falls, is implied by the presence of entrenched meanders and impaired rejuvenation terraces in the Nile Canyon, formed as the proto-Nile River cut down into the pre-existing Tortonian delta complex. The former Tortonian delta slope became an extensive linear erosional front with over 3 km of vertical relief, the uppermost levels of which were protected by tabular Oligocene basalt flows, preserved as mesas and buttes. The lower slopes were the site of coalescing piedmont fans fed by upper slope wadi systems. The piedmonts merged into the Qawasim fluvio-deltaic deposits of the proto-Nile fluvial flood plain.

The subcrop beneath the basal Messinian unconformity reveals a remarkable diversity of rock type, each with its own distinctive control on the geomorphology and geometry of the ensuing Messinian erosional surface. Fracture patterns within the Oligocene basalts produced a trellis drainage network which became later captured by a dendritic system developed on less resistant prodelta shales of the former Tortonian delta slope. Close study of seismic profiles clearly demonstrates that the basal Messinian erosional disconformity can be traced northward to depths of at least 2.5-3.0 km before becoming affected by later Pliocene faulting.

Very rapid sedimentation rates by the Messinian proto-Nile delta (1.82 cm/year) are indicated by an extremely wide range of lithofacies types, varying from poorly-sorted braided-stream conglomerates, through meander point-bar sequences to distributary mouth-bar sands, and finally subaqueous debris flows beyond the delta front. By
seismic-stratigraphic facies analysis, the Messinian of the Nile Delta can be divided into three major units: the Qawasim, Rosetta and Abu Madi Formations, which broadly represent three basinwide phases of sedimentological evolution. These are respectively:

(i) a fluvio-deltaic phase characterised by a restricted marine environment, later followed by persistent evaporitic conditions in the deeper Eastern Mediterranean basin;

(ii) an evaporitic phase with deposition of subaqueous gypsum;

and

(iii) a post-evaporitic phase characterised by brackish and freshwater conditions known as the "Lago Mare" episode.

This study therefore strongly supports a deep dessication model for the origin of the Messinian evaporites in the Eastern Mediterranean Basin.
1. Apart from the marked absence of the Palaeocene, there is an almost complete Cenozoic succession in the Nile Delta. The lack of Palaeocene rocks is attributed to non-deposition. This was caused by gentle uplift and emergence of the entire region during the Syrian Arc epeirogenic episode at the end of the Cretaceous period.

2. Basal Cenozoic sediments are composed of Early and Middle Eocene calcareous rocks which were deposited in shallow elongate synclinoriums, trending ENE-WSW, parallel to the Syrian Arc orogenic grain.

3. Rapid subsidence began during the Late Eocene coinciding with a change from calcareous to terrigeneous sedimentation.

4. The embryo Nile Delta originated in the southern Western Desert during the Middle Eocene. It shifted to its present position, north of Cairo, in response to diversion of the main Nile River channel along Middle Miocene faults parallel to the Red Sea Rift. Much of the sedimentary infill beneath the present delta is therefore composed of Middle Miocene and younger rocks.

5. The overall offlap nature of the Late Eocene to Holocene terrigeneous sequence is interrupted by two hiata. The first affected only the upper reaches of the delta and was caused by an Oligocene extrusive fissure eruption. The second and most pronounced is believed to have been caused by Late Miocene (Messinian)
subaerial erosion of the proto-Nile Delta as a consequence of evaporitic drawdown and dessication of the Mediterranean Sea (Messinian salinity crisis).

6. The concept of evaporitic drawdown and dessication of the Mediterranean is supported by the existence of erosional surfaces, fluvio-deltaic facies and interbedded evaporites in the Nile Delta.

7. The basal Messinian unconformity extends from sea level in the southern delta area to at least 5 km in the Nile Cone. The erosion surface is characterized by superimposed trellis and dendritic drainage patterns, and also by the 2.5 km deep Nile Canyon, cut by the proto-Nile fluvial channel. At the base of the former Tortonian delta slope, some 2.5 - 4.0 km below present sea level occurs the onlap of contemporaneously deposited fluvio-deltaic sediments.

8. The catastrophic nature of the Messinian salinity crisis can be observed in the Nile Delta by the abrupt change from Tortonian hemipelagic shale to Messinian continental and neritic deposits. A similar change occurs in reverse from the Messinian into the overlying Pliocene section.

9. The Messinian sequence of the Nile Delta can be divided into fluvio-deltaic, evaporitic and post-evaporitic brackish water facies. These correspond to three basin wide phases within the Messinian of the Eastern Mediterranean, which are the Lower
Evaporite, Upper Evaporite and the 'Lago Mare' stages respectively.

10. Alternative mechanisms such as submarine fan processes for the origin of the Messinian erosion surface and related sediments appear to be unsubstantiated. In addition to the existence of shallow benthic fauna in the Messinian sedimentary sequence, slope topography and depositional geometry are not characteristic of the submarine fan model.

11. The implications of the Messinian salinity crisis are far reaching. While dessication and related sedimentological affects can be perhaps documented during the initial stages of ocean basin evolution, continual seafloor spreading and uninhibited ocean circulation generally prohibit such events from re-occurring on well-established passive margins of the Atlantic type. In the latter, evaporites and interrelated carbonate sequences are commonly found at the base of thick fluvio-deltaic clastic wedges marking active progradation of the continental shelf. The Nile Delta, however, is unique in that unlike most other mature passive-margin deltas of the world, it was affected by profound dessication late in its history. This was a consequence of its singular position on the southern flank of the progressively closing Mediterranean basin, ultimately leading to the Messinian salinity crisis.

Hsu's (1973) hypothesis of the Messinian salinity crisis by which a whole ocean basin could be dessicated to several kilometres below global sea level cannot be observed in the world today. It is there-
fore in conflict with Lyell's Principle of Uniformitarianism, which states that the present is the key to the past.

Certain phenomena which have not been observed by man in his short history could indeed have happened. Although the geological processes may be always present, their effects both in magnitude and in frequency, may not be constant throughout geologic time. Indeed, in a sense, the present is the window through which one can see the past or future, as well as the present itself. But unless one is able to separate oneself from one's perception of the present, one will be unable to escape beyond the bounds of uniformitarianism and see that the past can also be the key to both the present and the future.


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APPENDIX I

Palaeogeographic evolution of the Proto-Nile delta during the Messinian salinity crisis

P.M. BARBER *

ABSTRACT

A resumed of the effects of the Messinian salinity crisis in the Nile Delta region is presented from detailed borehole and seismic facies analysis. The evidence for the development of an extensive subaerial drainage system is outlined and supported by the presence of related syndepositional fluvio-deltaic sediments deposited from the entrenched proto-Nile river. Seismic-stratigraphic interpretation suggests that at least 7 evolutionary events can be recognized during the Messinian which confirms a dessicated deep basin model for the origin of the Messinian evaporites in the Mediterranean.

RESUME

Les influences de la crise de salinité messinienne sur le delta du Nil sont présentées à partir des données détaillées de sondages et des faciès sismiques. Le développement extensif d'un réseau hydrographique sub-aérien est mis en évidence par la présence simultanée de sédiments fluvio-deltaïques arrivant par la vallée surcreusée du proto-Nil. L'interprétation sismique et stratigraphique suggère l'existence de sept événements successifs pendant la période messinienne, ceci confirme le modèle de bassin profond desséché pour l'origine des evaporites messiniennes dans le bassin méditerranéen.

Interpretation of over 8 000 kms of seismic reflection profiles with sub-surface control from 32 boreholes (Fig. 1) has resulted in a tentative synopsis for the Messinian evolution of the proto-Nile Delta. By Tortonian times, the proto-Nile had established a substantial delta complex along the northeastern Egyptian epicontinental margin which suffered severe subaerial erosion during the Messinian salinity crisis. Seismic records clearly illustrate the development of an extensive northward-trending incised drainage system. This system is unconformably overlain by basal Pliocene prodelta shale as defined by the presence of the *Sphaeroidinellopsis* Acme-zone M PL 1 (Cita 1975 ; Ryan 1978). As described by Ryan (1978), this unconformity, designated as Horizon 'M' on seismic profiles, represents subaerial denudation of the Eastern Mediterranean margins by evaporitic drawdown and subsequent dessication of the Mediterranean Sea.

Fig. 1. – Nile Delta and environs ; index map showing surface geology, boreholes used in study and trace of sections discussed in text.

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Egypte, Delta Nil, Messiniens, Paléogéographie, Géophysique.
Beyond the onlap of Messinian sediments in the upper levels of the Nile Delta cone, Horizon 'M' is characterised by a very distinctive high amplitude double reflector on seismic traces. By correlation with borehole data in the northern Nile Delta region and from studies of the Levant margin by Gvirtzman and Buchbinder (1978), this reflector corresponds to a series of widespread continuous anhydrite bands ranging from 4 to 50 metres thick which are close to the top of the Messinian sedimentary sequence.

The onset of the Messinian salinity crisis introduced a 3-4 km gradual drawdown of the Eastern Mediterranean to at least the level of the pre-existing Tortonian prodelta floor (Ross and Uchupi 1977; Ryan 1978). Concomitant with this drawdown, the proto-Nile fluvial channel became entrenched, forming a canyon 40 km deep and over 12 km wide at its narrowest point near Cairo. 60 km further to the north, the canyon widens and impaired river terraces become common (Fig. 2). Due to a greatly increased bedload and accelerated denudation rates during Messinian times, the proto-Nile deposited over 1500 metres of sediments at the foot of the former Tortonian delta slope. This slope formed an extensive linear erosional front with over 3 kms of vertical relief. Further up the slope, tabular Oligocene basalt flows were cut into by a dendritic pattern of wadi channels and preserved as mesas and buttes. These channels coalesced into piedmont fans and prograded onto the salinas and braided stream deposits of the fluvial plain (Fig. 3).

Detailed borehole studies demonstrate that the Messinian proto-Nile sediments are predominantly fluvio-deltaic in origin. Very rapid sedimentation rates are indicated by an extremely wide range of lithofacies types varying from poorly-sorted braided stream conglomerates, through meander belt point-bar sequences, to distributary-mouth bar sands typical of the delta front. The main depositional feature appears to have
been a highly lobate to elongate, fluvially-dominated delta system over the Tortonian pro-delta floor. Discordances on seismic profiles within intervals in the Messinian fluvio-deltaic section indicate periodic oscillations in Messinian sea base level which caused alternate minor transgressions and regressions of the Messinian palaeo-shoreline. Away from the high energy effects of local deltaic deposition, fine suspended muds and silts settled within interdistributary lagoons, where sabkha-clastic cycles were developed from time to time.

During the latter half of the Messinian, instability due to differential loading of the vertically stacked clastic units (sometimes up to 80 metres thick) caused large growth faults to develop, particularly in the offshore delta near the present day Abu Qir Bay (Fig. 3 and 4).

Just above the basal Messinian discordance which was formed during the first initial drawdown, several high amplitude seismic reflectors are noted (Fig. 4). Velocity analysis suggests that they are probably an early Messinian platform carbonate layer which may correspond to the Horizon 'P' noted in the deeper offshore seismic interpretations by Ross and Uchupi (1977). Originally, during Early Messinian times, the proto-Nile fluvial system flowed northward toward the restricted evaporitic lakes of the Herodotus Abyssal Plain (Gvirtzman and Buchbinder 1978, Ryan 1978). This situation continued with periodic base level oscillations, until growth faulting had reached such an extent that, by Late Messinian times, the fluvial channels flowed westward between the Abu Qir antithetic fault systems. This, coupled with a final steep drawdown in Messinian sea base level, caused minor erosion of the delta plain facies, as recorded by Rizzini and his co-workers (1978) near the top of the Messinian section in the southern Nile Delta area.

Subsequently, a gentle transgression at the close of the Messinian epoch caused shallow flooding of the Abu Qir fluvial channels, and once more the proto-Nile was able to flow northwards. The Messinian sea, despite a rising sea level, was still supersaturated in salts. Subaqueous gypsum (now anhydrite) was precipitated in low energy environ from the turbid effects of submarine flow channels derived from the receding delta front. It is these evaporites which constitute the high energy impulses reflected as Horizon 'M' on seismic profiles. They are invariably associated with interbedded grey siltstones and marly shales, and are probably equivalent to the gypsum-mudstone cycles noted in cores 16-20 at DSDP Site 374 (Garrison et al. 1978). Continual deltaic deposition by the proto-Nile renders difficult the recognition of uppermost Messinian 'Lago Mare' facies (Cita et al. 1978) in the Nile Delta area. There is, however, an abundance of Ammonia beccarii ostracod fauna in delta front sands. These sands, which are up to 50 metres thick, occur between

Fig. 4. - N-S seismic section across Abu Qir antithetic fault system.
the aforementioned anhydrite bands and a deeper-water sequence of distal deltaic sands and shales within the overlying *Sphaeroidinellopsis* Acme-zone. These delta front sands may be equivalent to the 'Lago Mare' facies.

Palaeogeographic reconstruction suggests that at least 7 stages of evolution can be recognised:

1. Initial dessication of the Eastern Mediterranean Sea by evaporitic drawdown to the level of the former Tortonian prodelta floor and deeper, with the accompanying formation of the Nile Canyon, and possible isolated carbonate platform growth beyond the seaward limits of the ensuing erosional surface.

2. Synchronous development of an extensive fluvial plain, with substantial modification throughout the Messinian by periodic oscillations in base level, causing alternate downcutting and aggradation by braided stream processes.

3. Commencement of large syndepositional, antithetic, east-west growth fault movement, especially in the Abu Qir Bay area.

4. Subsequent westward channeling of the proto-Nile fluvial system between confining Abu Qir faults during the last major fall in Messinian sea level.

5. Final Messinian sea level rise causing shallow flooding of fluvial channels, formation of open lagoons and precipitation of subaqueous gypsum (now anhydrite).

6. Deposition of 'Lago Mare' facies with continuing rise in sea level.

7. Basal Pliocene transgression and return to normal marine conditions.

The dense seismic control in the Nile Delta area irrevocably demonstrates that there has been no major post-Messinian faulting of the Egyptian margin as suggested by Gvirtzman and Buchbinder (1978). Although there has been some Pliocene faulting due to settling and continued activation of Messinian growth faults, at least 2.5 to 3.0 kms of subaerial relief is documented (Fig. 5). Moreover, the existence of a Messinian fluvio-deltaic sequence over 1500 metres thick, deposited at the foot of this erosional surface, emphatically validates a deep dessication model for the origin of the Messinian evaporites. Despite the probability of an initial complete dessication of the Eastern Mediterranean Sea, continual influx of fresh water via the proto-Nile with headwaters as far back as East Africa, and the later Paratethyan 'Lago Mare' brackish water influx (Hsu et al. 1978), ensured that the Messinian sea persisted at an average level of about 2-4 kms below the present. This is the level at which the Messinian proto-Nile fluvial-deltaic system developed. It also accounts for the reason why the Eastern Mediterranean was never completely dessicated for long periods of time unlike its western counterpart.

**Fig. 5.** - Diagrammatic N-S geologic section Khatatba to Rosetta-2.

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I would like to express deep thanks to Dr. L.G. Kessler (Phillips Petroleum Company) and Dr. G. Evans (Department of Geology, Imperial College) respectively for supervising this work. I am also indebted to the managements of Phillips Petroleum Company, Egyptian General Petroleum Company, Hispanica de Petroleos S.A., and the International Egyptian Oil Company (Agip) for permission to publish company data as part of a doctoral thesis programme. Special appreciation is expressed to Professor W.H. Kanes of the University of South Carolina for his encouragement and allocation of a National Science Foundation grant (No. OIP 75-07943) under the North Africa resources study scheme.
BIBLIOGRAPHIE


APPENDIX II

MESSINIAN SUBAERIAL EROSION OF THE PROTO-NILE DELTA

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ABSTRACT


The evaporitic drawdown and subsequent dessication of the Mediterranean basins during the Messinian salinity crisis has been confirmed by detailed seismic mapping of the ensuing erosion surface in the Nile Delta region. The basal Messinian unconformity, determined by seismic analysis and borehole correlation, extends from almost sea level in the southern delta area to depths of at least 5 km in the Nile Cone. The onlap of the contemporaneously deposited fluvio-deltaic clastics of the Qawasim Formation occurs at between 2.5 to 4 km below present. Gradual initial drawdown of the Mediterranean Sea with occasional sudden sporadic falls, is implied by the presence of entrenched meanders and impaired rejuvenation terraces in the Nile Canyon, formed as the proto-Nile River cut down into the pre-existing Tortonian delta complex. The former Tortonian delta slope became an extensive linear erosional front with over 3 km of vertical relief, the uppermost levels of which were protected by tabular Oligocene basalt flows preserved as mesas and buttes. The lower slopes were the site of coalescing piedmont fans fed by upper slope wadi systems. The piedmonts merged into the Qawasim fluvio-deltaic deposits of the proto-Nile fluvial flood plain.

The subcrop beneath the basal Messinian unconformity reveals a remarkable diversity of rock type, each with its own distinctive control on the geomorphology and geometry of the ensuing Messinian erosional surface. Fracture patterns within the Oligocene basalts produced a trellis drainage network which became later captured by a dendritic system developed on less resistant prodelta shales of the former Tortonian delta slope. Close study of seismic profiles clearly demonstrates that the basal Messinian erosional disconformity can be traced northwards to depths of at least 2.5–3.0 km before becoming affected by later Pliocene faulting. This validates a deep dessication model for the evolution of the Messinian evaporites.

INTRODUCTION AND GEOLOGIC SETTING

Said (1962) presented the first major synthesis of the geological evolution of northern Egypt with extensive revisions being made in Salem’s (1976) discussion of Eocene to Miocene sedimentation patterns. From subsurface biostratigraphic and lithological control, Rizzini et al. (1978) were able to reconstruct three sedimentary cycles in the Nile Delta province, varying...
in age from Langhian to Holocene, one of which included a Messinian regressive sequence. Ryan (1978) described the overall erosional and depositional affects of the Messinian salinity crisis along the southeastern margins of the Mediterranean Sea. In the present paper, Ryan’s theme of subaerial modification of the Nile Delta region is discussed in detail, with particular reference to the geomorphology of the Messinian erosional surface.

The contemporary Nile Delta (Fig.1) lies at the intersection of two
major extensional trends on the northeastern margin of the African continental plate, where east-west epicontinental subsidence along the Cyrenaican—Egyptian shelf intersects the aulocogenic trends of the Gulf of Suez. The sedimentary succession (Fig.2) is characterized by a sequence of Mesozoic and Lower Eocene carbonates overlain by a northward thickening Middle Eocene to Holocene prograding fluvo-deltaic complex. The Mesozoic carbonate succession was mildly folded, elevated, and eroded during the Syrian Arc epeirogenic episode at the Mesozoic—Cenozoic boundary (Said, 1962; Salem, 1976). Extensional subsidence of the ensuing synclinoriums allowed a very gentle marine transgression to advance over the penneiplained Mesozoic carbonates, with deposition of an unconformable layer of Lower Eocene shelf carbonates. By Late Eocene times, terrigenous clastics began to replace the earlier carbonates thus heralding a change to deltaic sedimentation. This change is a precursor of the contemporary Nile, albeit upon a much smaller scale than at present. In response to the gradual mega-continental uplift of Africa throughout the Cenozoic, and the associated rifting in the Gulf of Suez, the proto-Nile continually increased its sediment load, building out a successively larger deltaic complex through time. Middle Miocene normal faulting parallel to the Red Sea rift shifted

![Diagrammatic stratigraphic chart for subsurface of the Nile Delta. Collated from Said (1962), Salem (1976), and Rizzini et al. (1978).](image-url)
the proto-Nile fluvio-delta system from its earlier position in the Western Desert to approximately its present location (op. cit.). E—W to ESE—WNW directed normal faulting and subsidence of the northern Egyptian margin between Alexandria and the Suez Canal from sediment loading dates from this period. Because of this, the Oligocene and older rocks now dip rapidly northwards from their contemporary outcrops near Cairo.

Two well-marked unconformities and/or hiatuses occur within the Upper Eocene to Holocene fluvio-deltaic interval. The first occurred at the close of the Oligocene when extensive, tabular, fissure basalt flows erupted in the Cairo—Suez region (Said, 1962). The second and most pronounced hiatus was caused by the Messinian salinity crisis. During Tortonian times the proto-Nile had established a substantial delta complex which was severely eroded during the evaporitic drawdown and subsequent dessication of the Mediterranean Sea (Ryan and Cita, 1978; Hsu et al., 1978; Rizzini et al., 1978).

It has been long recognized in the Nile Delta, through petroleum exploration drilling programmes, that the basal Pliocene transgression following on from the Messinian salinity crisis is marked by the presence of the Sphaeroidinellopsis Acme-zone M Pl 1 (Cita, 1975). Correlation of boreholes in the Nile Delta area reveals a remarkable variety of strata beneath this marker zone, with great diversity in age, depth and lithology. For example, in the northern delta area, boreholes have penetrated thick sequences of Lower Pliocene Kafr el Sheikh deep water prodelta shales containing Sphaeroidinellopsis sp. which rest directly on Messinian fluvio-deltaic clastics of the Qawasim Formation (Rizzini et al., 1978). The latter represents sediments deposited by the proto-Nile at the foot of the former Tortonian delta slope during the Messinian event. Average subsea depths to the top of the Qawasim Formation vary from —2078 m at El Tabia-1 in the western delta area, to —3252 m in Abu Madi-2 towards the east. In several wells, notably in the Abu Qir Bay area and in the northern offshore region, the Qawasim and Kafr El Sheikh Formations are separated by anhydrites of the Rosetta Formation and overlying delta front sands of the Abu Madi Formation. The Rosetta Anhydrites, as they are sometimes called (Rizzini et al., 1978), may be the equivalent of the gypsum-mudstone cycles noted in Cores 16—20 at DSDP Site 374 (Garrison et al., 1978) while the Abu Madi sands could represent uppermost Messinian “Lago Mare” facies (Barber, in prep.).

From north to south, towards Cairo, the Sphaeroidinellopsis sp. marker zone becomes shallower and progressively onlaps older rocks. At Mahmoudyah-1, for example, it overlies postulated Tortonian prodelta shales at —1958 m. Further south it rests unconformably on Middle Miocene conglomerates at —1014 m in Mit Ghamr-1; Oligocene deltaics at —927 m in Shiben El Kom-1; and Oligocene basalts at —28 m at Khatatba-1. Clearly, a great diversity of relief is suggested beneath the basal Pliocene.
THE SEISMIC RECORD AND BOREHOLE CORRELATION

Extensive hydrocarbon exploration in the Nile Delta region, both onshore and offshore, began in the mid-1960's, with most of the geophysical and drilling activity being conducted under the auspices of two separate consortia led by Phillips Petroleum Company and the International Egyptian Oil Company. From these two sources, a total of over 8800 km of proprietary multichannel seismic reflection data has been utilized in this study (Fig.3). Quality ranges from early six-fold to the later, more sophisticated twenty-four-fold coverage. Integration of these seismic profiles with borehole data reveals the existence of a pronounced unconformity corresponding to the base of the Pliocene as defined by the presence of the *Sphaeroidinellopsis* sp. zone. This is the Horizon "M" of Ryan et al., (1971), Ryan (1978) and appears as a pronounced, continuous high-amplitude seismic reflector truncating numerous deeper horizons. By correlation with boreholes, the latter marks Upper Eocene to Miocene prograding delta sediments resting unconformably upon truncated Mesozoic carbonates (Figs.4 and 5). Seismic velocities as determined from borehole sonic logs and velocity surveys indicate that the Lower Pliocene section is of an acoustically low-amplitude character with average velocities ranging from 1800—2400 m/s. In contrast, the seismic velocities below Horizon "M" are usually much faster, examples.
Fig. 4. Seismic section showing escarpment and butte terrain produced on the Messinian erosion surface. Note how horizontally layered seismic reflectors continue from one erosional feature to the next.

Fig. 5. Seismic section showing major southwest-facing escarpment developed on the Messinian erosional surface. Nearly 0.7 s (two way time) of vertical relief on the escarpment is illustrated. Based on velocity analysis this transposes to 450 m of erosion in this particular area.
being 3400—3500 m/s., such as recorded in Messinian clastics at the Buseili-1 borehole and 2400—2800 m/s., through Tortonian shales at Damanhour South-1.

Northward, beyond the Messinian sedimentary onlap, Horizon “M” forms a strong reflector at the top of the Rosetta Anhydrite sequence, and in the deeper parts of the Eastern Mediterranean it marks the uppermost limits of the massive Messinian evaporite sequence (Ross and Uchupi, 1977; Hsu et al., 1978). It also corresponds to Horizon “A” of Finetti and Morelli (1973). As outlined by Ryan (1978), Horizon “M” in the Nile Delta area represents subaerial exposure, erosion and resedimentation of the southeastern Mediterranean margin during the Messinian salinity crisis.

Based upon the close seismic grid control, a contour map and 3-D model of the Messinian erosional surface has been constructed (Figs. 6 and 7). They depict the development of an incised drainage network upon an extensive palaeoslope with a generally northward-directed flow. The palaeoslope represents the former Tortonian proto-Nile delta-slope which became an extensive linear erosional front during the Messinian era. This palaeo-relief can be traced from an elevation of about 55 m near the Khataiba-1 borehole to approximately 2500 m just south of Buseili-1. It is not only modified by the presence of drainage channels, but also by large mesas, buttes and escarpments (Fig. 8). The Nile Canyon, cut by entrenchment of the proto-Nile river, trends northward from beneath Cairo where it is approximately 12 km wide and at least 1.5 km deep (assuming faster velocities for the overlying Pliocene sediments may increase this figure even deeper, to 2 km). The canyon can be traced northwards on the available seismic records to a depth of nearly 3750 m, which is approximately equal to nearly 3 s two-way travel time on seismic sections. By mapping strong seismic reflectors representing the tops of the underlying Mesozoic carbonates, Eocene carbonates, and Oligocene Basalt or equivalent, it is possible to construct a subcrop map beneath the Messinian erosional surface (Fig. 9). From this map the control of lithofacies type on the Messinian drainage patterns can be more clearly discerned.

From seismic mapping, the Oligocene basalt covers an area of at least 8000 km², extending from near Zebeida-1 in the west to the Gulf of Suez in the east. In subcrop, the Oligocene basalt forms an exposed plateau bounded by an eroded northern escarpment which extends along the entire southern and southwesterly upper margin of the palaeoslope. Occasional basalt-capped mesas form outliers, although several mesas are characterized by a variety of erosionally resistant rock bands, as confirmed at those drilled by Mit Ghamr and North Dilingat boreholes. At Mit Ghamr, the mesa is composed of Lower Miocene clastics overlying Oligocene basalts, while the North Dilingat mesa (Fig. 8) is capped by Tortonian limestones resting conformably on deltaic shales. In most of the southern Nile Delta wells, hematite staining, thought to be the product of subaerial erosion was observed in drill cuttings from immediately beneath the basal Messinian unconformity. Despite the ever deepening Messinian palaeoslope towards the north, the
Fig. 6. Basal Messinian unconformity: computerized depth contour map with 100-m interval. Minor faults omitted for clarity.

Messinian subcrop becomes progressively younger so that eventually, the unconformity truncates Tortonian prodelta shales before passing beneath the southern onlap of the Messinian Qawasim Formation further north (Fig. 10). This unconformity is the equivalent of the presalt discordance noticed by Ross and Uchupi (1977) on seismic profiles over the present day Nile Cone, and later confirmed by Ryan (1978).
Fig. 7. Basal Messinian unconformity: computerized 3-D model viewed from an azimuth of 23 degrees with 30 degree viewing angle from the horizontal. Differential rates of erosion are clearly shown: the continually flowing proto-Nile fluvial channel has clearly cut down much faster than the intermittent wadi systems, perched on the plateau rims.
Fig. 8. Seismic section showing mesa and butte development on the Messinian subaerial erosion surface. See Fig. 3 for location of section.
GEOMORPHOLOGY OF THE MESSINIAN EROSIONAL SURFACE

Very rapid entrenchment of the proto-Nile River must have occurred for the fluvial channel to erode a canyon 1200 km upstream to Wadi Halfa in the Sudan (Chumakov, 1973), and to a depth of at least 1.5 km near Cairo through erosionally resistant Oligocene basalts overlying Mesozoic and Eocene carbonates. This could only have been initiated by a very pro-
Fig. 10. Generalized N–S contemporary cross-section through the western Nile Delta, based on seismic and borehole data.
nounced drop in the Eastern Mediterranean sea level during Messinian time, enacting regradation of the proto-Nile upstream, cutting back into its former delta slope. The "V"-shaped nature of the resulting gorge cut by the Messinian proto-Nile channel in an attempt to regain equilibrium is clearly illustrated on the contour gradients across the Nile Canyon near Cairo (Fig.6). The subcrop map (Fig.9) demonstrates marked truncation of horizontally bedded Mesozoic and Eocene carbonates on the canyon walls. Northwards, away from the Oligocene basalt escarpment, the palaeo-relief is less pronounced as the Mesozoic and Eocene carbonates dip beneath a less resistant, thickening section of Oligocene to Miocene age fluvio-deltaic clastics. Consequently, the Nile Canyon widens out with entrenched meanders being common and the valley assumes a more open character in cross-profile (Fig.11). Paired and impaired rejuvenation terraces are clearly observed, suggesting a constant lowering of base level, with dramatic falls related to sudden changes in Messinian sea base level. These are a result of drastic alterations in the net Mediterranean water budget (Cita et al., 1978). Moreover, with the overall fall in Messinian sea base level, the strandline migrated northwards resulting in a series of WNW—ESE trending terraces parallel to the strike of the former Tortonian delta slope. A noticeable example can be observed on the seismic section, Fig.12, at 1.7 s (two-way travel time), which converts to a depth of approximately 1700—1750 m. A little further north, the onlap of the Qawasim Formation is reached, confirmed by the Mahmoudyah-1 borehole which penetrated 234 m of Messinian fluvio-deltaic clastics and sandy micritic limestones. Generally speaking, however, resolution of seismic data is rather poor in the onshore northern delta area. Thus it has proved difficult to determine seismically in many places the actual onlap of the Qawasim Formation over the basal Messinian discordance.

Two drainage pattern types appeared to have developed further inland on the upper levels of the Messinian subaerial erosion surface and can be related both to bed rock type and the physiography of the late Tortonian delta complex. To the west of the Nile Canyon, horizontally bedded homogeneous rock suites have been cut by a trellis drainage system originating from NE- and NW-orientated megafracture patterns developed within the readily exposed Oligocene basalts. Due to extensive erosion, this drainage pattern became superimposed onto the underlying Oligocene clastics and older sediments. In contrast, east of Nile Canyon, there is not such a marked drainage pattern (this is, in part, due to the lack of detailed seismic control) as the basalt dips gently eastwards beneath a cover of Miocene deltaic sediments, upon which presumably developed a northward-directed consequent channel system.

Likewise, more basinward, the gradient of the former Tortonian delta slope, now a linear erosion front, also guided the development of consequent fluvial channels fed by an elaborate upper slope network of dendritically orientated minor streams. These streams rapidly cut back into the easily eroded Tortonian pro-delta shales and captured channels of the higher trellis drainage system. This led to the formation of mesas and buttes as
Fig. 11. East-west seismic profile across lower levels of the Messinian proto-Nile canyon. Note impaired river rejuvenation terraces. See Fig. 3 for location of section.
Two way time in secs.

Fig. 12. Seismic profile showing development of substantial strandline beneath erosional escarpment. Further north occurs onlap of Messinian sediments penetrated by the Mahmoudyah-1 borehole. For trace of section see Fig. 3.
erosional remnants. A number of the erosional highs have pronounced west and south-facing cliff scarps (Figs.4 and 5). This is in marked contrast to gentler northern slopes which were formed where the Messinian subaerial erosion surface cut along bedding planes within the former Tortonian delta-slope shales, often leading to erosional remnants of hog-back characteristics (Fig.13).

In cross profile, the upper slope drainage channels have sharp box profiles typical of wadis in a desert badland environment (Fig.14). Certainly the climatic considerations of Chamley and Robert (1979) suggest the existence of arid conditions based on the presence of fluvially reworked smectitic continental clays in Messinian deposits. Van Gorsel and Troelstra (1979) have postulated from planktonic foraminifera studies in Indonesia that the Messinian climate was a warm-dry phase, probably caused by an expansion of the tropical belt, thus bringing the Mediterranean under the influence of the extremely dry belt presently over North Africa. The immature wadi profiles are in marked contrast to the “V”-shaped valley profile of the continually flowing proto-Nile fluvial channel in the Nile Canyon. These wadis

![North-south seismic profile illustrating characteristic “hog-back” erosional remnant on upper levels of the erosion surface onlap of Messinian sediments. See Fig.3 for location of section.](image-url)
coalesce into piedmont fans that merge into the deltaic and braided stream deposits of the Qawasim Formation, deposited by the proto-Nile at the mouth of the Nile Canyon (Barber, in prep.).

It has been difficult to recognize wadi deposits in the drainage channels particularly from seismic data, especially since most boreholes were drilled on topographic highs or to test deeper pre-Messinian structures. Nevertheless, discontinuous high amplitude reflectors, observed on some seismic profiles may indicate infilling of wadi channels. Only one well, the Itay El Barud-1 borehole, has been drilled into the flanks of such a channel (Fig.14) where it penetrated a basal pebbly sand unit 29 m thick. Electric log characteristics and well cuttings indicate a very immature conglomeratic sand with a very high argillaceous shale content up to 30% by volume. Porosity values vary from 6% to 48% suggesting poor sorting and immaturity as would be expected from a wadi deposit. High-amplitude reflectors on the seismic profile across the lower Nile Canyon (Fig.11) may indicate fluvial channel lag deposits, but without borehole correlation it is impossible to classify these features as fluvial sands of the Qawasim Formation, or conversely as deltaic or proximal turbidites of the Lower Pliocene.

CONCLUSIONS

The erosional discordance at the base of the Messinian can be clearly traced northwards on seismic profiles to depths of 2.5 to 3.0 km before any major Pliocene faulting is observed. As demonstrated on the diagrammatic cross section (Fig.10) much of this faulting originated during the Messinian, and has continued to the present day in response to isostatic loading of Pliocene overburden. The same unconformity extends northwards beneath the Nile Cone to depths of 3.0 and 5.0 s two-way time (Ross and Uchupi, 1977; Ryan 1978). The dessication of the Mediterranean by evaporitic drawdown is conclusively demonstrated by the existence of a deep canyon over 2.5 km deep cut by the proto-Nile fluvial channel, and by the development of dendritic and trellis drainage systems on the former Tortonian delta slope. A gradual drop in Messinian sea base with occasional rapid falls and quiescent episodes is implied by the presence of both rejuvenation terraces on the flanks of the lower Nile Canyon, and raised strandline platforms left behind by the northward receding shoreline. While the Messinian sea base level may have initially dropped to below 5.0 s (two-way travel time), the average base level probably oscillated at between 3–4 km below present. This contention is supported by the great thickness of fluvo-deltaic sediments of the Qawasim Formation at this stratigraphic level.

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Fig. 14. Seismic section showing well-developed wadi profile. See Fig. 3 for location of section.
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APPENDIX III

Cenozoic Evolution of the Proto-Nile Delta

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The Cenozoic succession of the Nile Delta can be subdivided into two main groups. The lower group is composed of Early to Middle Eocene carbonate shelf facies resting unconformably on truncated Mesozoic carbonates. These grade into the upper group of Late Eocene to Holocene fluvio-deltaic sediments which originated from an ancestral Nile river system. The overall offlap nature of the upper terrigeneous sequence is interrupted by two well-marked hiatus. The first was caused by an extrusive igneous episode at the end-Oligocene. The second and most pronounced was caused by the Late Miocene (Messinian) salinity crisis when the proto-Nile Delta was severely eroded as a consequence of evaporitic drawdown and dessication of the Mediterranean Sea.

Peri-Mediterranean tectonic events were largely responsible for the initiation of the proto-Nile and its subsequent progressive increase in catchment area to the present day. The Nile Delta area has been affected by both compressional and extensional tectonic events. The main compressional event was the Syrian Arc epeirogenic episode which occurred at Mesozoic-Cenozoic boundary time. This coincided with the period of overthrusting and large nappe development along the northern margin of the Eastern Mediterranean Basin especially in Turkey and Cyprus. Only mild folding occurred in the Nile Delta, creating gentle ENE-WSW trending ridges and troughs, which were later transgressed by shallow carbonate seas during the Lower Eocene. It was not until Oligocene times that the peneplained remnant high axes were finally submerged and covered by terrigeneous sediments.

The Nile Delta, per se, began to form in the southern Western Desert during Middle Eocene times, probably as a result of pre-rift (Red Sea) doming of the African continental crust, further attenuated by lithospheric cooling and post-orogenic subsidence of the Eastern Mediterranean floor. Middle Miocene faulting parallel to the Red Sea rift diverted the Nile River to its present course, allowing a large delta to accumulate north of Cairo. Sedimentation was mostly controlled by syndepositional movement along WNW-ESE trending normal faults parallel to the Egyptian-Cyrenaican coastline. Seismic data tentatively suggests that there may be some NE-SW trending wrench faults of Pliocene age in the offshore delta area. These may be a recent manifestation of sinistral shear along a postulated NE-SW trending transcontinental wrench zone, extending from the SE Mediterranean across central Africa into the Benue Trough of Nigeria.

The origin of the proto-Nile Delta is largely a product of tectonic processes rather than a consequence of sediment loading of the lithosphere. Palaeogeographic modelling suggests that the proto-Nile Delta was underlain by a relatively thin Cenozoic section until early Miocene time, prohibiting crustal subsidence by loading alone. Since this period, however, progradation of proto-Nile Delta sediments into the Eastern Mediterranean Basin has contributed to localised downwarp, occurring simultaneously with the driving tectonic mechanism responsible for regional basinwide subsidence.
APPENDIX IV

Qawasim-1 and Abu Qir-1 core and petrographic descriptions. (Note: Qawasim-1 cores, 1, 4 & 11 are not described due to disintegration and poor preservation).
## LEGEND

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QAWASIM - 1

Graded sandstone: grey-green, predominantly fine grained, subangular-subrounded. Cross bedded at base, ranging upward into slump structures and finally ripple bedding. Scour at top and bottom of sequence.

2720.5m - 2722.0m

Siltstone: light-grey brown. Laminated with ripple marks and high energy slumps. Great instability indicated by very steep dip of ripples at 2722.5m and high angle slip-faulting of semi-lithified beds at 2722.6m.

2722.0m - 2723.1m

Cross-bedded sandstone: light grey-tan, very fine grained to medium grained, subangular-subrounded; with climbing ripple lamination. Scour at base.

2723.1m - 2723.3m

Convoluted grey-black silty sands overlain by cross-stratified sands. Slumped beds of very fine grained, subangular quartz sands often unconformable over sheared foreset laminations in upper part. Shear-plane brecciation of load cast at 2724.6m. 30°-40° slip-faulting at 2724.0m.

2724.0m - 2725.1m

Convoluted grey-black siltstone becoming indurated clay towards top.

2726.0m - 2728.0m

Conglomeratic pebbly sandstone grading up into ripple bedded sands. Sands: white, grey-tan, coarse grained—occasionally medium grained, subangular-subrounded. Steep cross-bedding 30° and very conglomeratic at base decreasing upwards. Extremely quartzitic with feldspars and occasional heavy mineral grains.
QAWASIM-I

2771.0m - 2771.8m
Ripple bedded sandstone: light grey-green, very fine grained, well sorted. Occasional silty bands forming ripple surfaces.

2771.8m - 2772.0m
Shale: grey to grey-black indurated, slightly carbonaceous.

2772.0m - 2775.1m
Sandstone: light grey, medium grained to occasionally coarse grained, with trough-bedding and some planar cross-stratification. Coarser grained in lower part of bed units, with frequent basal scour. Moderate to well-sorted. Penecontemporaneous and postdepositional microfaulting with an average displacement of 2-4cms, especially at 2775.0m-2775.9m. Base of the sand sequence is scoured into shale.

2775.1m - 2775.2m
Shale: grey-green, grey-black, silty with faint ripple laminations where coarser-grained.

2775.2m - 2776.5m
Sandstone: grey-white, predominantly coarse grained, occasionally medium grained and very coarse grained, subangular-angular. Strongly trough-bedded, becoming planar bedded towards base. Some slight grading of cross beds units with coarse grained quartz at base of scours. Becomes very silty towards bottom of the sequence.

2776.5m - 2776.6m
Shale band: as above.

2776.6m - 2777.5m
Cross-bedded sandstone: grey-white, medium grained-coarse grained, subangular-angular, with possible mega-ripple or antiline bedding features; contains some shale clasts especially towards top of sequence.

2777.5m - 2777.6m
Shale band: as above.
Sandstone: yellow-white, speckled grey, coarse grained-very coarse grained, poor-moderate sorting, planar cross-bedded, becoming conglomeratic and poorly sorted towards base. Contains black pebbles basalt fragments. Very high energy storm sequence.

Siltstone-claystone with occasional very fine grained ripple-bedded sandstone. Silty layers: grey-black, earthy, micaceous. Heavily bioturbated in part. Convolute bedding and slumped units common throughout sequence except between 2886.9m-2889.0m. Most of the siltstone-claystone beds are horizontally laminated except where convoluted.
UPPER COARSE GRAINED POINT BAR SEQUENCE (ALMOST BRAIDED STREAMS)

2917

2918

2919

2920

2921

Metres

2917.0m - 2921.0m

Conglomeratic sandstone: grey-white, grey-brown, coarse grained—very coarse grained, angular—subangular, moderate to poorly sorted. Very steep cross-stratified units especially at 2919m-2920m which contain pebble-sized clasts. Some units of reworked fore-reef limestone and chalk. Basal units of cross-bedded sequences often indicate underlying horizons suggesting high fluvial energy.
An illsorted mosaic of rounded to angular quartz grains, detrital feldspar and minor calcite fragments. Latter may also be diagenetic replacement of plagioclase during early burial history. Occasional feldspars broken by hairline fractures possibly caused by compaction affects. No cement observed, although residual cement could have been leached by drilling mud fluids. This specimen comes from the upper part of the postulated coarse grained point bar sequence in the lower part of the Qawasim Formation.

Siltstone: grey-black, grading into claystone; sporadic convolute bedding throughout sequence. Evidence of burrowing, probably excessive in part, since sedimentary structure destroyed by intensive bioturbation.
QAWASIM 1-bis
CORE No. 7
2976.5 - 2977.0 m.

Qawasim-1  Core 7  2976.5-2977.0 m
Qawasim-1. Core 7. 2976.9m photomicrograph

Crossed polars (X20 mag).

Randomly orientated quartz, feldspar, mica, and calcite detritals set within a fine limonite-rich siltstone-claystone matrix. No sorting. Quartz grains vary from well-rounded to angular, and some appear to be reworked metamorphic-quartz derivatives. Some finer grained angular-rounded quartz fragments occur within a resedimented mud clast. Orientation of matrix is probably due to compaction rather than primary depositional effects. This section occurs within a postulated wadi debris flow within the upper part of the lower Qawasim Formation.
Sandstone: white, friable, coarse grained, subangular-subrounded with channel lag mud clasts in planar cross-beds. Well sorted with scour at base.

Claystone-siltstone: grey-black grading up into medium grained sandstone. Indurated siltstone with microfractures 45° dip and pressure release pipes at 3032.5m. Convolute bedding common with burrowing near top of siltstone sequence. Sands become coarser towards top, characterised by ripple bedding grading to planar bedding immediately below scoured surface.

Excluding scoured base of main cross-bedded sand; entire sequence of core exhibits overall coarsening upward grain size.
Qawasim-1. Core 8. 3030.0 m photomicrograph

Crossed polars (X20 mag).

Predominantly composed of well sorted sub-angular to subrounded quartz grains within a calcic-clay matrix infilling pore space. Abundant microcline and plagioclase feldspar detritals and also occasional limestone fragments. Possible secritization of plagioclase feldspars has occurred, possibly in situ. Rare heavy mineral grains (i.e. tourmaline). This section is derived from postulated distributary mouth bar facies in the lower Qawasim Formation.
**QAWASIM-1**

**3133.0m - 3138.0m**

Planar cross-bedded sandstone; grey-white, buff, medium grained-coarse grained; subangular-subrounded. Contains several slumped horizons with post-depositional microfaulting at 3134.4m. Calcareous clasts at base of planar units. Ripple bedded towards bottom of sequence. Major slump at base.

**3135.0m - 3138.0m**

Horizontally laminated green siltstone. Bioturbation is prevalent towards top of sequence, destroying inherent sedimentary structure. Siltstone grades up into fine grained sands with interbedded ripples and slumped horizons.

Entire core represents gradual change from low to high energy environment under very unstable basal conditions.
Conglomeratic sandstone: white, grey, buff, red and green speckles; very poorly to moderately sorted, ranging from pebble clasts to very coarse angular quartz grains. Abundant limestone clasts and immature mineral detritals, especially potash feldspar. Angular clasts lying with preferred orientation parallel to bedding. Low angle planar bedding recognised at base of graded units, with some minor fining upward in grain size.
Qawasim-1. Core 10. 3397.8m photomicrograph

Crossed polars (X20 mag).

Randomly sorted, variable grain-sized quartz sand, exhibiting angular to rounded sphericity. Contains plagioclase feldspar detritals although most of the section is predominantly quartz. Virtually no cement in the interstitial pore space. Rare heavy minerals. This specimen is derived from a braided stream sequence within the Lower Qawasim Formation.
ABU QIR-1

CORE 1

3049
No Preservation of Core from this Interval.

3050

3051

3052

3053

3054

5031.0m - 5051.5m

Pebbly sandstone: grey-white, very coarse grained, occasionally medium grained and pebbly, angular to sub-rounded, poorly sorted, friable. Contains numerous feldspar and re-worked clasts. No apparent bedding except towards base where conglomeratic material has been concentrated. Whole unit is slumped into the underlying semi-lithified sequence at variable angle of 45°-75°, with basal clasts scoured into underlying sequence.

5051.5m - 5052.7m

Slumped ripple-bedded sandstone: grey-green, very fine grained, angular-subrounded, well sorted, glauconitic (?). Contains much iron staining along silt-concentrated defining beds of the ripple sequences. Entire sequence is highly disturbed by syndepositional microfaulting, followed by post-depositional slumping. Basal part of sequence has been disturbed by fluidised coarse-grained silty sands penetrating and widening micro-fractures.

5052.7m - 5054.7m

Matrix supported sandstone: grey-green, very fine grained, extremely silty with clay supported randomly-oriented clasts of mud flakes and quartz pebbles. No sorting. No preferred orientation in clasts.

Metres

DEBRIS FLOW SLUMPS AND TRACTION RIFFLE FANS FROM UPPER SLOPE SUBMARINE FAN

P
Abu Qir-1 Core 1 3051.5-3051.7 m
Abu Qir-1 Core 1  3052.5-3052.7 m
Abu Qir-1. Core 1. 3051.3m photomicrograph
Crossed polars (X20 mag).

Moderately to poorly sorted sand, containing variable size quartz detritals, subangular to subrounded. Occasional plagioclase feldspars have been secritized implying migrating pore fluids. Also rare microcline feldspar grains present. Little or no matrix suggesting considerable tractive energy. Section interpreted to have been derived from the upper levels of a delta slope sequence, within the upper part of the Qawasim Formation.
Abu Qir-1. Core 1. 3052.55m photomicrograph

Crossed polars (X20 mag).

Section has been cut through a clast containing very fine detrital quartz grains (left and centre) surrounded by a coarser-grained agglomeration of quartz and feldspar fragments (right). The very fine-grained sand is quartz-rich with occasional plagioclase and rare microcline feldspar. The chlorite-rich matrix is secondary and is probably a diagenetic by-product as is also limonite coating of individual grains. Great angularity of the very fine quartz grains suggest that they are of aelion origin and have probably been reworked from older Pre-Messinian sediments. This specimen is derived from a ripple bedded sandstone unit within the top upper part of the Qawasim Formation.
Abu Qir-1. Core 1. 3053.1m photomicrograph
Crossed polars (X20 mag).
Poorly sorted lithic sandstone. Primary minerals are variable quartz, plagioclase and microcline feldspars. The original matrix was probably chlorite. Remaining interstitial pore space has been filled by migrating calcic-rich pore fluids leading to development of occasional twinned calcite crystals. The immaturity of the sample is reflected in the presence of a reworked Nummulite fragment (top centre) detrital carbonates and various heavy minerals (i.e. magnetite and possibly tourmaline). Not shown on the photo micrograph are calcic pseudomorphs of a "hopper-salt" crystal and also a gypsiferous void indicating possible reworking of evaporite deposits (sabkha?) prior to resedimentation and diagenetic alteration. Possible subaqueous debris flow mechanisms can be invoked to derive the extremely poor random sorting and great immaturity of the mineralogical assemblage. The section is cut from a core sample within the upper Qawasim Formation.