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SEQUENCE STRATIGRAPHIC EVOLUTION OF THE POST-RIFT MEGASEQUENCE IN THE NORTHERN PART OF THE NILE DELTA BASIN.

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ABSTRACT

The stratigraphic succession of the subsurface Pliocene-Quaternary post-rift megasequence in the north-central part of the Nile Delta includes the rock units; Kafr El-Sheikh Formation (Early-Middle Pliocene), El- Wastani Formation (Late Pliocene), Mit-Ghamr and Bilqas formations (Quaternary). These rock units were herein analyzed according to the sequence stratigraphic principles to investigate the stratigraphic architecture and discuss the depositional events influencing the evolution of the given megasequence. Accordingly, seven 3rd order depositional sequences were encountered, of which six 3rd order seismic depositional sequences (sequences 1-6) are encountered in the Early–Middle Pliocene Kafr El-Sheikh Formation, whereas the seismic depositional sequence-7 includes the Quaternary rock units. Moreover, the sequences nos. 1 and 7 were further subdivided, on the bases of high-resolution sequence stratigraphy into 8 and 11 4th order subsequences respectively. The results of the sequence stratigraphic analyses provided that the depositional evolution of the examined Pliocene-Quaternary megasequence represents a complete prograding depositional phase during the Nile Delta history. The lower part of Kafr El-Sheikh Formation (sequences 1, 2, 3 and 4) was deposited as a thick outer marine shelf succession over which the younger rock units were deposited. However, the depositional sequences nos. 5 & 6 of Kafr El-Sheikh

Formation and the lower parts of El-Wastani Formations proved deposition within active prograding prodelta sub-aqueous deltaic-subenvironments. The upper parts of El-Wastani Formation were deposited as a constructive delta-front pushing its way northward. The Pleistocene Mit-Ghamr Formation was evolved as a direct result of a huge fluvial input, organized as coalescing laterally extensive sand-rich bars laid-down by active fluvial distributary streams dominated the delta plain as the final phases of the present deltaic subaqueous environments.

1. INTRODUCTION:

The Nile Delta represents one of the world-wide largest delta, occupying an area of about 23,000 Km^2 with a general fan shape slopes northwards by about 1.0 meter per 10.0 kilometers. The Nile Delta province is primarily consisting of fine-grained sediments and forms a thick sedimentary, hydrocarbon-rich succession of Late Tertiary-Quaternary age. The Nile Delta basin is tectonically complicated as it is considered to be part of the passive leading edge of the African continental lithosphere along the southern shore of the Mediterranean Sea (Harms and Wary, 1990). It has undergone passive margin subsidence since the opening of Tethys and also a post-Mesozoic history which has been interrupted by other tectonic events especially in the Late Miocene age.

2. AIM AND METHODS:

This work aims to discuss the depositional evolution of the post-rift Pliocene–Quaternary subsurface megasequence (Sarhan, et al. 2013) in the north-central part of the Nile Delta. This discussion will be ground on the basis of the seismic sequence stratigraphic analyses that will be carried-out utilizing a No. of thirty (2D) seismic profiles, and the geophysical log-data of ten wells. The seismic profiles and logs were kindly provided by the PETROBEL under permission of The Egyptian General Petroleum Corporation (EGPC).

The study area (2700 km^2) encompasses the north central part of the Nile Delta, lying between Latitudes 31^o 12 ' and 31^o 52 ' N (a distance of 73 km), Longitudes 31^o 6 ' and 31^o 29 ' E (a distance of 37 km). It extends both in the northern onshore part of the Nile delta and in the southern offshore part of the Mediterranean Sea (Fig. 1).

Through this work, the seismic profiles will be used to subdivide the post-rift megasequence into smaller third-order depositional sequences that help understanding the regime of the expected sea-level fluctuations influencing the deposition of the Pliocene-Quaternary megasequence, and constructing the relative sea level curve characterizing that time in order to deduce the geologic evolution and the depositional models for the examined megasequence. The above-mentioned subdivision of the post-rift megasequence has been done using the detailed seismic sequence interpretations of the investigated seismic reflection profiles covering the study area. This analysis adopted Exxon model because the downward shifts in coastal onlap are obvious in all seismic reflection profiles, and also because the three part sequence model (LST, TST and HST) can be distinguished from seismic data in addition to the gamma ray responses for the investigated wells.

It is of worth mentioning that the seismic sequence stratigraphic analysis has been done for the N-S trending seismic profiles as they represent the dip seismic profiles, especially for the offshore seismic profiles and they also have relatively better resolution than those covering the southern onshore part of the study area. All of these seismic sequences have been then tied to the wells using the constructed time – depth curves depending upon the available VSP logs. Consequently, the depths to the interpreted sequences boundaries in addition to the thickness for each sequence have been calculated.

To carry out the seismic sequence stratigraphic analysis, access has been gained to thirty 2D seismic reflection profiles covering the study area (Fig. 2) and to the relevant shot point location map, in addition to geophysical log data of ten wells (Abu Madi-2, Abu Madi-7, Abu Madi-16, El-Qaraa-2, El-Qaraa-3, JG 63-1, JH 63-2, Nidoco-7, Nidoco-9 and Nidoco-10). The logs include composite logs, sonic logs and Vertical seismic profile (VSP). In addition, composite logs and time – depth curves were available for two wells (JC 65-1 & JC 65-2) which cut through the study area. Because of the available seismic data represents multiple seismic surveys (two onshore surveys; AM-81 and BIL-81 in addition to three other offshore surveys; JG-61, JG-64 and JF-63) with different acquisition and processing parameters, therefore the direct comparison of seismic facies between these different surveys is not possible and only qualitative descriptions within the individual seismic lines in different surveys have been applied.

The high resolution sequence stratigraphic analysis has been applied depending on the gamma ray logs to subdivide the 3rd order sequences (seismic sequences) into the higher 4th order (sub-seismic sequences). This analysis has been applied to the thickest seismic sequences in the post-rift megasequence (sequence -1 of Lower - Middle Pliocene in age and sequence -7 of Upper Pliocene-Pleistocene in age).

3.1 SEISMIC SEQUENCE STRATIGRAPHY:

Careful inspection of the well-logs of the drilled wells in the study area proved that the post-rift megasequence is lithostratigraphically represented by a series of successive rock units, namely from the base as; Lower-Middle Pliocene Kafr El-Sheikh Formation followed by the Upper Pliocene El-Wastani Formation which is overlain by a Quaternary succession of Mit-Ghamr and Bilqas formations respectively. The seismic sequence stratigraphic analyses for the examined time span has revealed seven sequence boundaries demonstrated by the reflector terminations approach in the geologic sense of Vail et al (1977). All the seismic-scale sequence boundaries are Type 1 boundaries. These boundaries separate seven-related seismic sequences (sequence 1 – 7). These sequences display the overall northward progradational pattern of the Nile Delta, reflecting the migration trend of the Nile Deltaic offlap break. Generally, the total geometry of all seismic sequences displays northward-dipping clinoforms in shape. However, both sequence-4 and sequence-6 display southward thinning, hence they disappear onshore-ward of the study area. In addition, it is herein suggested that the identified offlap break is migrated in an aggradational / progradational pattern. This is because the clinoforms of the shelf-edge break can be resolved seismically where it has enough thickness to be identified on the seismic profiles (several hundreds of meters in thickness), however the shoreline clinoforms (20 to 200 m thick) are hard to be recorded especially that the available seismic data are of low resolution. Also, the identified slope-angle in the examined seismic profiles thought to be more than 1^{o} which is a distinctive feature of the shoreline break (Helland-Hansen and Hampson, 2009).

In the present work, seven seismic sequences have been identified (Fig.3a & b) and discussed in details including the description of their boundaries, age relations, distribution, geometry, the interpreted system tracts and seismic facies analysis. The depositional sequences encountered are distributed so that six depositional sequence fall in the Early – Middle Pliocene Kafr El-Sheikh Formation, whereas the seventh sequence encompasses El-Wastani, Mit-Ghamr and Bilqas formations of Late Pliocene – Quaternary age. Table (1) summarizes the depths for different seismic sequences and their thicknesses in the investigated four wells that extend from south to north. The system tracts within each sequence have been investigated in each depositional sequence depending on both seismic profiles and well logs analyses. Moreover, the high-resolution analyses made using the available gamma-ray log have enabled subdivision of the depositional sequence-1 into eight 4th/5th order sequences, whereas, the depositional sequence-7 was subdivided into eleven 4th/5th order ones:

<u>3.1. The Seismic Sequence – 1:</u>

The seismic sequence-1 is the lower-most depositional sequence in the examined megasequence, lying over the top of the Upper Miocene syn-rift Abu Madi Formation (Sarhan et al, 2013). It encompasses most of the Early Pliocene Kafr El-Sheikh Formation (Fig.4a). The sequence is the thickest in the present megasequence, ranging between 0.90 s (northward) to 1.75 s (southward) with noticeable northward thickness decrease.

<u>3.1.1. Sequence boundaries</u>:

The seismic sequence-1 is bounded by SB-1 at the bottom and by sequence boundary SB-2 at the top. The lower boundary (SB-1) represents the top surface of Abu Madi Formation (i.e. the boundary between the syn-rift and the post-rift Megasequences). According to Schlische (1995) the surface between syn-rift and post-rift rocks is termed as the post-rift unconformity. This boundary is herein identified by the onlapping relation between the given boundary and the overlying seismic reflectors termination of sequence-1 as shown in Fig. (3a). According to the present attitude of the seismic characteristics of SB-1, it is herein regarded as of type-1boundaries of Van-Wagoner et al (1988). On the other hand, SB-2 is recognized by the onlapping relations with the lower internal reflectors of the succeeding seismic sequence–2. It is of worth mentioning that the northward-gradient of dip direction of SB-2 (0.90 to 2.05) exceeds that of SB-1 (2.65 to 2.95). This attitude results in the northward thinning of the present sequence.

<u>3.1.2. Seismic Facies and Systems Tracts:</u>

The reflectors of seismic sequence-1 exhibit continuous, high to very high amplitude with parallel to sub parallel orientation extending for 10 km in the lower part above SB-1. Similar reflector characteristics are displayed in the upper-most parts below SB-2. However, the seismic reflectors in the middle part of the sequence display laterally semi-continuous to discontinuous reflectors with moderately to low amplitude (Fig. 3a).The onlapping terminations of the internal seismic reflectors on SB-1 represent the downward shift in coastal onlap i.e. the prograding low-stand wedge of the lowstand systems tract (LST). It is of worth mentioning that the maximum flooding surface (mfs-1) has not been seismically distinguished due to the low resolution of the examined seismic profiles, especially at these great depths. This also enabled no detection of the transgressive systems tract (TST) and high-stand systems tract (HST) within sequence-1.

Based upon the gamma-ray responses available for the wells laying along the dip seismic profiles, the 3rd order seismic sequence-1 has been subdivided into eight 4th order depositional sequences (sub-seismic sequences) using to the high resolution sequence stratigraphic analysis. In this concern, these minor cycles reflect shot-lived sea level fluctuations during the Early – Middle Pliocene age (Fig. 4b).

3.2. The Seismic Sequence – 2:

This sequence is recorded all over the study area and the off-shore extension, displaying northward-thinning geometry (Fig. 3). It overlies the sediments of the seismic sequence-1, occupying the thickness range from 0.14 s to 0.34 s within the Early-Middle Pliocene Kafr El-Sheikh Formation. This age is further confirmed by tying the available seismic profiles with the composite well-logs drilled in the study area.

3.2.1. Sequence boundaries:

The seismic sequence-2 is defined by the boundary (SB-2) at the base and the boundary (SB-3) at the top. The time depths of SB-2 show increasing in depth from 0.9 s in the most southern part (onshore) to 2.05 s in the most northern part (offshore), SB-3 has been identified by the downward-shift of the coastal-onlap recorded between the given boundary and the internal reflectors of the overlying sequence-3 (Fig. 5). Seismic facies relationships and the attitude of the given boundary, as well as the confirming well-logs all support that both (SB-2) and (SB-3) are of type-2 boundaries of Van-Wagoner et al (1988).

3.2.2. Maximum flooding Surface (mfs-2):

The maximum flooding surface (mfs-2) has not been traced on the present seismic profiles as the TST is too thin to be resolved in the seismic profiles, however the TST has been traced in the available gamma ray well-logs of the examined wells between depths 1460 and 1470 m, just below the HST (Fig. 3c).

3.2.3. Seismic Facies and Systems Tracts:

Most of the sequence-2 is characterized by very high amplitude continuous to semi-continuous reflectors, extending for 25.0 km (Fig. 6). These reflectors show parallel to sub-parallel configuration that reflect uniform rates of deposition on a regularly subsiding basin floor. To the south of the study area, the onshore seismic profiles exhibit significant mound-configurations (Fig. 7). These mounds (4.0 km in width) are characterized by downlapping reflectors from the overlying strata, filling around the mounds. These Mound-features are interpreted in terms of subsequent deposition above the general level of the surrounding strata. According to Vail (1987), this configuration could be interpreted as basin-floor fan, and may represent a hydrocarbon prospect, so it can be herein recommended that such geometries should receive much care for hydrocarbon exploration in the study area.

The onlap characters of the internal reflectors of sequence-2 on SB-2 suggest a lowstand systems tract (LST), (Figs. 3a & 3b). Moreover, the interpreted mound-configurations (Fig. 3.a) suggest lowstand basin floor fans. Both transgressive systems tract (TST) and high-stand systems tract (HST) could not herein be resolved seismically; hence the maximum flooding surface (mfs-2) could not be seismically detected, however the gamma-ray well-logs proved such resolve (See 3.2.2).

3.3. The Seismic Sequence – 3

The seismic sequence-3 represents a part of the Middle Pliocene Kafr El-Sheikh Formation, conformably overlying the sediments of seismic sequence-2. This sequence extends all over the study area, ranging in thickness from 0.07 s to 0.32 s. Generally, this sequence displays a specific geometry; while it thins northward and southward, it however muchly thickens in the east-central part of the study area (Fig. 3).

3.3.1. Sequence boundaries:

The seismic Sequence-3 is defined by sequence boundaries (SB-3) at the base, and by (SB-4) at the top. Both sequence boundaries have been recognized by the downward shift in coastal onlap which described by the onlapping terminations of the overlying internal reflectors on both boundaries. The time depths of SB-3 show gradually increasing in depth from 0.80 s in the south to 1.85 s in the north direction.

3.3.2. The Maximum Flooding Surface (mfs-3):

The maximum flooding surface (mfs-3) has not been traced on the present seismic profiles, however the precise inspection of the available well-logs proved that the TST occurs between depths 1110 m and 1135 m and the situation of the mfs-3 at depth 1110 m below the HST in the examined wells (Fig. 3c). The reason why the given surface was not traced seismically is related to the marked thinning of the TST (See 3.3.3).

3.3.3. Seismic Facies and Systems Tracts:

The reflectors of seismic sequence-3 shows relatively high to moderate amplitude and laterally semi-continuous to discontinuous reflectors extends approximately over a maximum distance of 5 km (Figs. 5 & 6). These reflectors display sub-parallel configuration, although subtle downlapping reflectors occur in the upper part of this sequence (Fig. 3a).

The lower part of sequence-3 reflectors shows onlapping terminations against SB-3 and this architecture has been interpreted as progradational lowstand wedge of a lowstand systems tract (LST). As regard to the transgressive systems tract (TST) of this sequence, it was difficult to trace this tract along the seismic profiles where it is too thin to appear on the profiles. Well logs indicate that this tract only attains 25 m thick (Fig. 3c) which is too hard to be detected on seismic profiles, since a single reflector expresses 40 – 50 m at least (Emery & Myers, 1996). The well logs show that the TST is characterized by retrogradational-aggradational stacking pattern which identified from the gamma ray logs by the fining upward parasequences set. The HST, on the other hand, follows the TST and displays upward change from aggradational to progradational stacking patterns (Fig. 3c).

As previously recorded along the basin floor of the depositional sequence-2, there is a clear basin floor-fan has been identified in sequence-3 (Fig. 3a) in the offshore dip seismic profile (No. JG 63-5). Accordingly, further recommendation is advised to pay more attention for hydrocarbon exploration in such parts based upon the findings of Vail (1987).

3.4. The Seismic Sequence – 4:

Seismic sequence-4 overlies the sediments of the seismic sequence-3 in the Middle Pliocene Kafr El-Sheikh Formation. This sequence only extends in the offshore part and pinches-out southward toward the onshore part of the study area (Fig. 7). It ranges in thickness between 0.00 s (in the onshore part) and 0.23 s northward showing relatively NW-SE trending sedimentary body (Fig. 3a).

3.4.1. Sequence boundaries:

The seismic Sequence-4 is defined by sequence boundary (SB-4) at the base, and sequence boundary (SB-5) at the top. SB-4 is onlapped by the overlying reflectors of seismic sequence-4, reflecting downward shift in coastal onlap. The time depths of SB-4 show gradually increase in depth northward from 0.75 s in the south to 1.70 s in the north. The upper SB-5 has been recognized as an onlapping surface for the internal reflectors lie within sequence-5.

3.4.2. The Maximum Flooding Surface (mfs-4):

The maximum flooding surface (mfs-4) has been traced as a downlapping surface separates between the lower retrogradational transgressive systems tract (TST), and the upper progradational clinoforms of the high-stand systems tract (HST) (Fig. 3).

3.4.3. Seismic Facies and Systems Tracts:

The seismic reflectors of seismic sequence-4 have moderately to high amplitude in the lower and middle parts of the sequence. Generally, this sequence is characterized by continuous parallel to semi-parallel reflectors (expands laterally over 6 km) that change laterally into semi-continuous reflectors (Figs. 3a & 6). Moreover, the reflectors in the upper-most part represent downlapping termination against a relatively continuous reflector with moderate amplitude (Fig. 3a) which reflect the progradational pattern indicating that the rate of sedimentation exceed the rate of subsidence.

The seismic reflectors-stacking pattern of sequence-4 can be subdivided into two successive parts. The lower part displays the onlapping character on SB-4 which can be interpreted as the lowstand systems tract (LST) followed by the transgressive systems tract (TST) however; the upper progradational clinoforms pattern matches the high-stand systems tract (HST). This high-stand systems tract (HST) is downlapping on the maximum flooding surface (Figs. 3a & 5). It is worth to mention that the transgressive systems tract (TST) is very thin to be resolved from seismic profiles but it has been identified from the well-log with 10 m thick (from depths 1010 m to 1020 m).

3.5. The Seismic Sequence – 5:

The seismic sequence-5 overlies seismic sequence-4, and occupies the upper levels of the Middle Pliocene Kafr El-Sheikh Formation. This sequence is well traced all over the study area. It ranges in thickness from 0.10s to 0.20 s with general northward thickening (Fig. 3a).

3.5.1. Sequence boundaries:

The seismic sequence-5 rests directly above the sequence boundary (SB-5) and is topped by the sequence boundary (SB-6). The sequence boundary (SB-5) has been traced as onlapping surface reflecting the downward shift in coastal onlap. The time depths of SB-6 display progressive increasing depth from 0.75 s in the south (onshore) to 1.50 s toward north direction (offshore).

3.5.2. The Maximum Flooding Surface (mfs-5):

The maximum flooding surface (mfs-5) is herein recorded as the surface separates between the lower retrograding parasequences of the transgressive systems tract (TST), and the upper prograding parasequences of the high-stand systems tract (HST), (Figs. 3a & 3b).

3.5.3. Seismic Facies and Systems Tracts:

The seismic sequence-5 is characterized by semi-continuous to discontinuous reflectors with relatively moderate to low amplitude, extending laterally over a distance of 8.0 km (Figs. 3a & 5). Most of the internal reflectors show minor parallelism in configuration. Generally, the lower reflectors display southward retrogressive onlapping bundles. On the other hand, the upper reflectors display northward progressive downlapping bundles (Fig. 8), a pattern that is recorded for the first time in Early-Middle Pliocene Kafr El-Sheikh Formation. These northward progressive reflectors indicate the first northward deposit-loads derived into the present basin from the southward territories. They are herein regarded as the initial terrestrial distal fluvial input derived from far-situated southern River Nile System. Finally, the most top reflectors are toplapped by the upper SB-6.

The seismic reflector-stacking pattern of the lower parts of the sequence-5 display onlap relation to the lower boundary (SB-5) representing the lowstand systems tract (LST) followed by the transgressive systems tract (TST). This transgressive systems tract (TST) is topped by the high-stand systems tract (HST) whose reflectors display downlapping termination on the maximum flooding surface (mfs-5), (Figs. 3a, c & 5).

3.6. The Seismic Sequence – 6:

The sequence-6 represents the upper-most sequence in the succession of the Middle Pliocene Kafr EL- Sheikh Formation. It terminates the depositional history of Kafr El-Sheik Formation in the study area. This sequence has been only recorded in the offshore part of the study area because it displays marked southward-thinning before it disappears in the onshore part of the study area (Fig. 7). It ranges in thickness from 0.00s to 0.24s. The thickest part in the seismic sequence-5 is recorded in the far northward region of the study area, reflecting south-north depositional dispersal trend (Figs. 3a & 9).

3.6.1. Sequence boundaries:

The seismic sequence-6 is defined by key sequence boundaries (SB-6) at the base and (SB-7) at the top. The time depths of (SB-6) show northward gradual increase in depth from 0.67 s in the south to 1.27 s. The boundary is recognized by the downward shift in coastal onlap which is represented by the onlapping terminations of the reflectors directly overlying SB-6. The upper boundary (SB-7) displays toplapping surface to the upper-most internal reflectors of sequence-6 (Fig. 3).

3.6.2. The Maximum Flooding Surface (mfs-6):

The maximum flooding surface (mfs-6) has been recognized on the seismic profiles as a downlapping surface separates between the retrogradational parasequences of the transgressive systems tract (TST) below and the progradational parasequences of the high stand systems tract (HST) above (Figs. 3a & 3b).

3.6.3. Seismic Facies and Systems Tracts:

The onlapping reflectors constituting the lower part of sequence-6 against the lower SB-6 represent the lowstand systems tract (LST) followed by the transgressive systems tract (TST) of the given sequence (Figs. 3a & 10). On the other hand, the downlapping reflectors in the middle part of the sequence may be interpreted as the high-stand systems tract (HST) with progradational nature (Figs. 3a & 5). The interpreted channel fill scoured into the SB-6 as shown in Figs. (8 & 9) may represent sub-aqueous erosional process during the formation time of the SB-6. According to Vail (1987), this interpreted buried channel fill could be recommended from the present work for the future exploration activities as it may represent a hydrocarbon prospect in the study area.

Most of the reflector-packages of sequence- 6 display slightly low to moderate amplitude with laterally semi-continuous to continuous reflectors, extending over a minimum distance of 10 km (Fig. 6).These reflectors represent relatively sub-parallel to parallel configuration and display a unique seismic facies pattern, herein recorded for the first time. This facies pattern declares that the depositional sequence is entirely formed of northward downlapping parallel to sub-parallel reflectors with full absence of southward coming onlapping ones (Fig. 3.a). This further supports the findings recorded before in sequence-5 concerning the terrestrial loads coming by distal distributaries from far-situated river system. However, here during the time of sequence 6, the southern terrestrial-input becomes greater and more significant, so that the northward-input became insignificant or disappeared. Moreover, a striking northward erosional feature cut through SB-6 (Figs. 9 & 10) is herein further recorded. It has 3.0 km width and displays trough-shaped pattern filled with reflectors terminate against the trough-flanks (onlapping patterns). This feature suggests later filling-sediments as channel-fills laid-into the study basin during a falling stage of the relative sea level, thus it is regarded as representing an incised valley. This interpretation is further supported due to the stratigraphic position of such features, commonly reported during the final depositional stages of depositional sequences, especially that the present sequence terminates the actual marine sedimentation in the Nile Delta prior to the progradation of the overlying Quaternary fluvial distributaries.

3.7. The Seismic Sequence – 7:

The seismic sequence-7 represents the upper part of the Neogene-Quaternary sedimentary succession Nile Delta megasequence. Seismic sequence-7 encompasses the Late Pliocene El-Wastani Formation and the overlying Plio-Pleistocene-Holocene Mit-Ghamr and Bilqas formations. This sequence extends all over the study area and varies in thickness between 0.67 s and 1.07 s northward (Figs. 3a), following sequence-1 in thickness.

3.7.1. Sequence boundaries:

The seismic sequence-7 is defined only by the lower sequence boundary (SB-7) which displays northward increasing in depth from 0.67 s to 1.07 s. This boundary is defined by downlapping characters of the overlying sequence-7 internal reflectors; also it acts as toplapping surface on the internal reflectors of the underlying sequence-6 (Fig. 3a).

3.7.2. Seismic Facies and Systems Tracts:

Seismically, the internal reflectors of the seismic sequence-7 display a specific architecture of well-stacked reflectors having narrow-spacing and strong parallelism. This reflector-architecture made it very difficult to trace the maximum flooding surface (mfs-7). The internal reflectors display moderate to high amplitude especially in the lower and upper parts of the sequence. Most of these internal reflectors show laterally extensive continuous parallelism with horizontal orientation extends over than 12.0 km (Figs. 9 &10).

Based upon the gamma ray well log analysis, the Late Pliocene – Pleistocene seismic sequence-7 (including El Wastani, Mit-Ghamr and Bilqas formations) has been classified into eleven 4th to 5th order depositional sequences. These small cycles reflecting the relative sea level fluctuations during the Late Pliocene - Pleistocene time (Fig. 11).

4. THE SEA-LEVEL REGIME DURING THE PLIO-QUATERNARY MEGASEQUENCE OF THE NILE DELTA:

The generalized curve representing the relative sea level fluctuations over the Nile Delta basin during the Pliocene-Quaternary times has been constructed depending upon the above-discussed sequence stratigraphic interpretations. Comparison of the encountered sea-level fluctuations (short-term) with those long-term eustatic sea level fluctuations curve of Haq et al (1987) reflects an overall regression phase during the Neogene – Quaternary times (Fig. 12.a).

Recently, Al-Husseini (2013) has established and investigated the implications of the Antartica's glacio-eustatic sea-level curve during the entire span of Aptian and late Miocene–Holocene along the Arabian Plate. The Plio-Pleistocene sea-level fluctuated cycles are simplified in Fig (12.b). Inspection of Al-Husseini (2013) Plio-Pleistocene sea-level cycles in correlation to the concluded sea-level fluctuations concluded herein during the same time span (Fig. 12.a) provide the following remarks:

1- The Plio-Pleistocene was a time-span of world-wide general gradual sea-regression, especially during the Pleistocene.

2- The sea-level oscillations recorded during the deposition of the Early-Middle Pliocene Kafr El-Sheikh Formation, especially those belonging to the depositional sequences (Nos. 1 - 4), are most-likely echoing the Zanclian-Piacenzian sea-level cycles (Nos. 13(?) – 9) of Al-Husseini (2013).

3- The youngest depositional sequences during the Lower-Middle Pliocene Kafr El-Sheikh Formation (depositional sequences Nos. 5 & 6) could be related to the Upper Piacenzian-Lower Gelasian sea-level cycles (Nos. 8 & 7) of Al-Husseini (2013).

4- The generally regressive depositional phase encompassing the Pleistocene-Holocene depositional sequence No. 7 (El-Wastani, Mit-Ghamr and Bilqas formations) with its 4th order fluctuations matches with the Upper Gelasian-Holocene regressive depositional sea-level cycles (Nos. 6 – 1) of Al-Husseini (2013).

It is in worth to mention that not all the Pliocene-Quaternary glacio-eustatic cycles of Al-Husseini, (2013) represented in the limited study area in the northern part of the Nile Delta. This may be due to the autocyclic switching of the position of the Nile River on the delta top. Accordingly, some cycles may only have been developed (to a seismically identifiable scale) to the east or west of the study area. So it is not a surprise to distinguish fewer cycles in the study area than there are in the complete (global) sea level curve.

5. THE SEDIMENTOLOGICAL EVOLUTION OF THE PLIO-QUATERNARY MEGASEQUENCE OF THE NILE DELTA BASIN:

The depositional history for the Pliocene - Quaternary post-rift subsurface megasequence of the Nile Delta basin can be summarized based upon the conclusions of the aforementioned sequence stratigraphic analysis, together with concerned previous literatures whose role can not be denied to express the most conclusive sedimentation history:

5.1. Early - Middle Pliocene

By the Early Pliocene times, a major marine transgression took place, submerging the Miocene and older syn-rift sediments. This is matching with the findings of the subtle global-warming trend from 6.0 Ma to 3.2 Ma, indicated by the increasing δ O18 values (Zachos et al, 2001). According to Pipkin & Trent (1996) the straight of Gibraltar was reopened with the Early Pliocene time, thus a huge marine-water invasion of the Atlantic Ocean pushed its way eastward into the almost-dry Mediterranean basin and rapidly flooded the northern parts of Egypt where a widespread marine transgression accompanied with sea level rise took place submerging the northern Egypt and even the southern territories (Zaghloul et al, 1977). Accordingly, the lower part of Kafr El-Sheikh Formation was deposited in the Early Pliocene time as a thick deep marine shale section interbedded with poorly consolidated sands under strongly transgressive sea conditions (Zaghloul et al, 1977), most likely within an outer shelf depositional environment (EGPC, 1994) or outer neritic environment (Abd El Aal et al, 1994).

In the present study, the Early- Middle Pliocene Kafr El-Sheikh Formation constitutes a considerable part of the subsurface succession of the Plio-Quaternary megasequence. The formation is seismically subdivided into six 3rd order depositional sequences (namely from the base; sequence -1, sequence -2, sequence -3, sequence -4, sequence -5 and sequence -6) of which the depositional sequences nos. 1, 2, 3 and 4 represent the widespread marine transgressive phase of the outer marine shelf depositional setting (Fig. 12) upon which the other depositional subenvironments were developed. This is conformable with the findings of Zaghloul et al (1977) and Said (1981) who reported a sea transgressive phase over the Egyptian territories that reached maximum during the deposition of Kafr El-Sheikh Formation where it pushed its way through a narrow embayment (Delta and Nile Valley), and reached as far south as Aswan.

As regard to the depositional sequences nos. 5 and 6 forming the top-most parts in the succession of Kafr El-Sheikh Formation, they were found to have a unique facies architecture not recorded in the lower four sequences. These two sequences proved a significant terrestrial-input which effectively participated in the evolution of the concerned sequences. This terrestrial-input was interpreted in terms of successive loads derived by distal fluvial distributaries of a south-situated river system. Accordingly, it is herein considered that the depositional sequences no. 5 and no. 6 of the upper part of Kafr El-Sheikh Formation as forming together a part of a progressively growing (prodelta) started at the final stages of the Middle Pliocene (Fig. 13).

5.2. Late Pliocene - Pleistocene

The Late Pliocene and Pleistocene sediments of the present megasequence are represented by El- Wastani Formation, Mit-Ghamr Formation and Bilqas Formation; respectively. In this concern, Bilqas Formation attains a thickness does not exceed 60.0 m (Zaghloul et al, 1977). In case of seismic facies analysis, a single reflector summarizes the lithological character of about 40-50 m. Therefore, it was very difficult to resolve the seismic reflectors representing Bilqas Formation. Accordingly, this study could not separate Bilqas Formation from the underlying Mit-Ghamr Formation and treated them as one seismic unit and regarded as one depositional sequence -7 of Pleistocene age.

5.2.2. The Late Pliocene Phase:

The Late Pliocene depositional phase of the Nile Delta subsurface Megasequence encompasses the total sediments of El-Wastani Formation, base of Sequence-7. El-Wastani Formation is depositionaly composed of sheet sands with shale interbeds which were stacked successively as northward downlapping strata over the former successions (Zaghloul et al., 1977). The seismic reflectors of the lower parts of this formation are always seen at the base of the depositional sequence-7. They display successive downlapping seismic facies pattern with northward progradation. The comparative seismic facies analysis of the lower parts of El-Wastani Formation and the underlying depositional sequence nos. 5 & 6 of Kafr El-Sheikh Formation support that they constitute a similar continuous seismic facies pattern evolved under the same depositional conditions. These parts proved a gradual basin progradation coupled with a noticeable terrestrial charge into the basin of deposition from nearby, southward-situated large fluvial system. Therefore, it is herein considered that the lower parts of El-Wastani Formation and the underlying sequence no. 5 & 6 of Kafr El-Sheikh Formation represent the prodelta subenvironment of the Nile Delta receiving the early fluvial loads derived from the distal distributaries of the River Nile into the Mediterranean basin during the Late Pliocene times. These findings match well with those of Zaghloul et al. (1979).

As regard to the remaining upper parts of El-Wastani Formation, the seismic reflectors representing this part display a well-stacked toplapped architecture indicating a considerable terrestrial-input laid into the basin. This assumes considerable detrital-sediment charge by terrestrial loads driven into the depositional basin, resulting in considerable volume reduction of El-Wastani Formation accommodation zone (S>A). Consequently, the upper part of El-Wastani Formation is herein suggested to represent the subaqueous delta-front of the present Nile Delta megasequence. These findings are conformable with those of El-Fawal, 1979; Zaghloul et al. (1979 and 2001).

5.2.3. The Pleistocene-Holocene Phase:

As regard to Mit-Ghamr and Bilqas formations forming the remaining succession of the Pleistocene depositional sequence-7, their seismic reflectors exhibit well stacked, closely-spaced, parallel, and continuous to sub- continuous reflectors. This architecture represents a progressively huge rapid sediments influx strongly laid-into the Pleistocene accommodation zone whose volume is now strongly diminished (S>>A). Therefore, Mit-Ghamr Formation is herein regarded as a unit deposited under a depositional regime, mostly similar to that started below during the final phase of El-Wastani Formation delta-front; however, it is more active and more prominent. In other words, the depositional regime during Mit-Ghamr Formation was a continuation of the early started active fluvial charges, however in huge quantities. Therefore, Mit-Ghamr Formation is herein considered as deposited with huge fluvial-input organized as coalescing distributary mouth-bars; commonly close the history of the deltaic-sub-aqueous environments (Coleman, 1981; Miall, 1984 and Reading, 1996)

6. CONCLUSIONS:

6.1. The Pliocene-Quaternary post-rift megasequence (Sarhan et al, 2013) beneath the north central part of the Nile Delta basin encompass Kafr El-Sheikh, El- Wastani, Mit-Ghamr and Bilqas formations. This megasequence has been subdivided in the framework of sequence stratigraphic analyses into **seven** 3rd order depositional sequences. Kafr El-Sheikh Formation (Early–Middle Pliocene) encompasses **six** 3rd order seismic depositional sequences (depositional sequences nos.1-6). Moreover, the first depositional sequence-1 was further subdivided into **eight smaller** forth and/or fifth order smaller sequences based upon the available gamma-ray logs. On the other hand, the depositional sequence-7 encompasses the sediments of El-Wastani, Mit-Ghamr and Bilqas formations. This sequence was further subdivided into **eleven** forth and/or fifth order smaller sequences based upon the available data of gamma-ray logs.

6.2. The comparison of the concluded local sea-level fluctuations with the standard long term eustatic sea-level fluctuation curve of Haq et al. (1987) reflects an overall marine regressive phase during the Pliocene - Quaternary times.

6.3. The present sequence stratigraphic analysis of the Pliocene-Quaternary megasequence subsurface succession in the north central part of the Nile Delta basin has enabled the following remarks concerning the depositional evolution of the given succession:

a) By the Early Pliocene time, a major marine transgression took place due to the reopening of the Straight of Gibraltar and the invasion of the Atlantic Ocean into the almost dry Mediterranean basin, and hence a widespread sea level rise took place submerging the northern Egypt. These conditions have resulted in the deposition of the lower part of Kafr El-Sheikh Formation (sequence 1, 2, 3 and 4) as a thick deep outer shelf marine succession, representing the shelf sub-aqueous succession of the Pliocene-Quaternary subsurface deltaic megasequence under study (Fig. 14).

b) During the Middle-Late Pliocene times, the depositional sequences nos. 5 & 6 of Kafr El-Sheikh Formation and the lower parts of El-Wastani Formations, all constituted a sedimentary package deposited within active prograding basin under the influence of a terrestrial detrital charge from far distal fluvial distributaries of the River Nile system situated to the south. This sedimentary package represents the prodelta sub-aqueous deltaic subenvironment of the Pliocene-Quaternary subsurface megasequence (Fig. 15).

c) The final stages of the Latest Pliocene including the upper parts of El-Wastani formation witnessed more significant basin prograding and more terrestrial detrital charge than recorded below. The upper parts of El-Wastani Formation represent a sequence deposited within more active prograding basin under continuous supply of terrestrial sediment-charge by more prominent fluvial distributaries of the south-coming river Nile. The Upper parts of El-Wastani Formation are suggested to represent the delta-front sub-aqueous deltaic subenvironment of the Pliocene-Quaternary subsurface megasequence (Fig. 16).

d) During the Pleistocene Mit-Ghamr Formation, a huge terrestrial detrital loads derived into the depositional basin by the active fluvial distributaries of the River Nile leading to a marked basin prograding accompanied by a noticeable reduction of the accommodation zone relative to the sediment-charge (S>>A). Thus, the basin of the Plio-Quaternary sub-aqueous Nile Delta megasequence came to the filling-state, giving way to the sub-aerial facies (Holocene Bilqas Formation) to dominate. The Pleistocene Mit-Ghamr Formation is thus regarded as the sedimentary body developed due to the successive loads of the laterally coalescing River Nile distributary mouth bars (Fig. 17).

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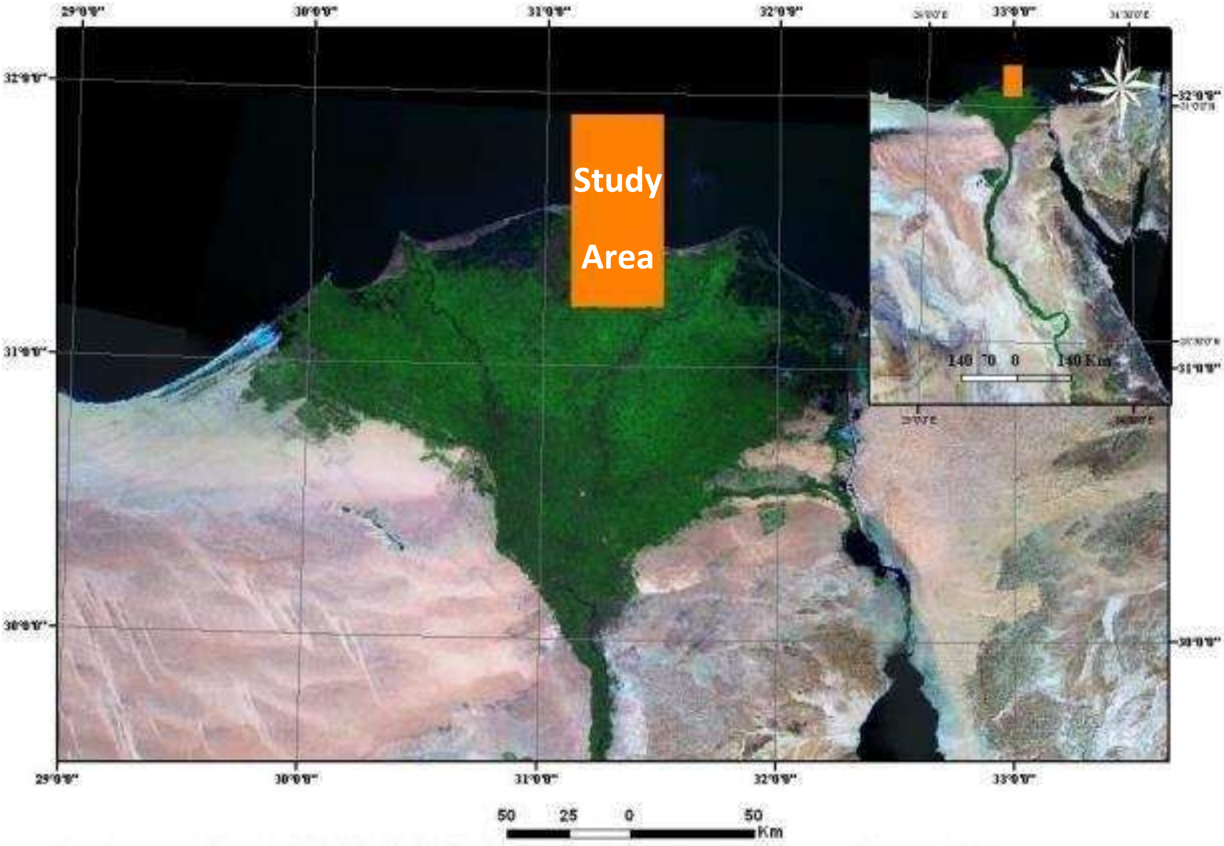


Fig. (1): Landsat satellite image showing the location of the study area

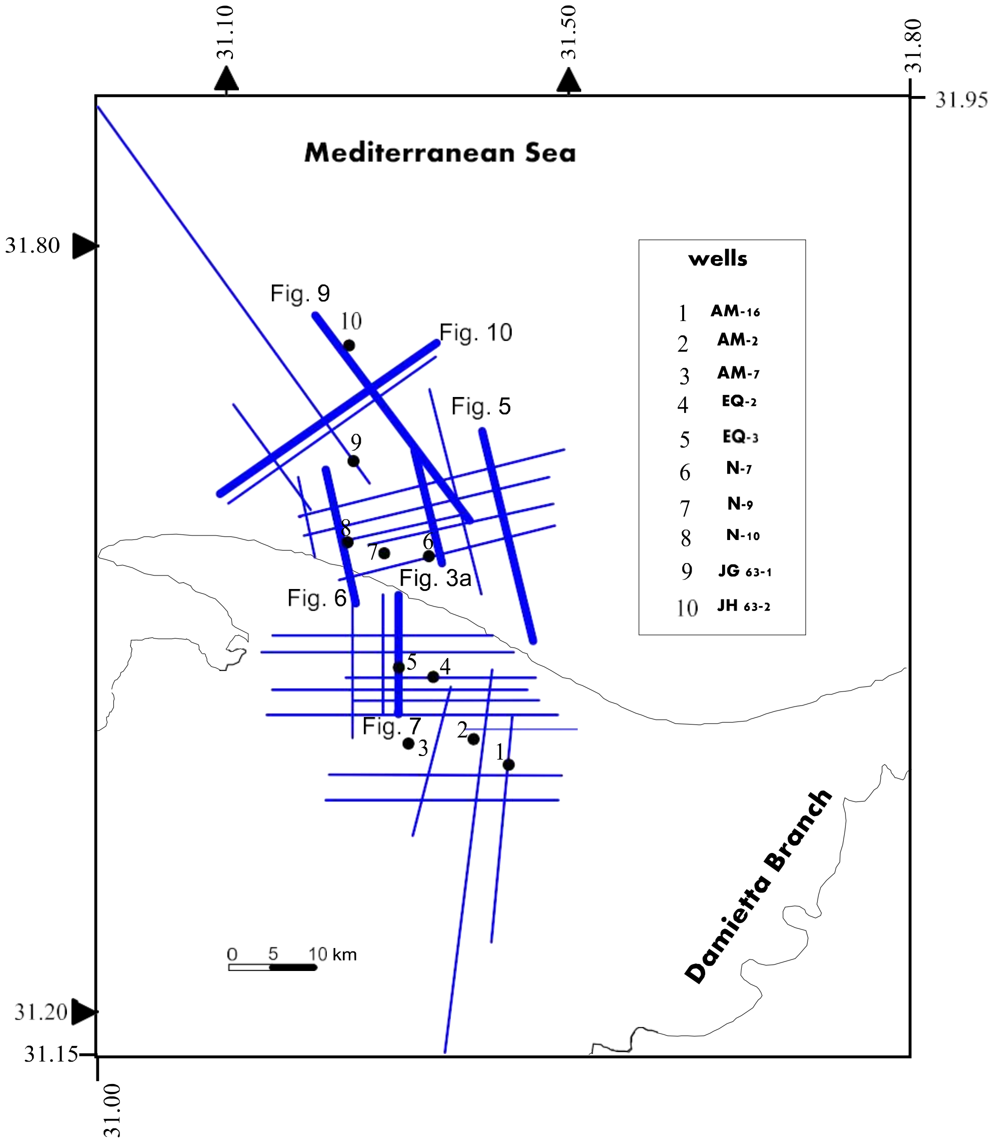


Fig.(2): Seismic reflection profiles covering the study area with well sites cut throw the study area.

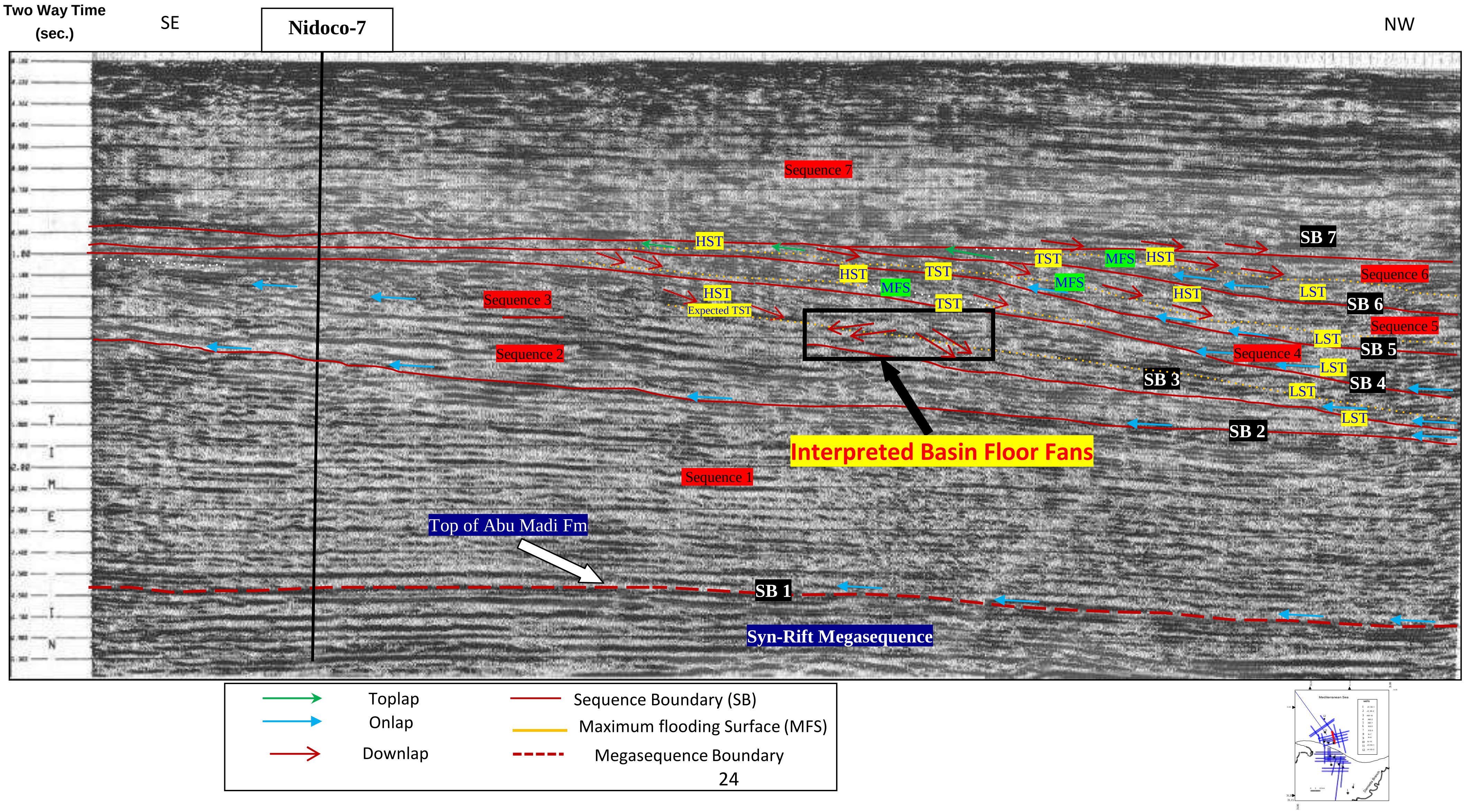


Fig. (3.a): Offshore Seismic Reflection Profile (Line No. JG 63-5) along NW-SE direction shows the subdivision of the post-rift megasequence into seven seismic sequences with their related systems tracts and the expected migration of the Nile Delta shelf break.

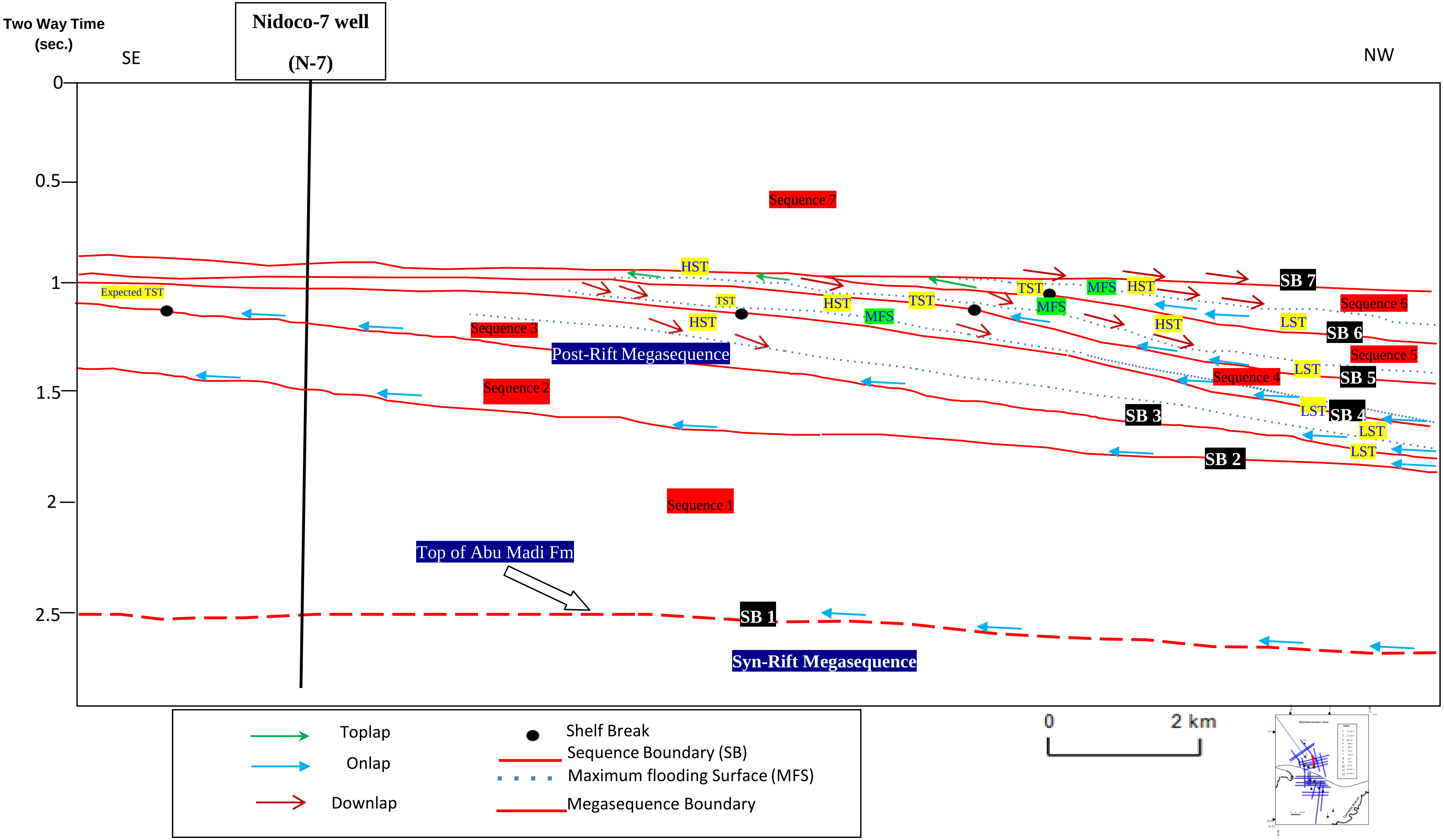


Fig. (3.b): Sketch based on the Offshore Seismic Reflection Profile (Line No. JG 63-5) along NW-SE direction shows the subdivision of the post-rift megasequence into seven seismic sequences with their related systems tracts and the expected migration of the Nile Delta shelf break.

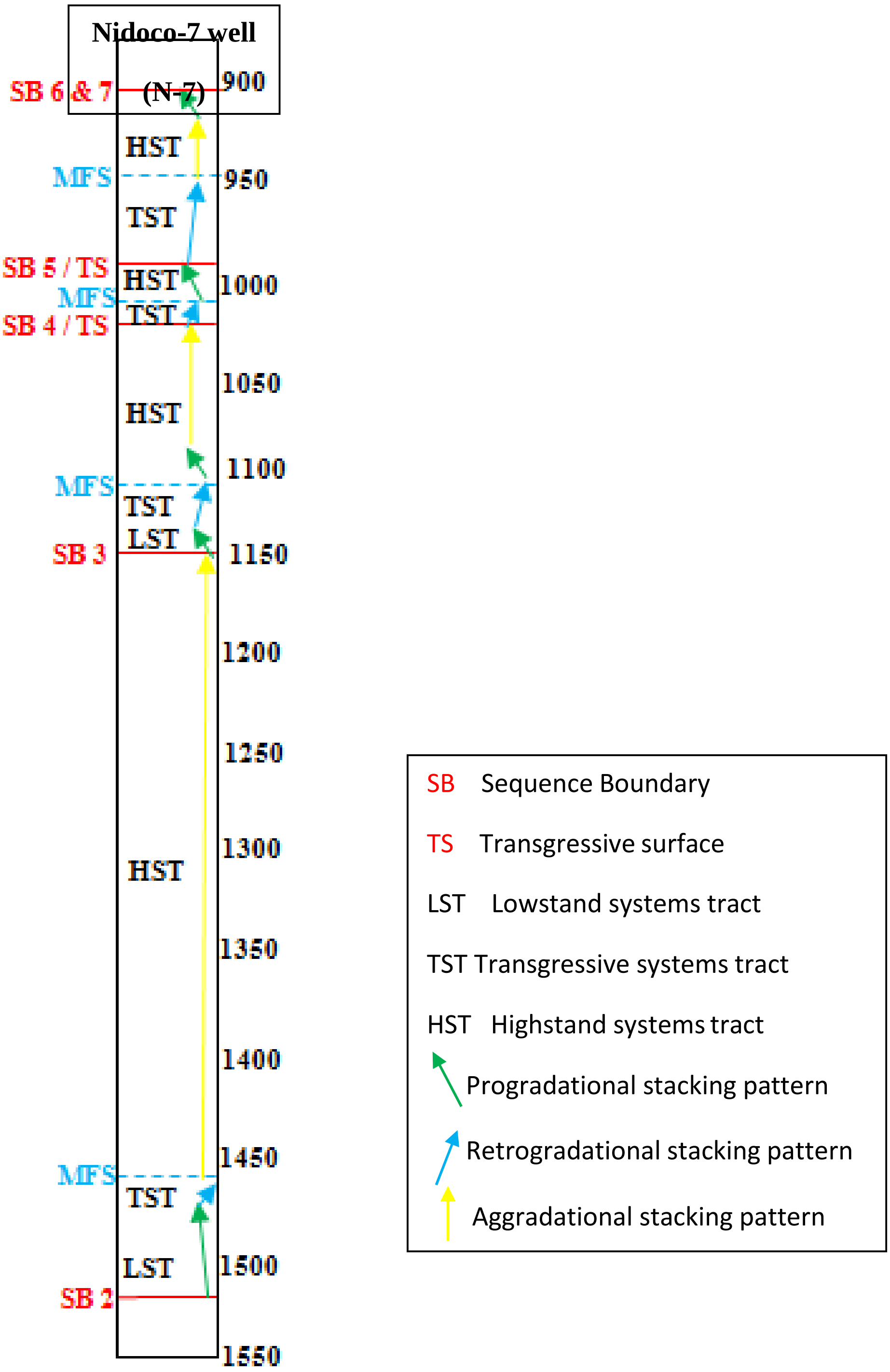
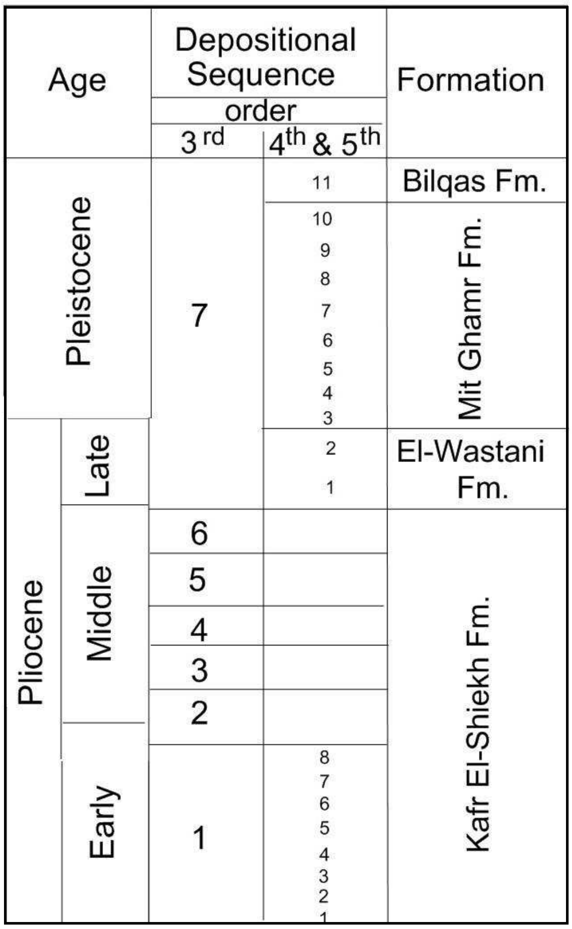


Fig. (3.c): Sequence stratigraphic subdivisions for Nidoco-7 well which cut through seismic Profile Line No. JG 63-5 (Fig.3.a) using gamma ray log shows the different systems tracts within each depositional sequence related to depths below sea level in meter unit.



Age		Depositional Sequence order		Formation
		3rd	4th & 5th	
Pleistocene		7	11	Bilqas Fm.
			10 9 8 7 6 5 4 3	Mit Ghamr Fm.
Pliocene	Late		2 1	El-Wastani Fm.
	Middle	6		Kafr El-Shiekh Fm.
		5		
		4		
		3		
		2		
	Early	1	8 7 6 5 4 3 2 1	

Fig. (4.a): The subdivision of the Plio-Pleistocene age into depositional sequences in the northern part of the Nile Delta.

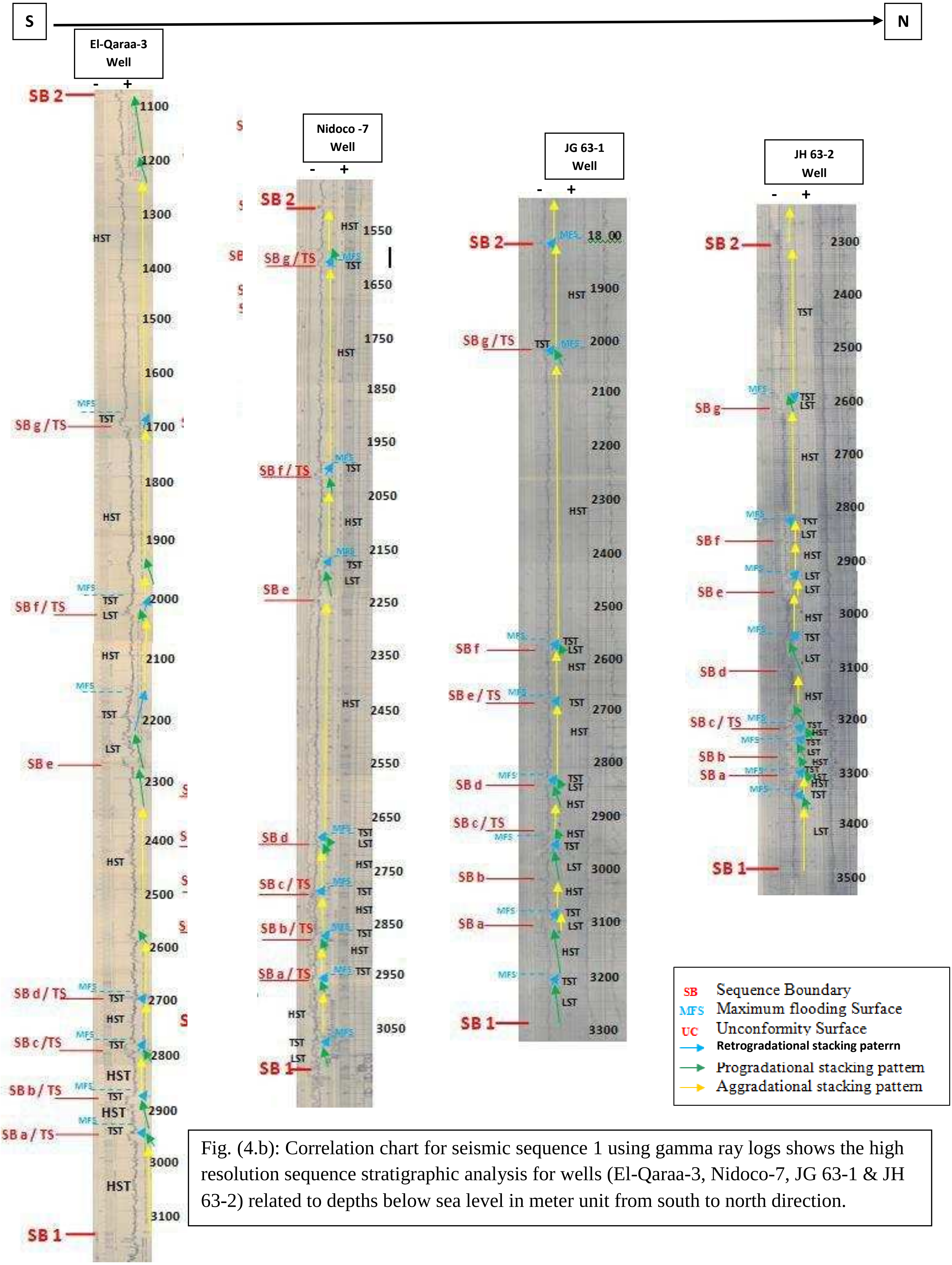


Fig. (4.b): Correlation chart for seismic sequence 1 using gamma ray logs shows the high resolution sequence stratigraphic analysis for wells (El-Qaraa-3, Nidoco-7, JG 63-1 & JH 63-2) related to depths below sea level in meter unit from south to north direction.

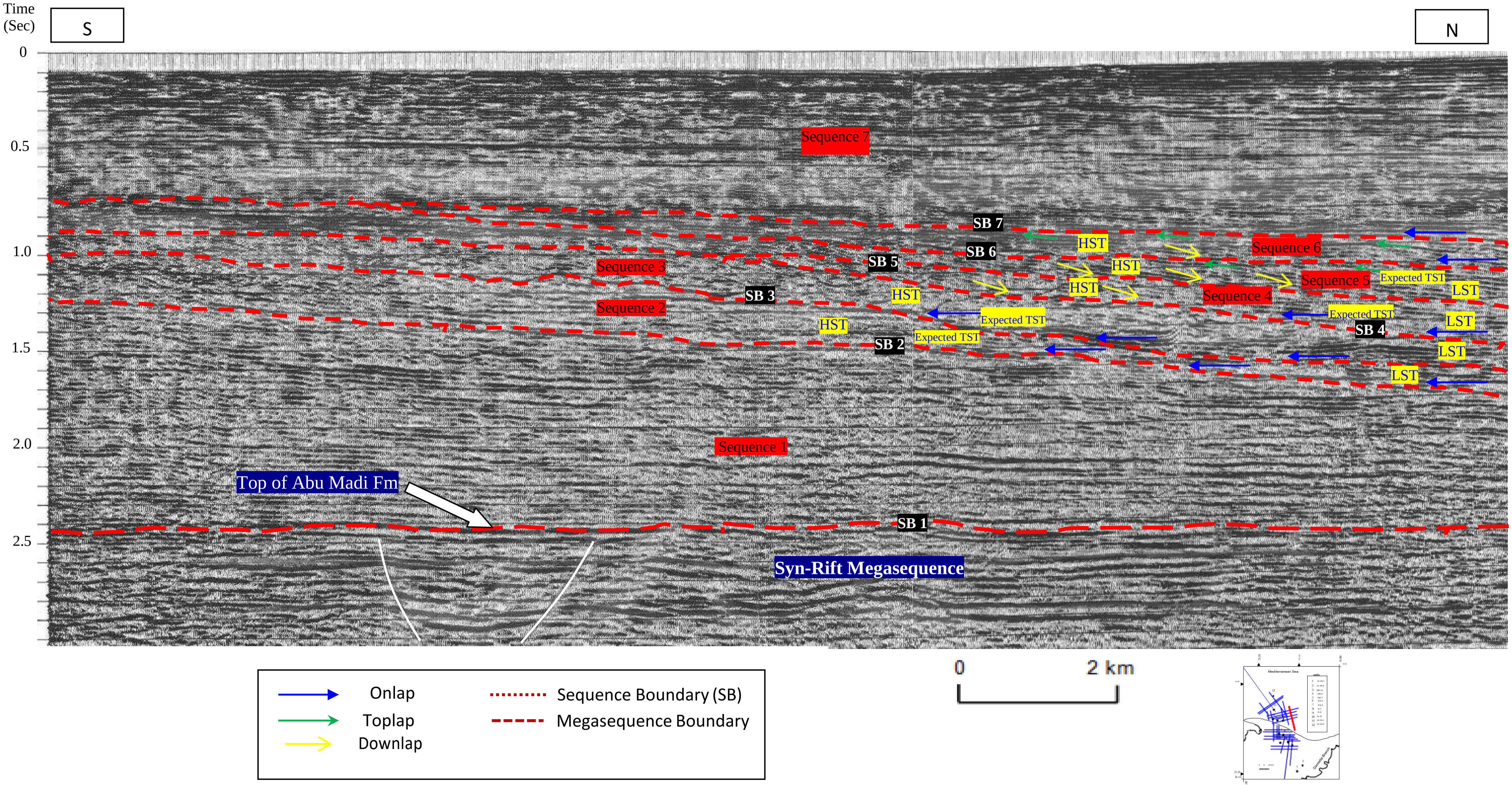


Fig. (5): Offshore Seismic Reflection Profile along N-S direction shows the subdivision of the examined sedimentary succession into sequences and related systems tracts. (Line No. JG 64-11)

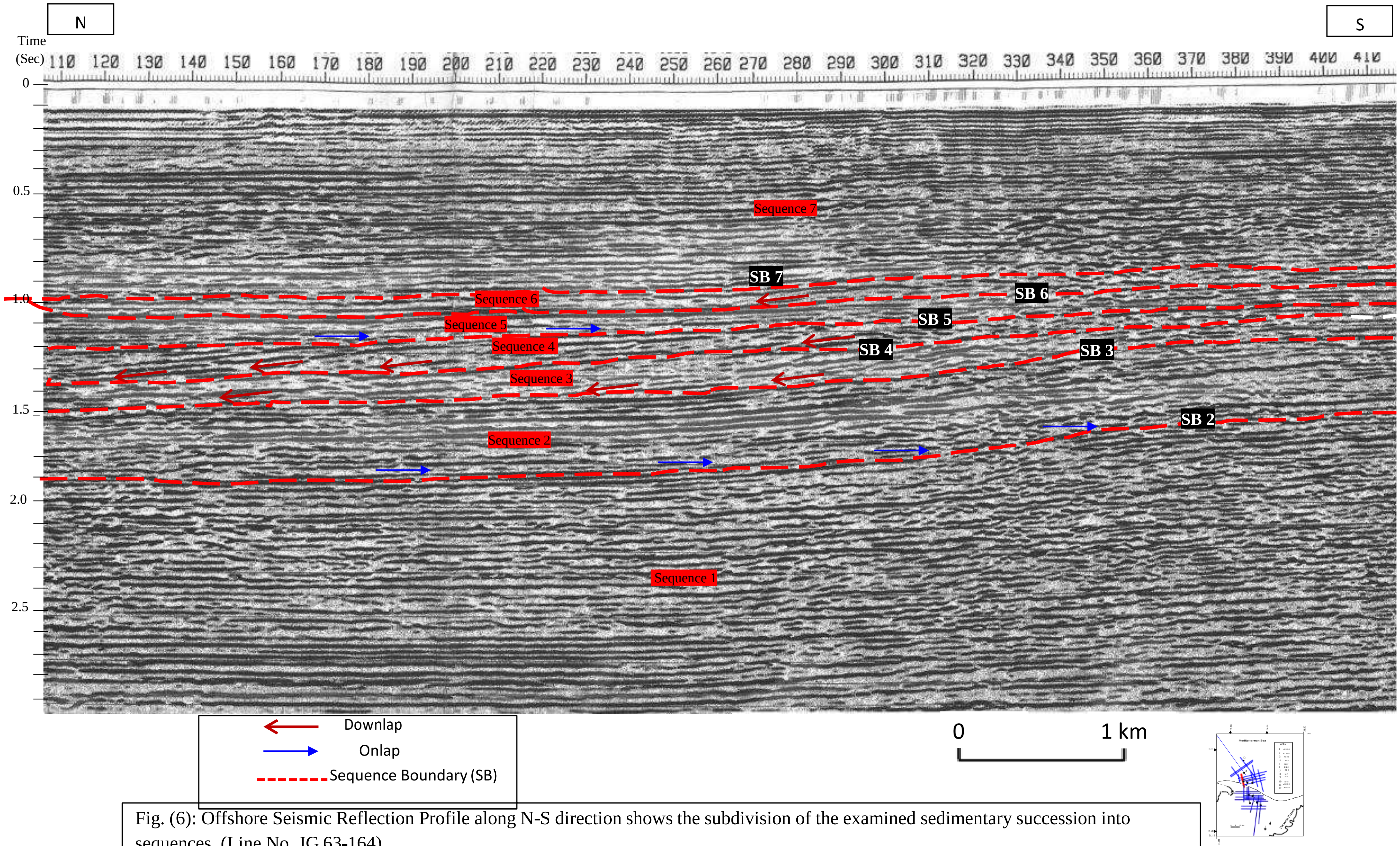
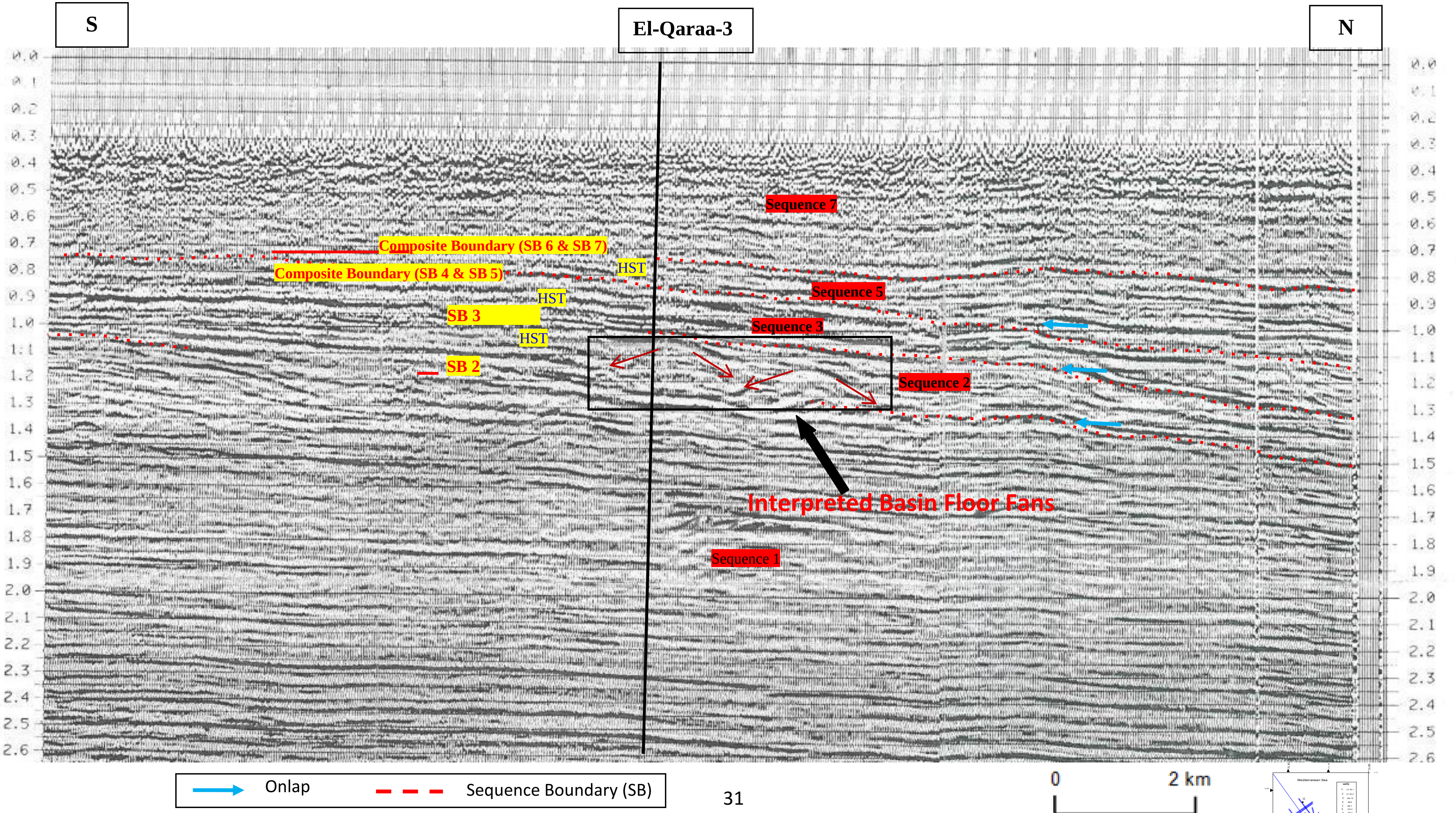


Fig. (6): Offshore Seismic Reflection Profile along N-S direction shows the subdivision of the examined sedimentary succession into sequences. (Line No. JG 63-164).



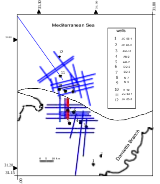


Fig. (7): Onshore Seismic Reflection Profile along N-S direction cut by El-Qaraa-3 well shows the subdivision of the examined sedimentary succession into sequences (Line No. Bil 725-81).

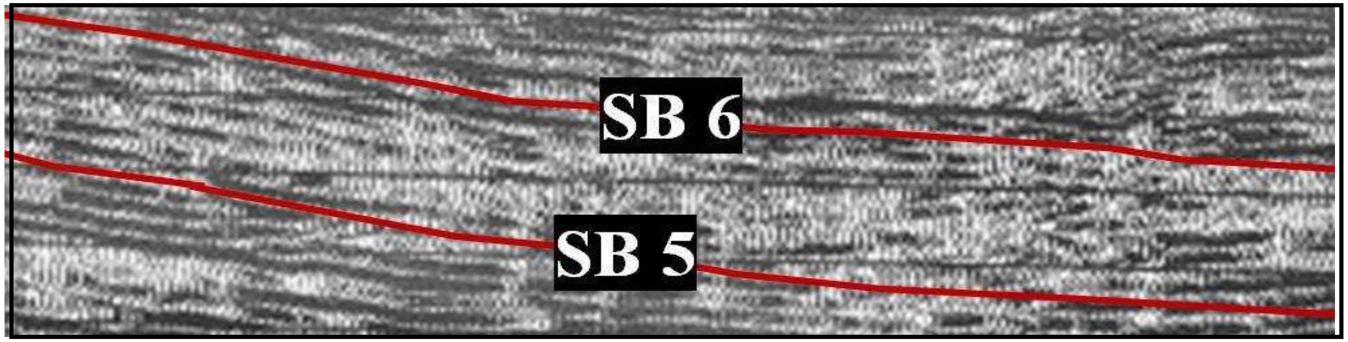
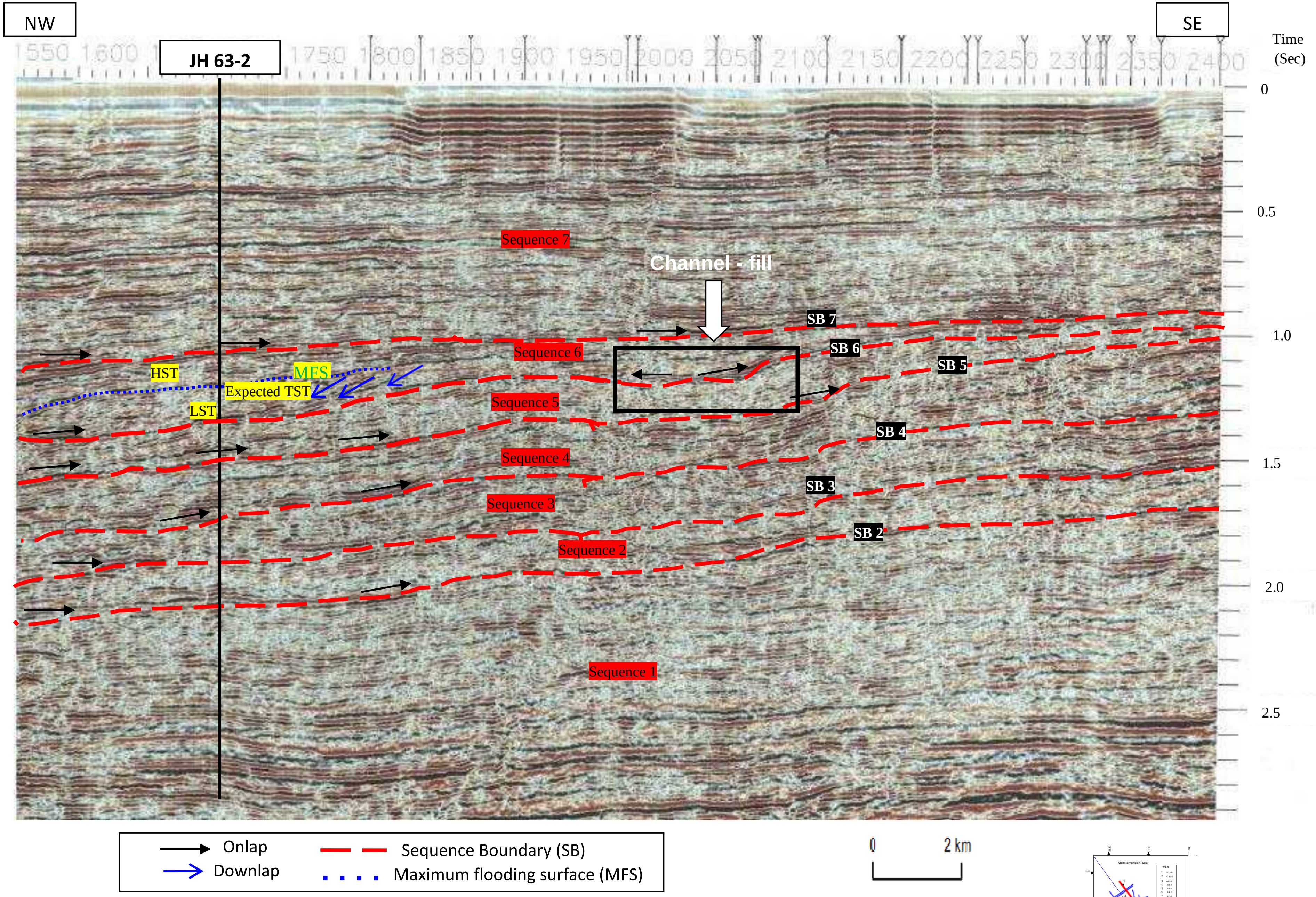


Fig. (8): Close up through the seismic sequence no. 5 whithin Kafr El-Sheikh Formation showing the onlapping and downlapping character of the internal reflectors



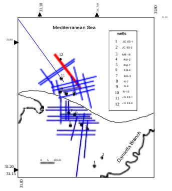


Fig. (9): Offshore Seismic Reflection Profile along NW-SE direction cut by JH 63-2 well shows the subdivision of the examined sedimentary succession into sequences (Line No. JG 64-10A)

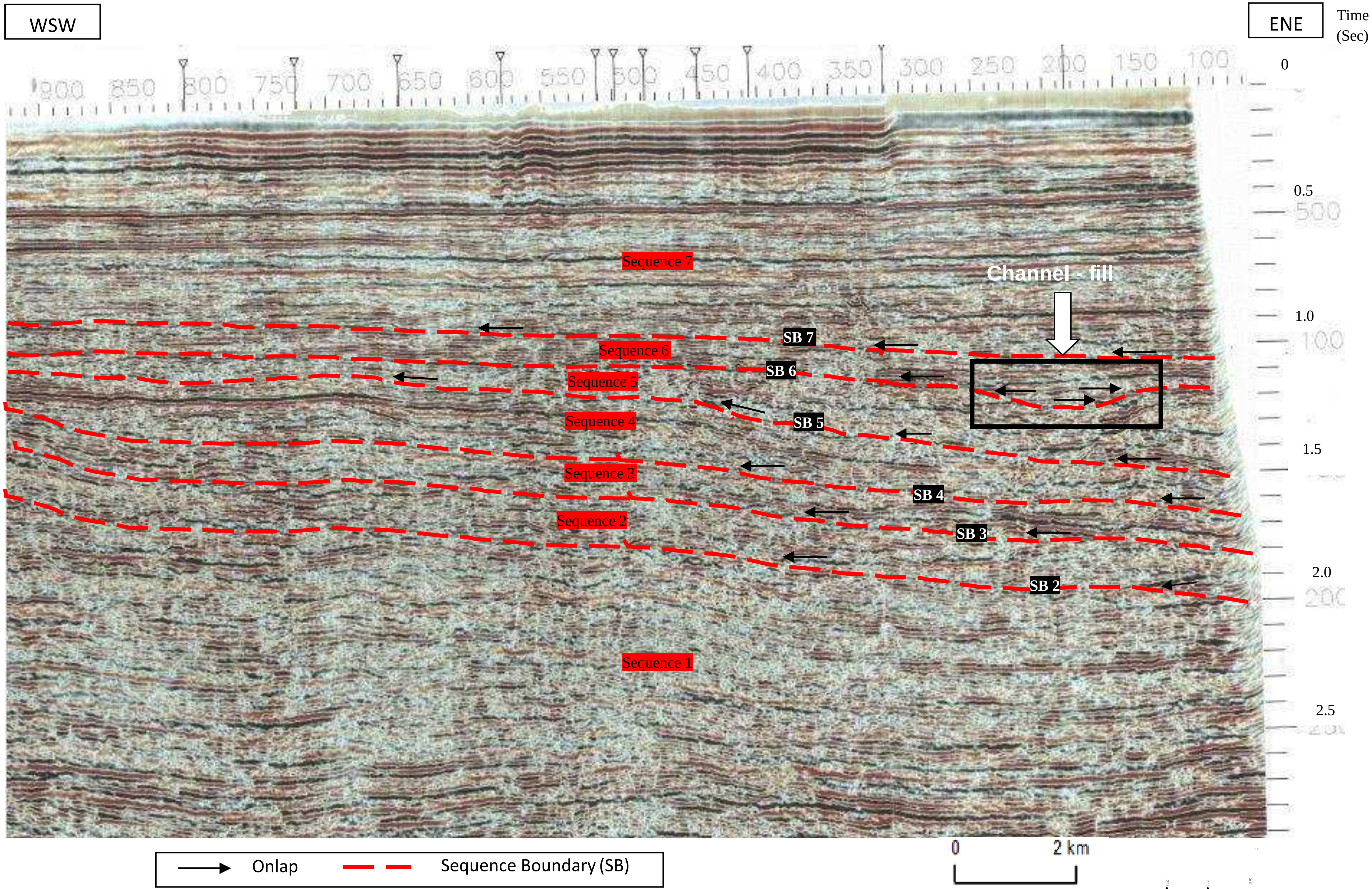
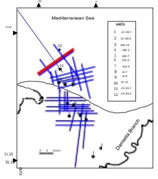
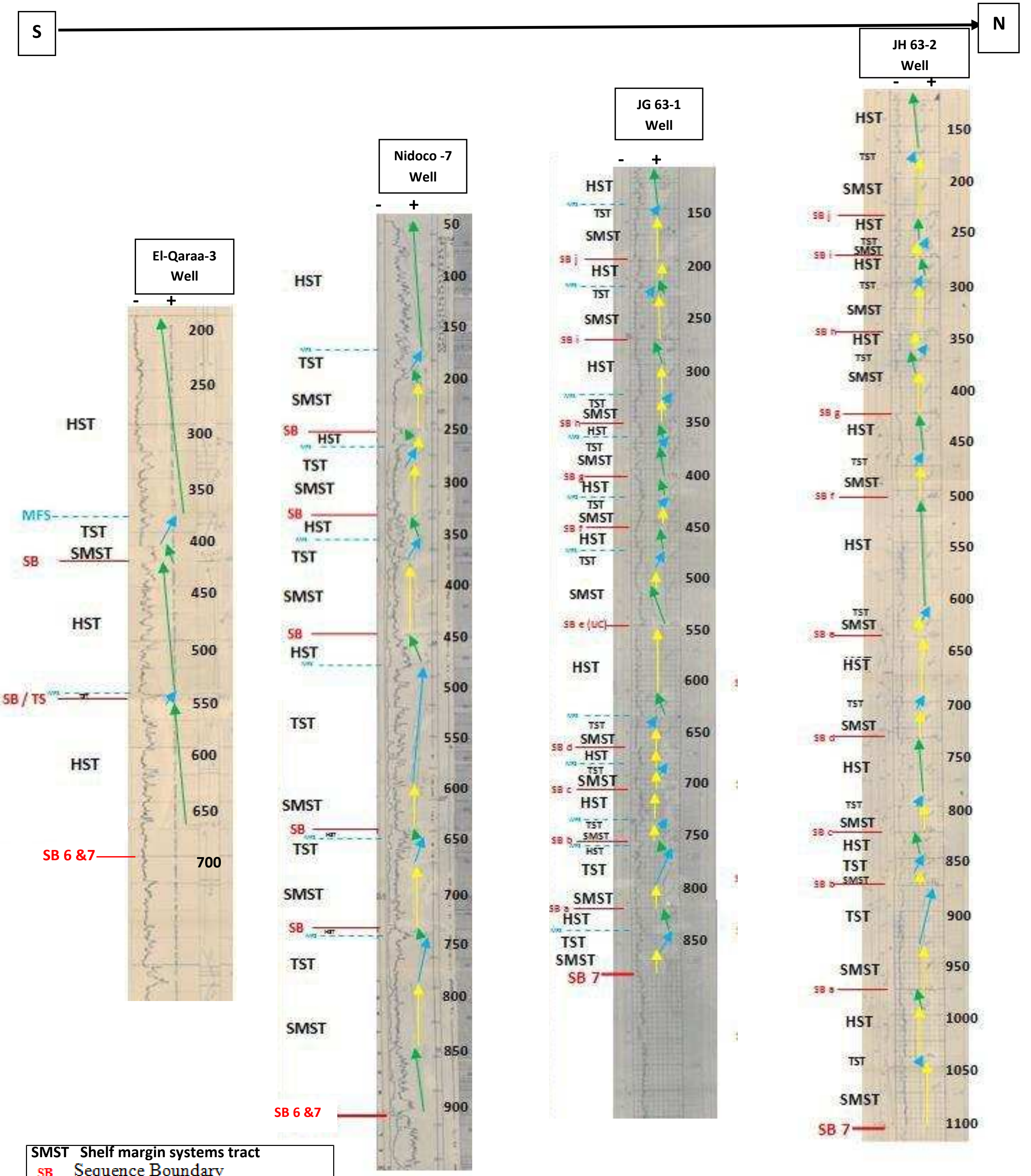


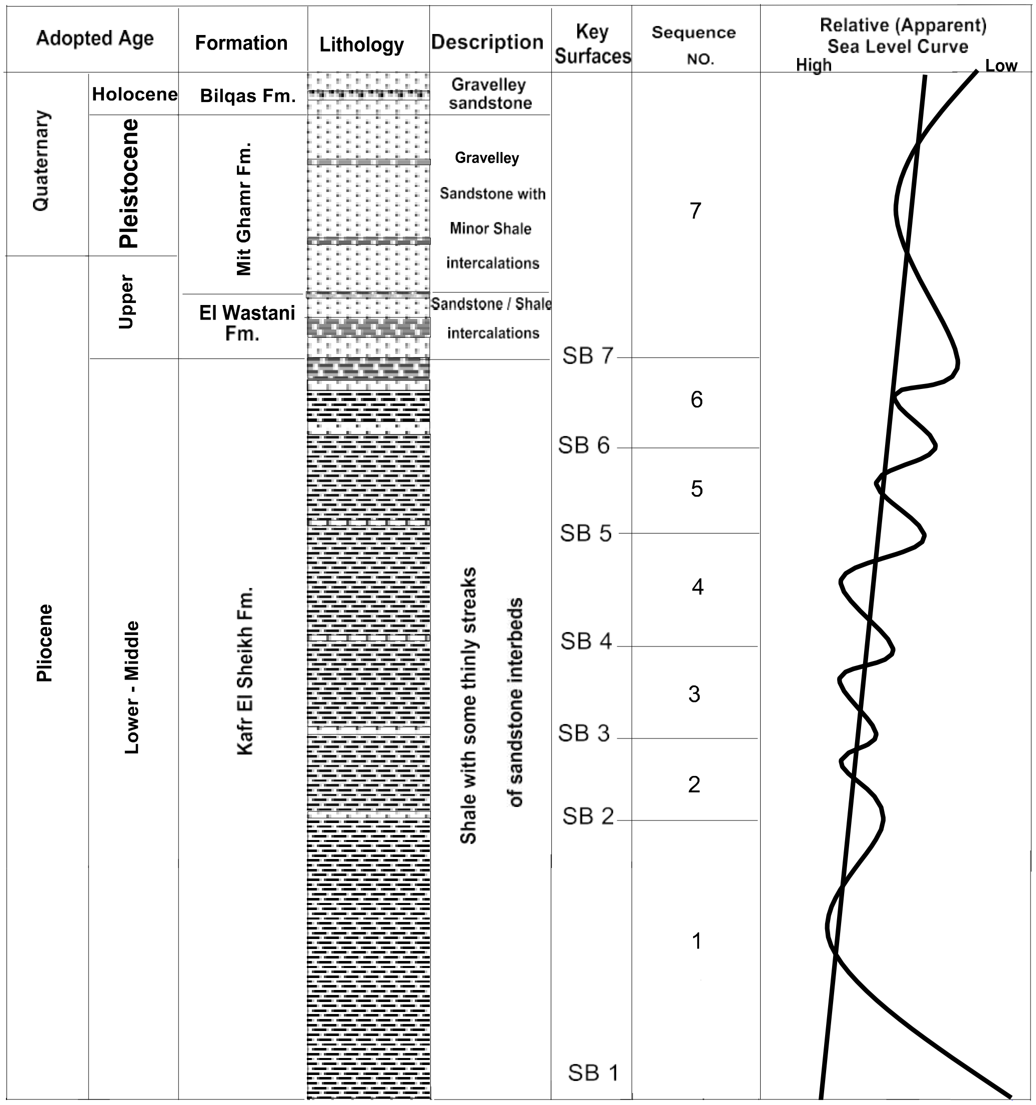
Fig. (10): Offshore Seismic Reflection Profile along NW-SE direction shows the subdivision of the examined sedimentary succession into sequences and related systems tracts. (Line No. JG 61-49)





SMST **Shelf margin systems tract**
SB Sequence Boundary
MFS Maximum flooding Surface
UC Unconformity Surface
→ Retrogradational stacking pattern
→ Progradational stacking pattern
→ Aggradational stacking pattern

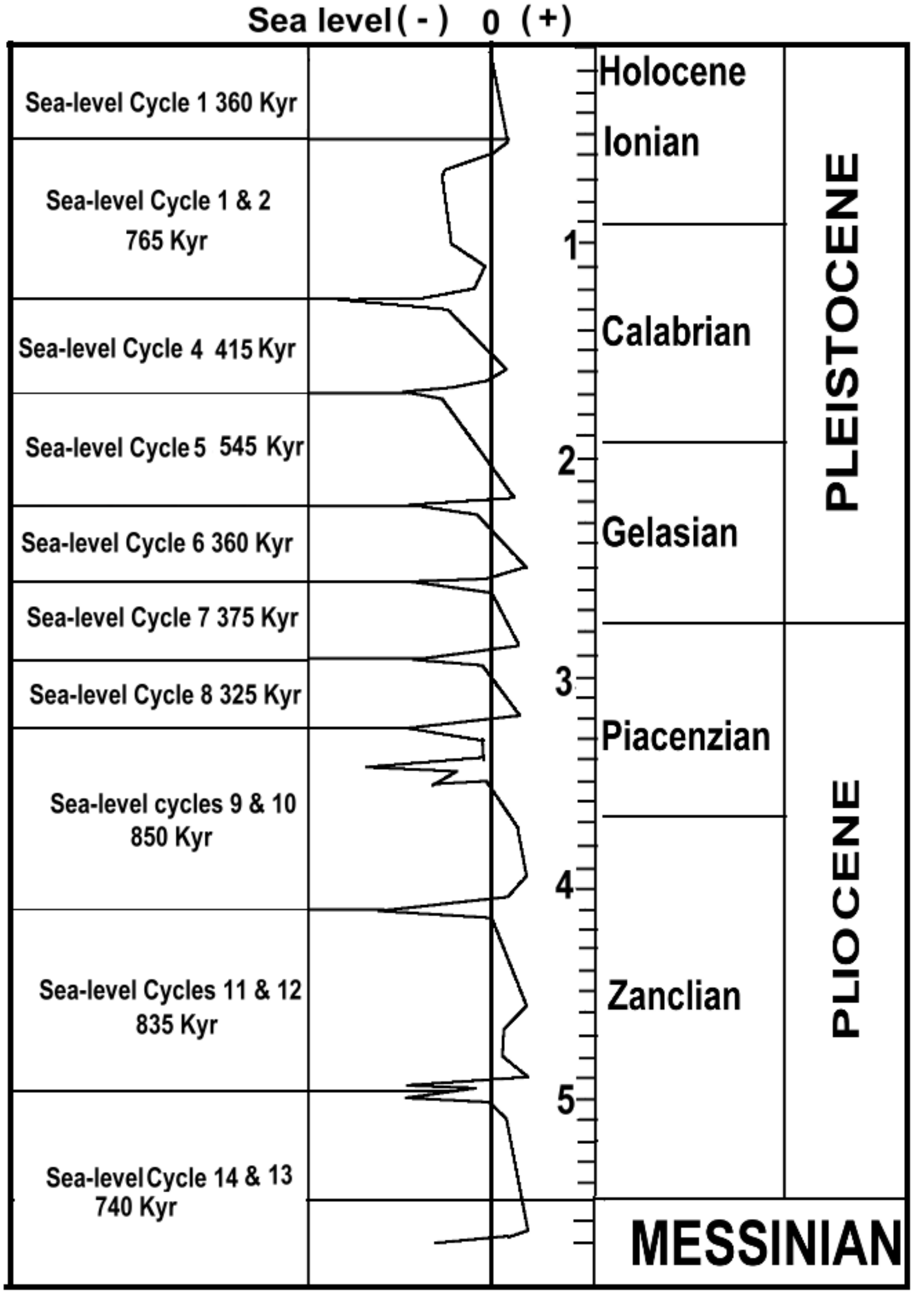
Fig. (11): Correlation chart for seismic sequence -7 using gamma ray logs shows the high resolution sequence stratigraphic analysis for wells (El-Qaraa-3, Nidoco-7, JG 63-1 & JH 63-2) related to depths below sea level in meter unit from south to north direction.



Straight Line..........Long term eustatic curve of Haq et al, (1987).

Curved Line..........Relative sea level curve according to the present work seismic sequences.

Fig. (12.a): The constructed relative sea level curve depending on sequences stratigraphic analyses compared to the eustatic sea level curve of Haq et al, (1987).



(Fig.12.b): Eustatic sea level curve and sea-level cycles during the Pliocene-Pleistocene (modified and simplified after Al-Husseini, 2013).