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DEPOSITIONAL EVOLUTION OF THE PLIO-PLEISTOCENE SUCCESSION AS A KEY FOR UNRAVELING THE EXPLORATION POTENTIAL OF THE POST-MESSINIAN PLAY IN THE CENTRAL NILE DELTA, EGYPT

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التطور الترسيبى لتتابع بلايوسين- بليستوسين كدليل على الامكانيات البترولية لرواسب ما بعد الميسنيان فى منطقة وسط دلتا النيل بمصر

الخلاصـة: نظرا للتنامى المتزايد فى احتياطيات الغاز المستكشفة برواسب العصر البلايوسين و البلاستوسين فى مناطق دلتا النيل والبحر المتوسط فقد رأينا التوجه بالنظر إلى أهمية دراسة التتابع الترسيبى للدلالة على إمكانية وجود مكامن بترولية فى تلك الرواسب فى مناطق امتياز بتروبل وتحديداً منطقة الحوض الترسيبى الأوسط بدلتا النيل فى مصر.

و قد تم الاعتماد فى هذه الدراسة على قطاعات سيزمية ثلاثية الأبعاد و بعض الخرائط المستنبطة من الخصائص السيزمية وكذلك التسجيلات الكهربية للآبار محل الدراسة.

و قد تبين وجود أنماط ترسيبية مختلفة تحتوى على تجمعات غازية واعدة بمنطقة الدراسة و من أهم الأنماط الترسيبية التى تم التعرف عليها القنوات المتعرجة الموجودة فى عصرى البلايوسين المبكر و البلاستوسين و كذلك بعض العدسات الرملية المنتشرة فى البلايوسين الأوسط و المتأخر.

و بناءً على نتائج الدراسة فإننا نلفت النظر إلى احتمالية وجود تجمعات غازية واعدة لم تكتشف بعد فى منطقة الدراسة.

ABSTRACT: *The reconstruction of the depositional evolution and of the stratigraphic pattern of the Plio-Pleistocene succession contributed to put in a context the recent discoveries and to outline the residual potential of the post-Messinian section from onshore to distal offshore of the Central Nile Delta. Besides the traditional DHI supported sand prone targets, this sector of the Nile Delta wedge, characterized for most of the Pliocene, by a generalized sediment bypass, has being revealed prone of unconventional silty reservoirs, referable to turbidite channel-levee complexes and late stage fine grained channel fill facies, which, notwithstanding their less attractive petrophysical parameters, have been proved to have a good production performance in recently drilled wells.*

Some additional unrealized potential for the area is related to the no DHI supported gas bearing elements that have been successfully tested within the lower Pliocene section. A deeper understanding of petro-elastic model allowing to overcome the traditional DHI/AVO indicators is needed. In addition a detailed interpretation and understanding of their relation with some gas chimneys recognized in the area can contribute to the reduction of the high exploration risk connected to these targets.

INTRODUCTION

Huge reserves have been discovered until now in the Nile Delta province, most of which within the Plio-Pleistocene slope succession. After a long exploration phase, started in early sixties, when attention was focused to Miocene targets the Plio-Pleistocene play assumed an important role in the last decade, due to the development of 3D seismic techniques which allowed the identification of gas prone depositional elements within the shaly Nile Delta continental slope succession. The area considered in this paper consists of a narrow band comprised between longitudes 31^{o} 3’ 13” and 31^{o} 29’ 31”, extending for more than 120 Km from onshore to offshore through the central Nile Delta (Fig. 1).

Its 3D seismic coverage has been recently completed with 3 new surveys extending from onshore to the shallow water offshore. The area comprises 12 Development Leases from East Delta South to Baltim NE, originally individuated around some gas discoveries within the Messinian Abu Madi paleovalley. These permits are now operated by Belayim Petroleum Company, on behalf of the shareholders IEOC and EGPC in partnership with RWE Dea and BP. The aim of this paper is to delineate the depositional evolution of the Pliocene to Quaternary Nile Delta, whose better comprehension can contribute to the unraveling of a considerable exploration potential still present in the area.

Geological setting

Since the early Oligocene the Nile river sediment discharge formed a huge fluvio-deltaic to deep-marine wedge, lying on a transform continental margin, related to the oblique separation of the African and Arabian plates and the opening of the Red sea. The present day Nile Delta established in the Early Pliocene, above a regional transgression surface, on top of the Messinian sequence.

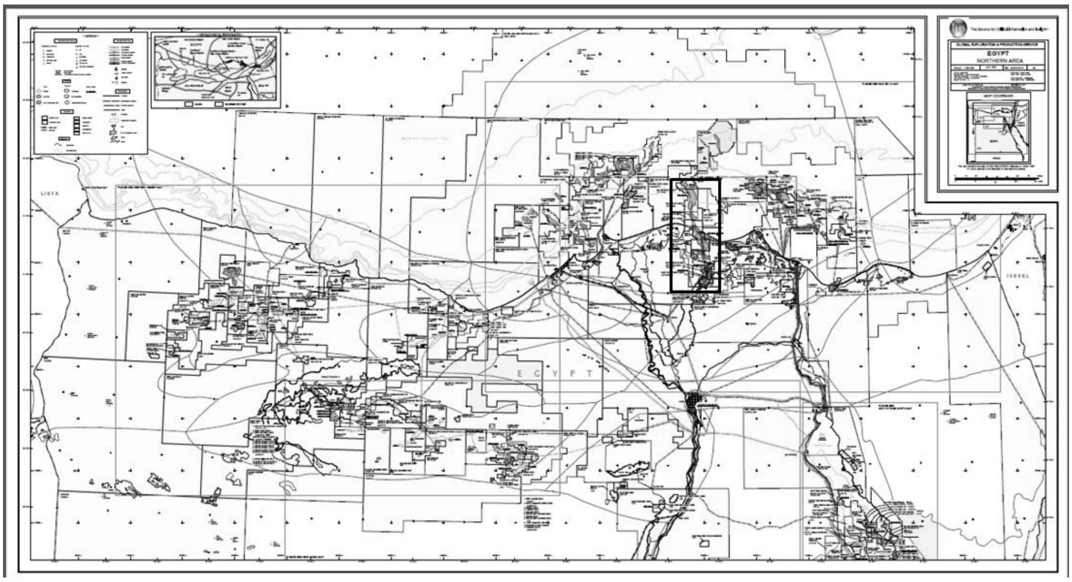


Fig. (1): Study area location map.

The overall sedimentary pattern of the Plio-Pleistocene succession is characterized by a dominant progradation, with large scale clinoforms and an evident northward migration of the shelf break, nevertheless some backstepping phases occurred.

Three main depositional units have been traditionally recognized from older to recent are:

1. Kafr El Sheikh Formation: deep marine continental slope shales interbedded to turbidite sands
2. El-Wastani Formation: sand/shale alternances deposited in a delta front/prodelta environment
3. Mit Gahmr Formation: mainly sands deposited in a delta plain/delta front environment.

This paper will be mostly focused on the Kafr el Sheikh unit which contains the great part of the exploration potential of the area.

The Messinian section plays a major role in the Plio-Pleistocene sedimentary evolution of the whole Nile Delta cone. Desiccation of the Mediterranean Basin led, during Messinian, to the deposition of a strongly variable thickness of evaporite sediments: from several hundred meters in the eastern sector to few tens at the margin of the evaporitic basin in the western Delta. The Central Nile Delta Sub-basin was instead characterized by deeply incised multi-phase unconformities overlain by fluvio-deltaic facies (e.g. Abu Madi – Baltim paleovalley) (Fig. 2).

The strong variability of evaporites thickness is responsible for the different tectono-sedimentary settings of the entire Nile Delta province (Fig. 3). Thick evaporitic deposits triggered the generation of gravity driven growth faulting in the eastern sub-basin, which originated evident sea-bottom irregularities acting as sand traps and forming a succession of minibasins along the slope.

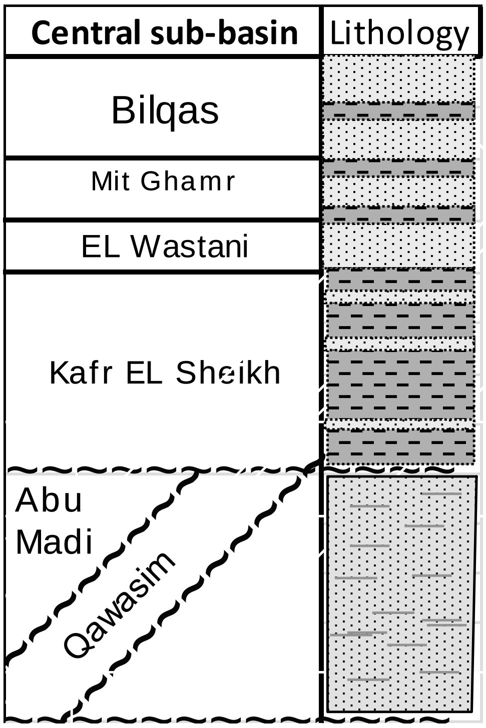


Fig. (2): Nile Delta stratigraphic column (after Rizzini 1988).

The Central and most of the Western sector, being deposited outside the main evaporitic basin, are instead characterized by an undeformed shale prone slope which dips gently towards the abyssal plain, only affected by minor gravitational buried normal faults. No evident intraslope basins are recognized and coarse grained depositional features mainly consist of long slope channels, feeding deep water turbidite lobes. Sediment bypass dominates in the upper slope.

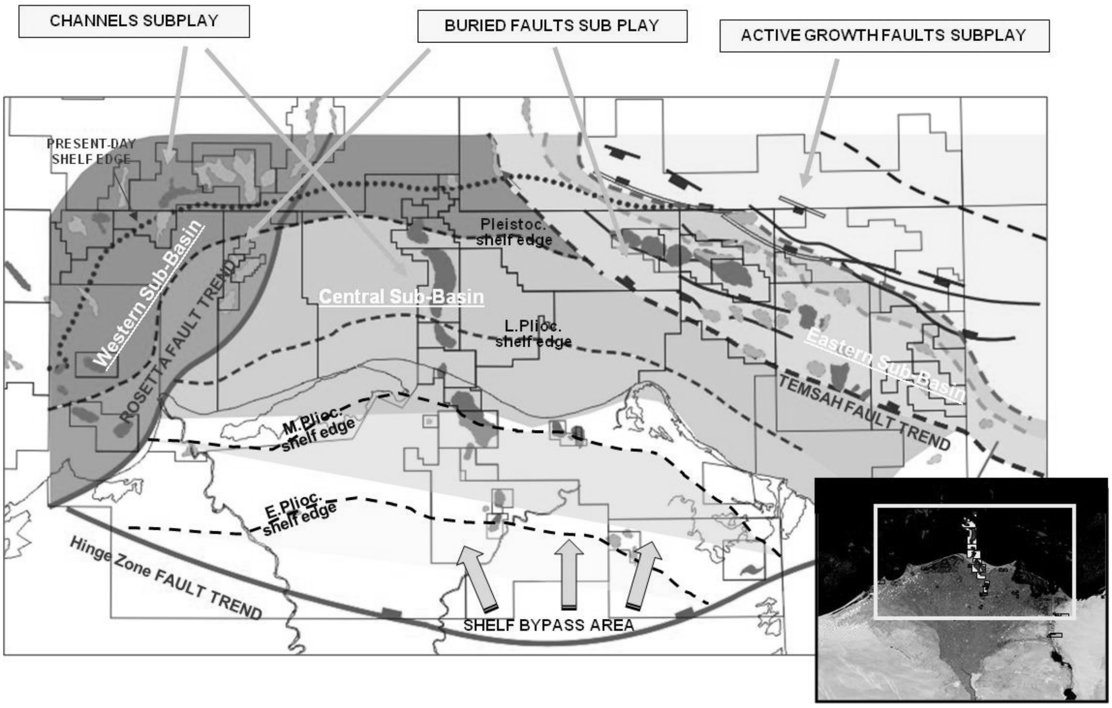


Fig. (3): Nile Delta basin Structural-Depositional domains (Nini, et al 2010).

The area of interest is located in the Central Nile Delta Sub-Basin, bounded southward by the Hinge Line, an E-W belt of growth faults showing a huge total downthrown of some thousands of meters and West and East respectively by the Rosetta and Temsah/Bardawil fault trends.

Plio-Pleistocene basin stratigraphy:

The Plio-Pleistocene Nile Delta wedge is dominated by a strong progradation, occurring due to a general overbalance of sediment supply on available accommodation space. Particularly in the Central sector of the Nile Delta wedge, the lacking of the Messinian evaporites, which led in the eastern Nile Delta to the formation of intraslope rapidly subsiding minibasins, reduced the sediment accommodation space. The result is a higher progradation rate with the shelf -break reaching its maximum distance of more than 50 kmfrom the present day coastline, El Heiny and Enani (1996). Recently acquired 3D volumes on both onshore and shallow marine areas of the Central Nile Delta, joined to the available streamer 3D in the offshore, allow to have a continuous image of the Nile Delta cone along a more than 120 km long transect. The recent Nile Delta progradation developed during the late Tertiary with a discontinuous pattern, being affected by eustatic sea level variations, probably combined with climatic factors affecting the Nile river sediment discharge. As a consequence, discrete depositional sequences can be recognized within the slope apron, outlined by clear unconformity surfaces. In particular eight main stratigraphic sequences have been distinguished from the top of Messinian to the Pleistocene (Fig. 4). The cross correlation of biostratigraphical Nile Delta well zonation and the global sequence chronostratigraphy (Hardenbol et al. 1998) allowed to relate them to the main sea level drops occurring in the late Tertiary. Each sequence boundary was recognized through the identification of a major basinward shift of sedimentation, indicated also by rapid migration of the shelf break estimated as varying from 4 to more than 10 Km within the lowstand phases. Aggradation and new acceleration of prograding is then observable during the rising and standstill of sea level until the subsequent major drop generates a new unconformity. Huge incisions along the slope are observed at the base of the sequences often overlain by mass transport units originated by the collapse of the slope profile during rapid sea level changes.

Petro-acoustic characterization of the late Tertiary succession:

The target reservoir sands within the Plio-Pleistocene succession are characterized by a different acoustic behavior that is following a clear trend linked to depth.Within depositional objects showing comparable thickness and net to gross, the experience in the Nile Delta indicates that this variation is directly related to changes in reservoir and rock properties as compaction, overpressure, lithology, cementation, fluid fill and consequently to variations in acoustic impedance that affect the AVO response of reservoir levels.

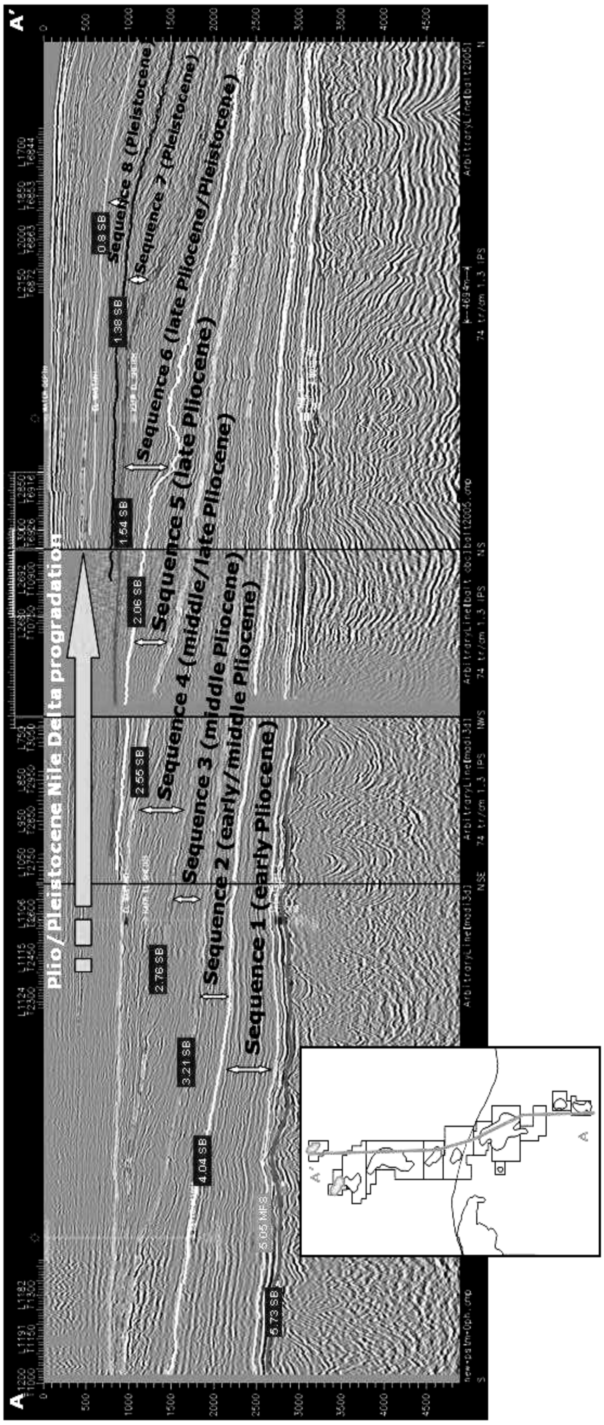


Fig. (4): Sequence Subdivision of Plio-Pleistocene succession in the Central Nile Delta.

The uppermost section of the Plio-Pleistocene is characterized by gas sands having significant lower acoustic impedance than the encasing shales. Wet sands are showing even higher values. Plotting acoustic impedance against porosity and clustering couplets of values measured at different depths it become evident that going deeper in the section, acoustic impedance of both wet and gas sands are higher than that detected in shales.

The comparison of amplitude extracted from near and far volumes and analysis of CDP gathers show that AVO response changes with depth accordingly with the described acoustic behavior variations. From typical Class 2-3 anomalies (Rutherford & Williams, 1989) in the upper part of the Plio-Pleistocene section to Class 1 in the deepest portion of the section immediately above the top of Messinian.

From the interpretation of isochronous sequence boundaries in the Plio-Pleistocene succession it is clear that the petro-acoustic characteristics variation is not a matter of age but it is related to depth, better to the burial of reservoir levels or shale characteristics. Going through the sequence 2 from South to North in fact it is evident that gas bearing sand packages within the same stratigraphic interval responds as AVO class 3 or class 1 depending on the lower or higher burial. Changes in petrophysical characteristics linked to burial history should therefore be the reason of different acoustic behavior more than change in lithological composition that should remain constant within the same sequence (Fig. 5).

Depositional elements characterization and their explorative significance/potential:

The progradation of the Nile Delta allows observing in the study area the complete vertical evolution of the sedimentary systems within the Nile Delta apron from distal to proximal continental slope depositional settings.

Toe of the slope depositional lobes:

The Lower Pliocene sequence 1is characterized by the stacking of blocky sandstone packages showing a good continuity in the drilled wells. The thickness of each depositional element is varying between 15 and 25 m, with Net/Gross comprised between 70and 85%. The lateral extent of these sand bodies can be hardly evaluated, due to the poor resolving power of seismic at depth below 2500 m and the sand bodies geometry itself, hampering their detection on seismic attributes extraction maps. Only the smallest lobes, few sqkm wide, can be resolved on some amplitude extractions. The existence of wider elements is anyway suggested by well log data. The exploration potential of these unconfined sand bodies is limited. No hydrocarbon accumulations have been found associated to them until now. The high pressure regime found within the lower Pliocene, together with lack of structuration and high continuity of porous facies, hampering stratigraphic trap development, is probably enough to explain the absence of gas bearing reservoirs. It is anyway worth to notice that the high acoustic impedance of these compacted porous levels does not allow for the detection of HC bearing levels through Amplitude Versus Offset(AVO) analysis, indicating still possible unrealized potential within the lower Pliocene section.

High sinuosity feeder channels:

At the boundary between sequence 1 and 2 three turbidite channels, more than 40 Km long, are clearly imaged by windowed amplitude extraction made in near stack around the top trough (Fig. 5).

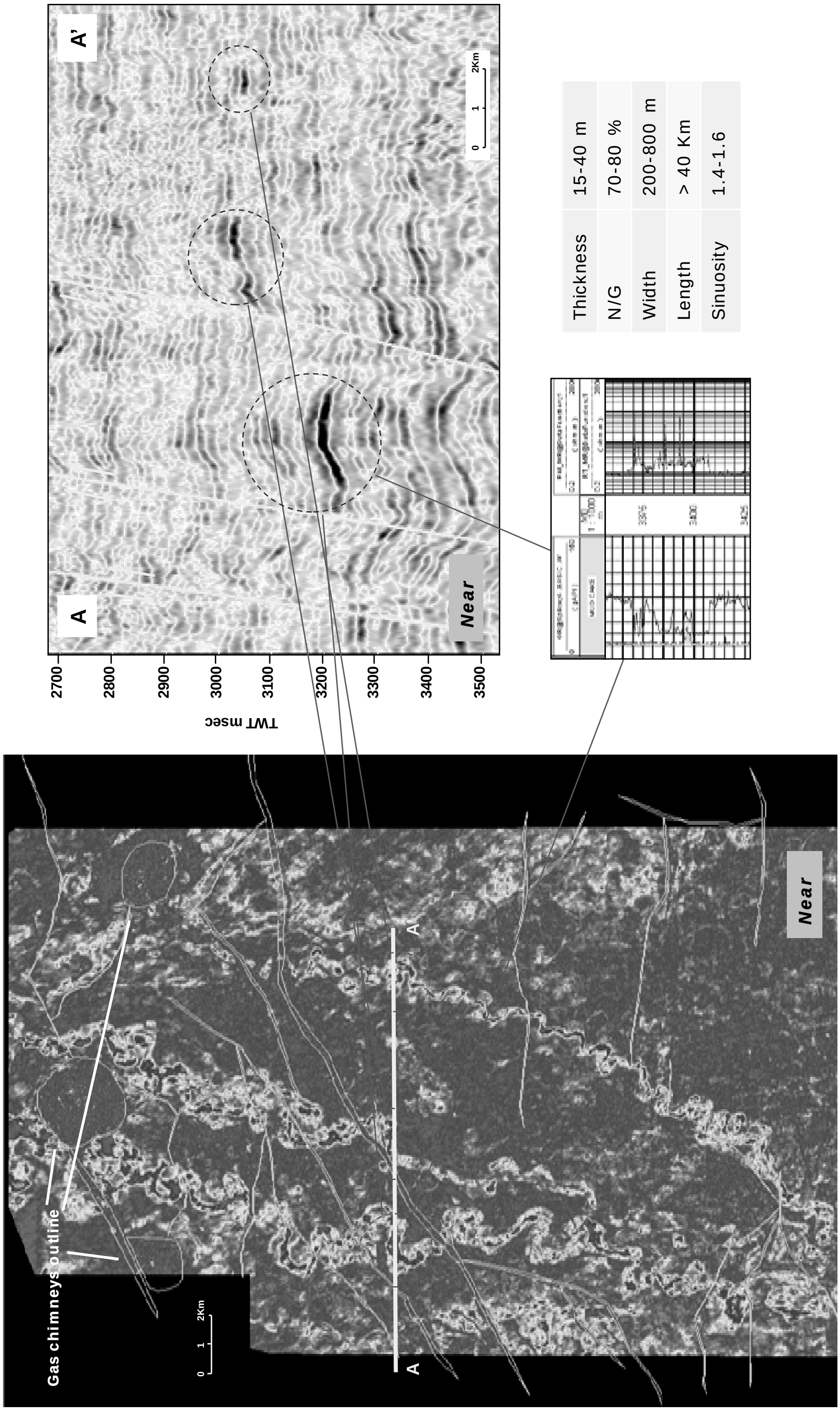


Fig. (5): High sinuosity feeder channels.

They likely represent a good example of the feeder systems of lower Pliocene unconfined lobes. The channels appear to be bed-load dominated elements with poorly developed levee facies. The aspect on well logs is not so different from the underlying turbidite lobes, constituted as well by sharp based blocky sands 15to 40 m thick with slight gradation on top. The N/G is 70-80%. The thalweg width ranges between 200 and 800 m. Their sinuosity, defined as the ratio between channel axis length to channel belt length, is quite high: between 1.4 and 1.6. The poor seismic resolution at this depth does not allow observing the internal structure of lateral migration events, but the sinuous shape of the channel suggest the occurrence of lateral loop migration. The axis is made by a monophase seismic event only evident on the near stack volume.

The lower Pliocene channels have been perforated in three wells. In two cases they have been found gas bearing, but, as mentioned in the petroacoustic characterization paragraph, they are related to AVO class 1, with amplitude generally decreasing in the far stack,therefore discrimination of fluid content is not evident from traditional AVO analysis.

An attempt of elastic inversion feasibility was also performed, but Inverted P-Impedance attribute was not resolutive and the inverted Rho Lambda gave indications about fluid prediction only for the upper pliocene gas bearing levels of the tested well. Other elastic domains should be investigated in order to reach a better comprehension of the rock/fluid physical model for the lower Pliocene elements characterized by hard kicks.

In this context some geologic considerations in the area can give an aid to exploration derisking of these objects. From seismic interpretation it appears in fact that the mineralized sectors of the channels are the ones laterally connected to some gas chimneys that have been recognized in the area (Fig. 5).

In the above example three huge gas chimneys across the Messinian sequence, put in communication the Oligocene thermogenic hydrocarbon kitchen with the Pliocene succession, normally characterized only by dry gas, generated by the Pliocene shales. The role of gas chimney as preferential hydrocarbon migration pathway is testified by the numerous DHIs within the upper Pliocene – Pleistocene reservoirs that are in contact with the boundaries of the gas chimneys. In addition, geochemical analysis on gas samples from targets drilled in the upper Pliocene – Pleistocene indicates the presence of thermogenic gas. Therefore, even if not DHI supported, the sectors of the lower Pliocene in contact with the gas chimneys can be partially derisked and can still represent a remarkable potential in this mature area.

Low sinuosity leveed channels:

The upper portion of the Plio-Pleistocene succession, from sequence 3 to 8, is represented in the study area by the upper to middle slope depositional setting. In this sector of the Nile Delta the slope is affected by strong sediment bypass. Deep incisions are evident on 3D seismic testifying for the downslope transfer of huge amounts of sediment eroding the substrate during its transport. The incisions are often filled by chaotic mass transport units which evolve upward in aggrading low sinuosity cannel complexes characterized by strong facies variations. These channel complexes are deposited by suspended load dominated turbidite flows, generating thick levee facies which confine the channel thalweg (Fig. 6).

The result is the occurrence of linear low sinuosity depositional elements stretching along the slope. These elements, usually made of poorly consolidated sands, are DHI supported and belong to AVO class II or III. They have been successfully drilled in the area within both thick levees facies and channel axis. Levees are up to 100 m thick, mostly silt prone, with low net to gross between 15and 40%. Notwithstanding the very fine grained facies these elements are characterized by good production performance as demonstrated recently by well testing that allowed the estimation for these facies of a maximum open flow rate around 1 MMScm/d with a maximum achieved flow rate of 540 MScm/d.

The channel thalwegsare constituted by 20 to 90 m sand prone section with a N/G ratio of 60-80%. The observed width is variable between 100 and 400 m while their sinuosity is normally low (1.2-1.3) indicating higher slope gradient than the lower Pliocene systems. Only the late stage events are showing high sinuosity reaching a value of 1.5.

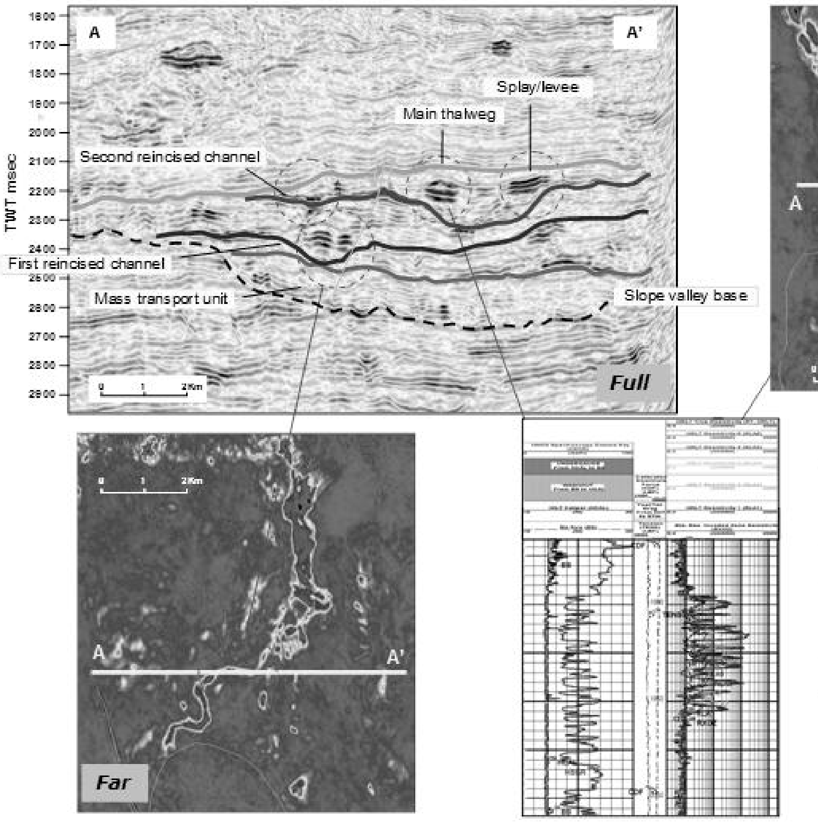
Upper slope ponded lobes and gullies.

In the internal sector of the Nile Delta slope the dominant coarse sediment bypass lead to sedimentation of an almost exclusively shaly succession. The only exception is given by small coarse grained depositional features deposited as confined turbidite lobes or filling of gullies originated by erosional flows along the slope.

The small lobes are associated to synsedimentary normal faults and deposited in the downthrown block, where the fault displacement temporarily creates local sea bottom irregularities (Fig. 7). In these areas the turbidite flows are decelerated and deposit part of their suspended load.

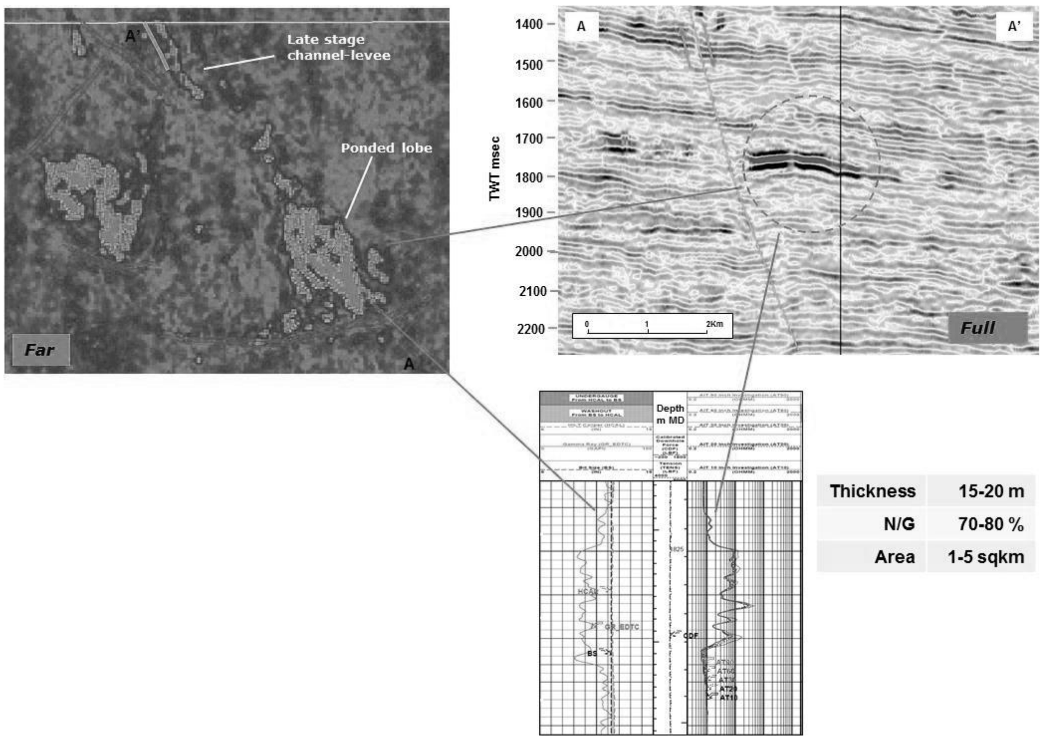
The drilled example of gullie fill is composed by high Net/Gross (87%) 12 m thick blocky sands, passing upward to a 20 m thick abandonment facies made of thick bedded siltstone showing a Net/Gross of 37%.

The ponded lobe facies is given by 15-20 m thick blocky sands. One example from the study area shows on top a fining upward section that indicates the upward evolution to a leveed channel, evident on amplitude maps, testifying for the forestepping of deposition and reactivation of sediment bypass. The overall net to gross is quite high, around 80%.



Thalweg facies	
Thickness	20-90 m
N/G	60-80 %
Width	100-400 m
Length	> 10 Km
Sinuosity	1.2-1.5

Fig. (6): Low sinuosity leveed channels.



Thickness	15-20 m
N/G	70-80 %
Area	1-5 sqkm

Fig. (7): Upper slop ponded lobes.

Some thin bedded silty gas bearing facies, hardly detectable on seismic, have been recorded in this sector of the slope. They probably represent the tail of bypassing turbidite flows within broad incisions or very fine grained thin layered slope lobes deposited by diluted flows due to slight local decrease of the slope gradient. These facies are hardly detectable on both gamma ray and conventional resistivity logs: the recording of OBMI log was fundamental for the net reservoir evaluation and MDT (Modular Dynamic Tester) sampling. The interpretation of the image microresistivity log allowed evaluating a total thickness of around 50 m and 20% of net to gross. By usingMDTs testified for a good mobility indicating that thin beds can represent an overlooked potential in the area that could be evaluated through work over interventions in old wells of exhausted fields.

CONCLUSIONS

- The almost continuous prograding of the Nile delta wedge during the Plio-Pleistocene deposition led to a partial superimposition of different depositional settings. Consequently, the reservoir distribution and occurrence of coarse grained depositional elements is varying in depth and space. The most sand prone section is given by the lower Pliocene section containing, in the northern sector of the studyarea, stacked deepwater turbidite lobes. Detached leveed channel complexes, pinching updip against the shale prone upper slope facies, are the dominant depositional features along the Nile Delta wedge. They normally fill wide deep incisions formed by higher energy flows eroding the slope substrate. The upper slope is dominated by coarse sediment bypass and the reservoir facies are represented by small sized gullie fill and ponded turbidite lobes.
- Considering depositional elements with comparable thickness and Net to Gross the AVO response in the study area is varying according to acoustic impedance changes with burial: class 2/3 in burial depths less than 2400-2500 m, passing to class 1 for higher depths.
- Silt dominated facies, detected in the area as low resistivity unconventional pay, have been proved to be highly productive, representing an overlooked potential.
- Charging of Plio-Pleistocene reservoirs has been proved to be favored by gas chimneys which conveyhydrocarbons from pre-Messinian thermogenic kitchens to the sand prone depositional elements embedded in Kafr el Sheikh shales. Some unrealized potential in no DHI supported Lower Pliocenesection can be associated to the sectors of depositional elements intersected by gas chimneys.

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