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# High resolution sequence stratigraphic analysis of the Late Miocene Abu Madi Formation, Northern Nile Delta Basin

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## KEYWORDS

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Gamma ray logs;  
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**Abstract** Abu Madi Formation represents the Upper Miocene Messinian age in the Nile Delta basin. It consists mainly of sandstones and shale intercalations and because of its richness in hydrocarbon, it has been subdivided by the petroleum companies into Level-I, Level-II and Level-III, respectively according to the increase in the sandstone to the shale ratio.

The Miocene cycle in the northern subsurface section of the Nile Delta encompasses three main formations namely from the base; Sidi Salim formation, Qawasim Formation and Abu Madi Formation at the top. The high resolution sequence stratigraphic analysis, using gamma ray responses, has been done for the Late Miocene formation in the northern part of the Nile delta subsurface section. For this purpose, the gamma-ray logs of ten deep wells, arranged in four cross-sections trending in almost north–south direction throughout the northern region of the Nile Delta, were analyzed.

The analysis has revealed that the interpreted 4th order depositional cycles within Abu Madi Formation display great variations in both number and gamma ray responses in each investigated well, and cannot be traced laterally, even in the nearest well. These variations in the interpreted 4th order depositional sequences could be attributed to the presence of normal faults buried in the inter-area laying between the investigated wells.

This finding matches with the conclusion of that Abu Madi Formation represents a part of the Upper Miocene Nile Delta syn-rift megasequence, developed during the Upper Miocene rift phase of the Red Sea – Gulf of Suez province in Egypt. Accordingly, in the sequence stratigraphic approach, the depositional history of Abu Madi Formation was strongly overprinted by the

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tectonic controls rather than the relative sea-level changes which are assumed to be of a secondary influence.

Regarding the hydrocarbon aspects of the Abu Madi Formation, the present work recommends to direct the drilling efforts into the stratigraphic traps in the sandy intervals of the LST, TST and HST within the 4th order interpreted depositional sequences in both level-II and/or level-III.

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## 1. Introduction

The Nile Delta basin represents one of the largest deltaic basins in the world, covering a fan-shaped area of  $\sim 250,000 \text{ Km}^2$  (Sestini, 1989). It consists of about 6.0 km thick Oligocene-Quaternary sedimentary subsurface succession, essentially of fine-grained siliciclastic facies (Hussein and Abd-Allah, 2001; Kellner et al., 2009). The Nile Delta basin is a passive margin basin resulted by the thermal subsidence subsequent to the tectonic extension separated the Afro-Arabian plate away from the Eurasian plate initiated in the Late Triassic up to the Early Cretaceous times (May, 1991; Dolson et al., 2001, 2005).

The Miocene – Pliocene sediments of the Nile Delta basin have a long history of oil and gas exploration, however the explored Late Miocene (Messinian) Abu Madi Formation

natural gas was the main target for many working companies since 1963 in both the onshore and the offshore parts (Abu El-Ella, 1990).

Rizzini et al. (1976) were the first who applied the term Abu Madi Formation for a lower Pliocene rock unit in the subsurface section in the northern part of the Nile Delta. The type section lies within Abu Madi Well-1, between the subsurface interval 3002 and 3229 m. It is mainly composed of medium to coarse grained sandstone and shale interbeds. The lower Pliocene age stated by Rizzini et al. (1976) was later re-adjusted by many workers (e.g. El-Heiny and Morsi, 1992; EGPC, 1994) to be Messinian (uppermost Miocene).

The present work adopted this re-adjusted Messinian age for the present Abu Madi Formation. Tectonically, this formation represents the final event during the evolution of the Upper Miocene syn-rift megasequence beneath the Nile Delta

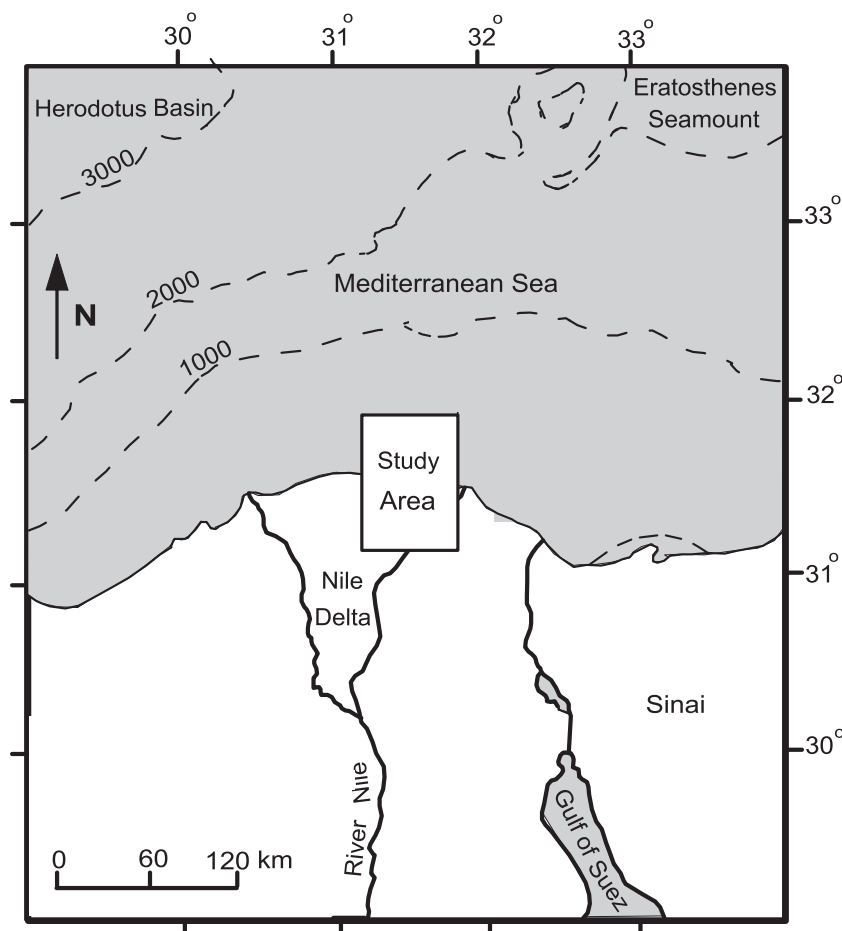


Figure 1 Study area.

(Sarhan et al., 2014). The formation uncomfortably overlies Rosetta Formation (EGPC, 1994) or Qawasim Formation (El-Heiny, 1982; El-Heiny and Morsi, 1992) in the northern parts of the Nile Delta.

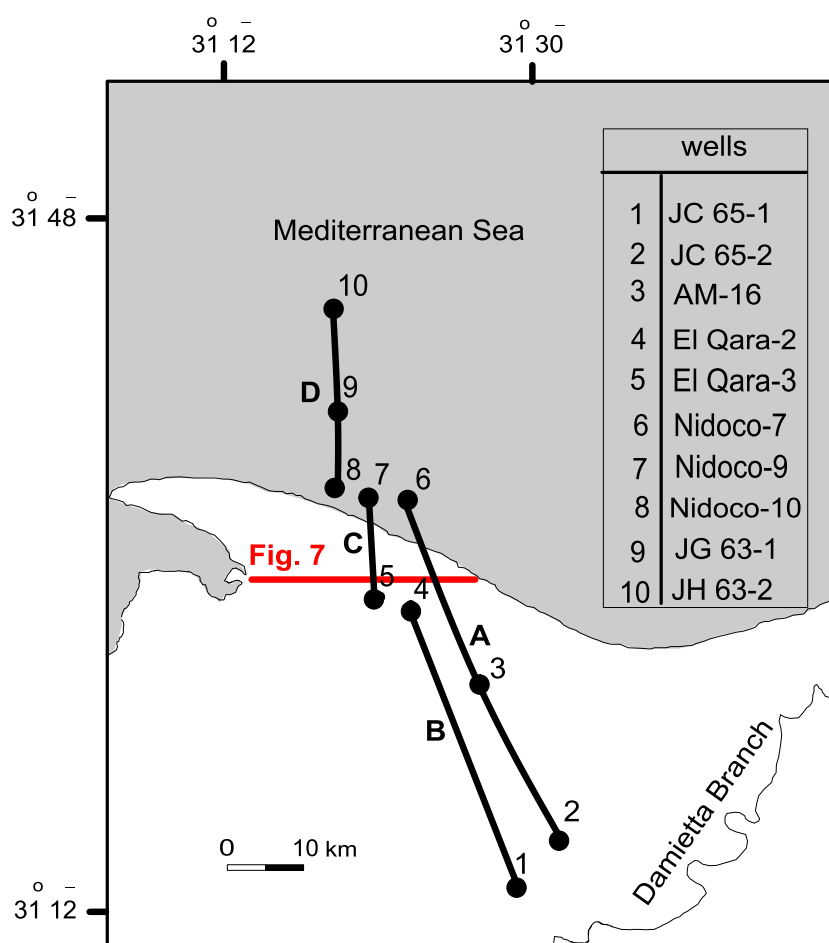
According to Harms and Wary (1990), a stratigraphic hiatus marks the top of Abu Madi Formation within the onshore Nile Delta. The chronologic span of such hiatus is estimated to be about 0.5 million years. Pipkin and Trent (1996) have declared that during the Messinian time, a northward drift of the African-plate resulted in the closing of the Strait of Gibraltar, isolating the Tethys (Mediterranean) Sea from the Atlantic Ocean. This situation was associated with a significant drop in the global sea; consequently the Mediterranean Sea was no longer flooded by sea-water and changed into isolated shallow lagoons and/or almost dried-up (Gvirtzman and Buchbinder, 1977; Barber, 1981).

A significant stratigraphic hiatus was then resulted, and a prominent unconformity (Messinian Unconformity) was developed. This situation initiated the terrestrial erosive agencies, where the northward-trending distributaries of the proto-Nile river incised a wide fluvial net cut through the pre-existing Mediterranean continental shelf (Barber, 1981; Sestini, 1989; Harms and Wary, 1990). So, Abu Madi Formation filled the topographic relief of the Messinian unconformity surface by

onlapping the margins of the incised valleys (Sarhan et al., 2014).

Generally, the deposition of the Abu Madi Formation had taken place during Messinian time by means of northward entrenched channels confined by topographic and structural highs. El Heiny et al. (1990) assumed Abu Madi Formation to be deposited under variation of different depositional environments, started with fluvial conditions at its lowermost part followed by lagoonal depositional environment and topped by more marine conditions. Salem et al. (2005) suggested Abu Madi Formation to be deposited as incised-valley fill representing the fluvial low-stand systems tract (LST) up to the transgressive systems tract (TST) estuarine depositional conditions. The distribution and facies of Abu Madi Formation were controlled by paleotopography initiated by faulting, low stand erosion and rapid deposition at the end of the Messinian age (El Heiny et al., 1990).

Abu Madi Formation represents the most common gas and condensate bearing intervals in the Nile Delta region. Abu Madi Formation is normally divided by the petroleum companies into three levels, namely I, II & III. Level-I is characterized by the dominance of shale while Level-II consists of interbeds of sandstones and/or siltstones with shale streaks. Level-III is almost the thickest and mainly consists of sandstones.



**Figure 2** Study area with well sites, location of an interpreted seismic profile and the locations of the suggested cross sections (A, B, C and D).

## 2. The approach of the high-resolution sequence stratigraphy

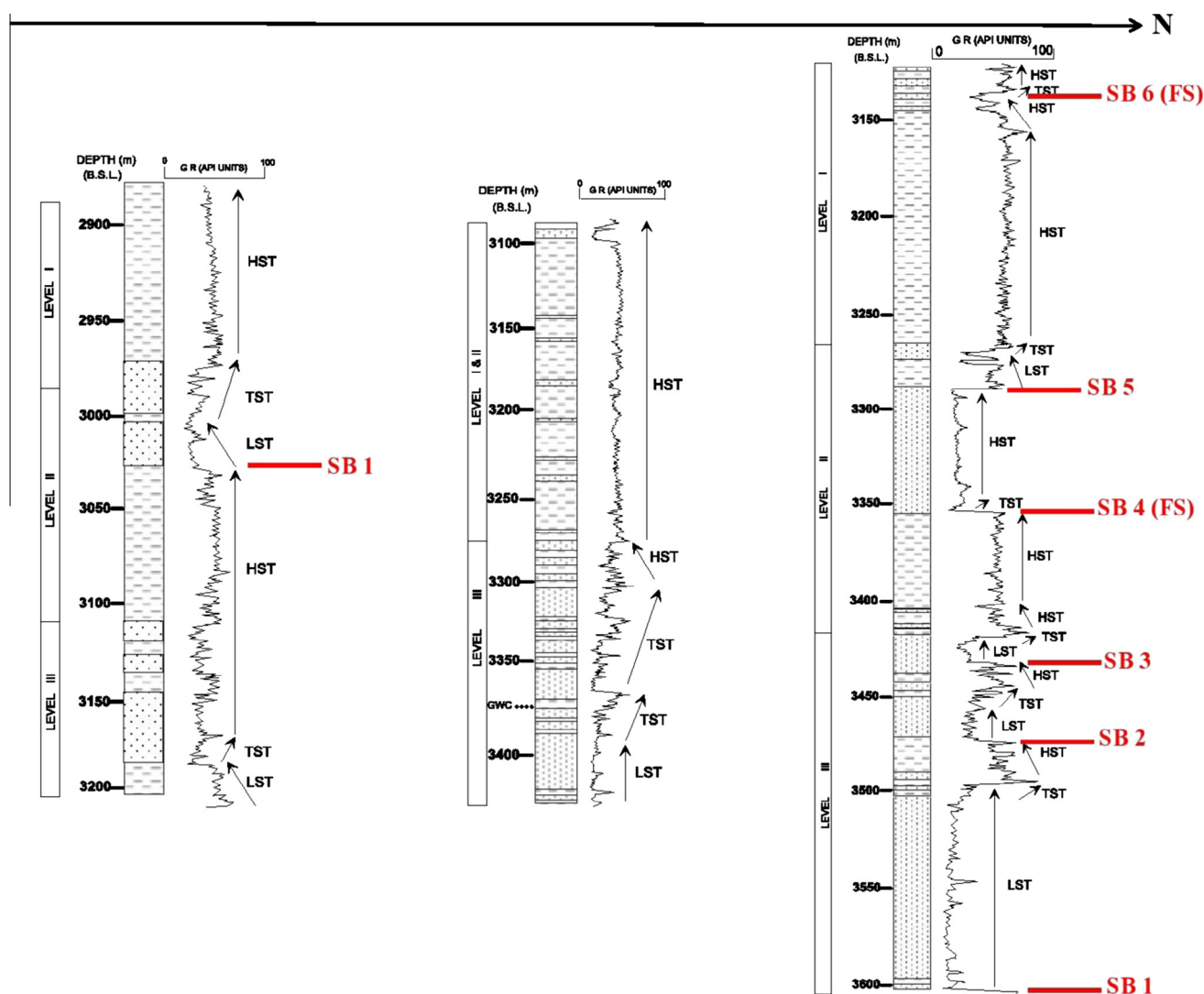
Generally, the high resolution sequence stratigraphic analysis is usually carried out to subdivide the seismic 3rd order depositional sequences into sub-seismic scale cycles. This approach is now increasingly used as a tool in hydrocarbon reservoir description (Emery and Myers, 1996; Van Wagoner, 1995). The 4th and the 5th order cycles are commonly termed as parasequences by VanWagoner et al. (1990). He defined the parasequences as a relatively conformable succession of genetically related beds bounded by marine flooding surfaces and their correlative surfaces. However the similar parasequences in the stacking pattern (architecture of a vertical succession of parasequences) can be grouped into parasequence set (Van Wagoner et al., 1988). According to Van Wagoner (1988)'s subdivision, the parasequence set may display progradational, retrogradational or aggradational architecture:

(a) In the progradational parasequence set, the shoreline moves basin-ward and the facies at the top of each

parasequence become progressively coarser in grain size and the shale content becomes lesser (cleaning upward trend). The progradational parasequence set characterizes both the high stand systems tract (HST) and the low stand systems tract (LST).

(b) However, in the retrogradational parasequence set, the shoreline moves landward and the facies at the top of each parasequence become progressively finer in grain size with increasing in the shale content upward (dirtying upward trend) reflecting the decrease in depositional energy. The retrogradational parasequence set represents the transgressive systems tract (TST) lying above the underlined LST and topped by the HST.

(c) The final type is called the aggradational parasequence set which forms when the shoreline does not move and hence the grain size becomes constant upward. Sometimes the aggradational pattern may characterize the LST and/or the HST if the sediment supply equals to the rate of subsidence (i.e. creation of accommodation).



**Figure 3** Cross section A: displays the high resolution sequence stratigraphic analysis of Abu Madi Formation using gamma ray logs for wells from south to north JC 65-2, AM-16 and Nidoco-7, respectively with the related depths below sea level in meter unit.

Moreover, the gamma ray log is one of the most powerful tools used in sequence stratigraphic analysis. The gamma ray response depends on the measure of the rock radioactivity which reflects the clay-mineral content and hence the grain size and depositional energy. The increase in the measured radioactivity reflects the increase in clay content and hence the decrease in the depositional energy (Emery and Myers, 1996).

### 3. Aim of the work

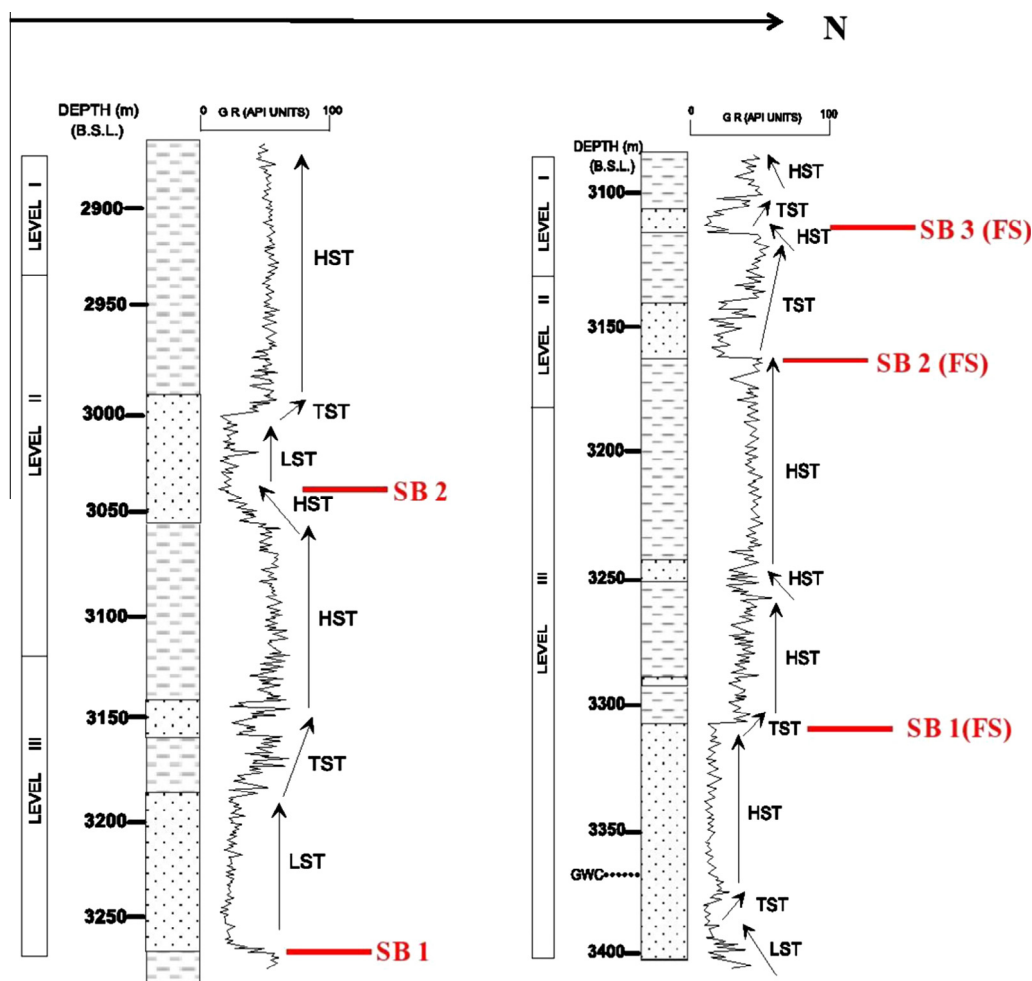
The Abu Madi Formation represents the Messinian age (deposited from 6.7 to 5.2 million years ago according to the stratigraphic column of Harland et al., 1990). This work aims to subdivide the Upper Miocene Abu Madi Formation, in the framework of high-resolution sequence stratigraphy, into fourth-order depositional sequences ranging in age between 500,000 and 200,000 years (Nichols, 2009), using the gamma ray logs for ten wells dug through the study area.

This work will consider the influence of the sea-level changes due to either eustatic or tectonic factors upon the aimed subdivision, how far these factors affected the formation's depositional history.

### 4. Study area, data and methods

The study area lies in the north-central part of the Nile Delta. It extends in both the onshore and the offshore of the Mediterranean Sea (Fig. 1). In the present work, the study will be concentrated upon Abu Madi Formation representing the uppermost part of the Late Miocene age in the Nile Delta basin. The high resolution sequence stratigraphic analysis of Abu Madi Formation was carried out using the lithologic logs and the gamma ray responses of the formation in ten wells dug through the study area. The names of the examined are as follows: AM-16, El-Qaraa-2, El-Qaraa-3, JG 63-1, JH 63-2, Nidoco-7, Nidoco-9, Nidoco-10, JC 65-1 and JC 65-2. These wells have been arranged in different four cross sections running roughly from south to north (basin-ward) in the examined area to easily distinguish the change in pattern and the number of sequences between different wells.

It is of worth mentioning that the well data were kindly provided by the Belayim Petroleum Company (PETROBEL) with official permission from The Egyptian General Petroleum Corporation (EGPC). The lithologic logs of the wells in the study area indicated that the Abu Madi Formation is variable



**Figure 4** Cross section B: displays the high resolution sequence stratigraphic analysis of Abu Madi Formation using gamma ray logs for wells from south to north JC 65-1 and El Qara-2, respectively with the related depths below sea level in meter unit.

in thickness from 194 m in JC65 Well-1 to 344 m in AM Well-16. The thickness distribution of the given formation shows that Abu Madi Formation displays a general thickening toward the northward of the study area with maximum value of 480 m thick in Nodoco Well-7.

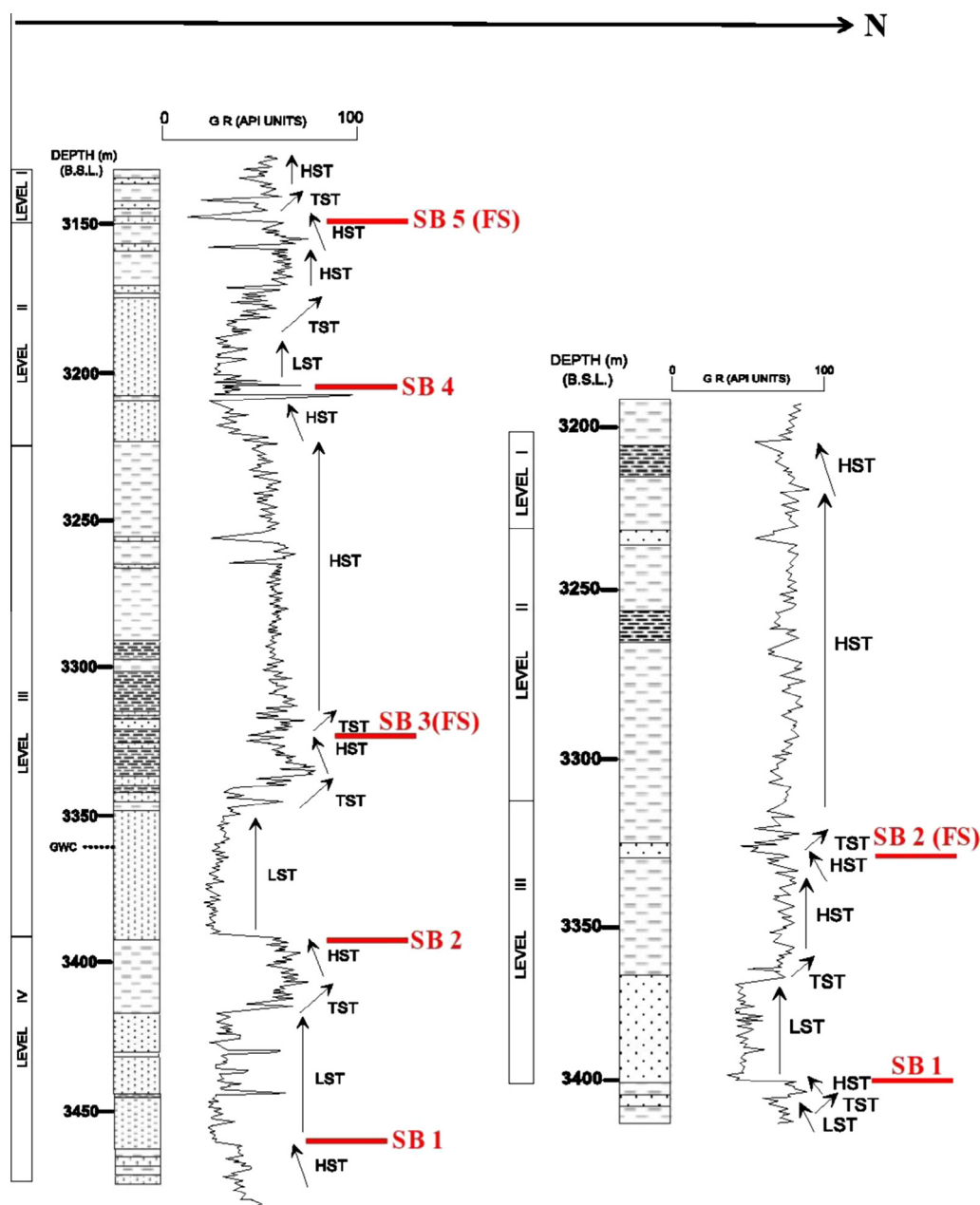
### 5. Sequence stratigraphic interpretations

The high resolution sequence stratigraphic analysis for the Abu Madi Formation in the examined well logs displays variations in both number and gamma ray responses of each of the interpreted sequences. For example in Fig. 3, the examined formation represents a non-complete interpreted depositional sequence (without any interpreted lower or upper sequence

boundary) in Abu Madi-16 well, however it has been subdivided into six 4th order depositional cycles in Nidoco-7 well which lies close to the Abu Madi-16 well in the study area and this reflects the great variation in the depositional setting of the examined formation along the study area.

The ten examined wells have been arranged in four cross sections running roughly from south to north (Fig. 2) to reflect the depositional dip direction (basin-ward direction) in order to display the highest number of the occurred depositional sequences (as this number increases with the depositional dip direction) and also to easily correlate the similar suggested 4th order depositional sequences with each other.

The four correlation charts for the chosen ten wells showing the high resolution sequence stratigraphic analysis for Abu

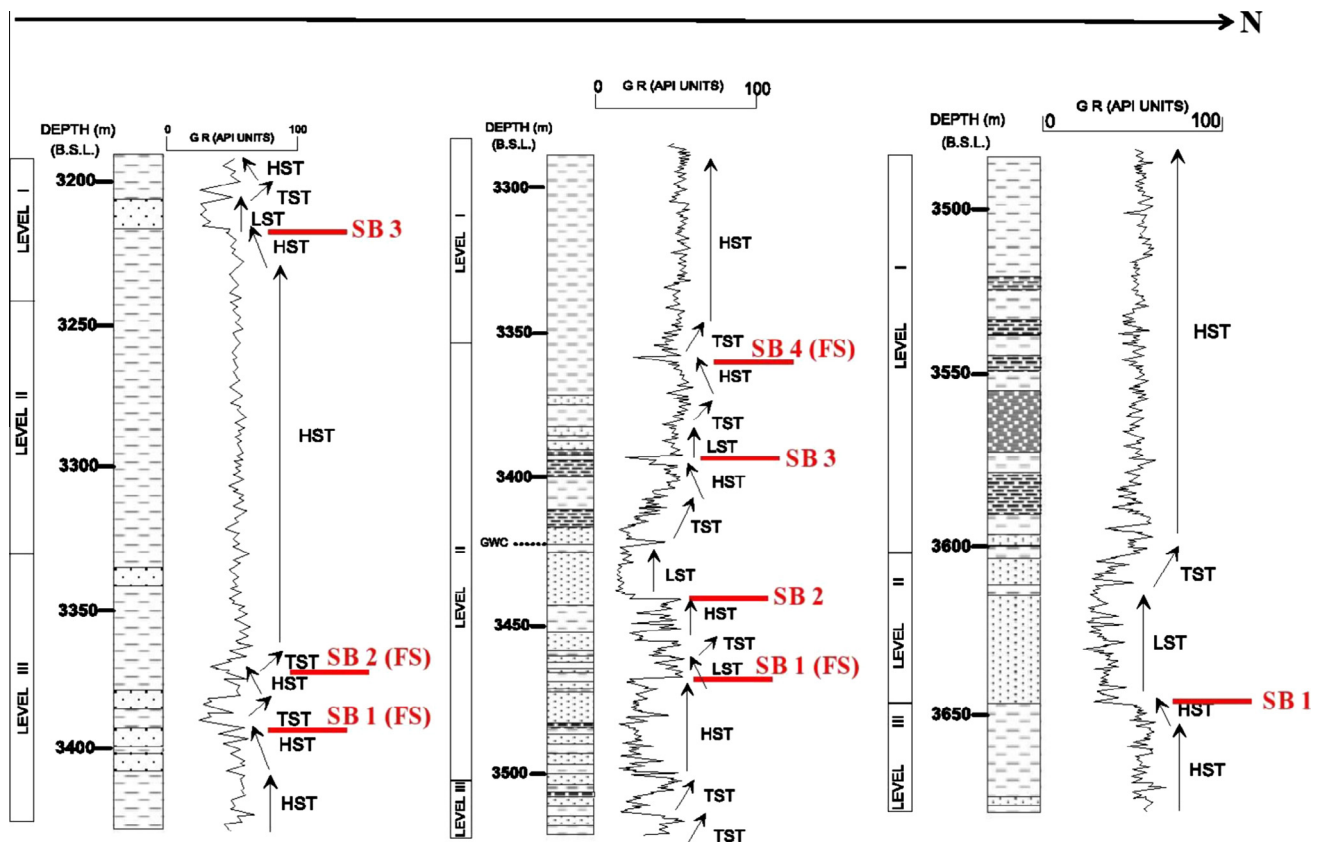


**Figure 5** Cross section C: displays the high resolution sequence stratigraphic analysis of Abu Madi Formation using gamma ray logs for wells from south to north El Qara-3 and Nidoco-9, respectively with the related depths below sea level in meter unit.

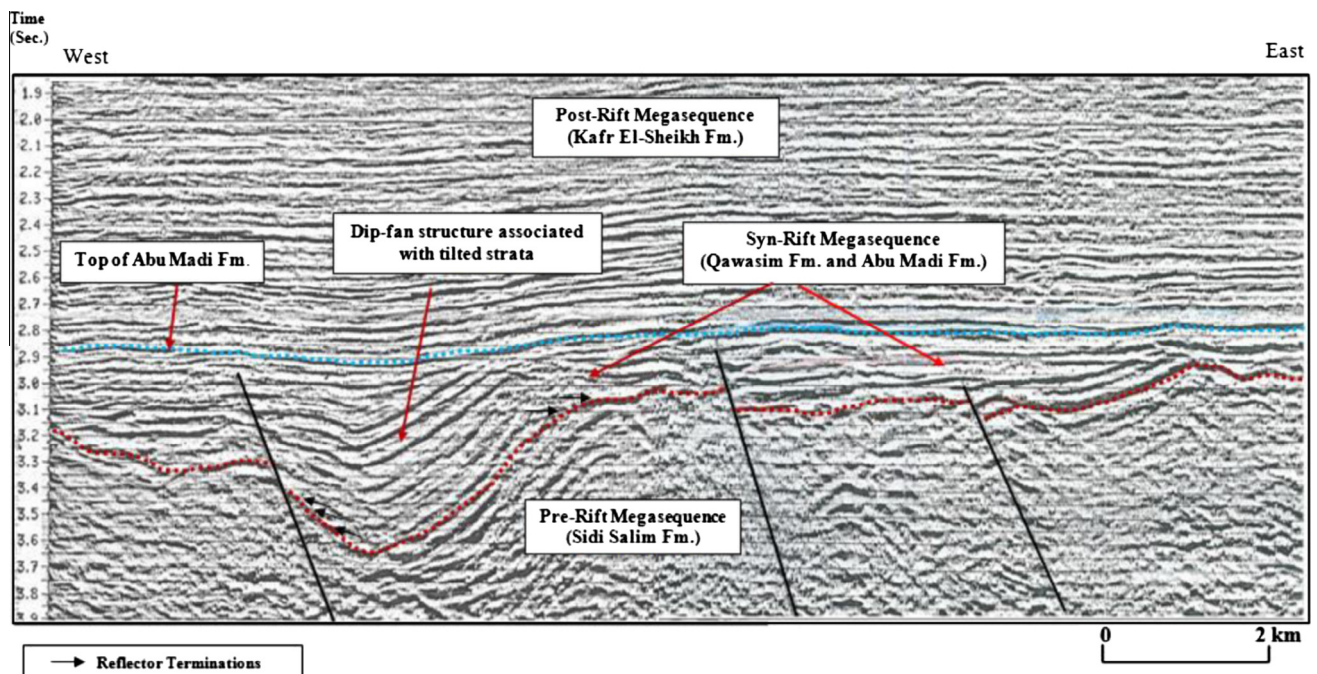


Madi Formation have been displayed in Figs. 3–6. The depths in each well are displayed in meter unit below the sea level. It is observable in these correlation charts that the TST is

represented by the clear retrogradational stacking pattern (the gamma ray increase by the increasing in shale content reflecting the reduction in the grain size and the decrease in



**Figure 6** Cross section D: displays the high resolution sequence stratigraphic analysis of Abu Madi Formation using gamma ray logs for wells from south to north Nidoco-10, JG 63-1 and JH 63-2, respectively with the related depths below sea level in meter unit.



**Figure 7** Interpreted onshore seismic reflection profile (Line No. Bil 824–85) along E–W direction shows the normal faults and the dip-fan structure associated with tilted strata characterizing the syn-rift megasequence (Qawasim Fm. and Abu Madi Fm.).

the depositional energy). Both LST and HST in some cycles display progradational stacking pattern (the gamma ray decrease by the increasing in sand content reflecting the increment in the grain size and the rising in the depositional energy). However, the aggradational stacking pattern is very clear in most LST and HST in each cycle which matching the filling behavior in the incised valley fills when the sea level was steady or started to rise.

Moreover, most of the interpreted sequence boundaries in different wells act as the maximum flooding surfaces (mfs) in other words the interpreted sequences have no aggradational or progradational LST. This may take place if the investigated well lies further landward away from the shelf break and hence the development of only TST would take place above the sequence boundary followed directly by the HST and hence in this situation the sequence boundaries act as transgressive surfaces and overlain directly by the TST without LST.

## 6. Conclusions

The interpreted depositional cycles in the high resolution sequence stratigraphic analysis of the Late Miocene Abu Madi Formation in each well are hard to be correlated with the adjacent well in the four suggested cross sections as they exhibit different responses in gamma ray log. These variations in the interpreted 4th order depositional sequences are assumed to be due to the occurrence of buried faults in the spacing area between the investigated wells.

This observation suggests that Abu Madi Formation was deposited during an unstable tectonic status, representing a part of the syn-rift sedimentary succession whose depositional time was characterized by a lot of normal faults (Sarhan et al., 2014). The age of these normal faults is the Upper Miocene, matching with the rift phase of the Red Sea- Gulf of Suez in Egypt (Sestini, 1989; Hussein and Abd-Allah, 2001; Khalil and McClay, 2002; Dolson et al., 2005).

This rifting is expected to affect the Upper Miocene sedimentary succession beneath the Nile Delta province. The distinctive features characterize a syn-rift megasequence including the presence of the normal growth faults, the increasing of sediments thickness toward faults planes on the down-thrown side and the presence of the dip-fan structure in the hanging-wall reflecting the progressively rotated fault block. Fig. 7 represents an interpreted onshore seismic reflection profile along E–W direction displaying the previous features including the presence of normal growth faults and the dip-fan structure associated with tilted strata characterizing the syn-rift megasequence (Qawasim Fm. and Abu Madi Fm.). This confirms that Abu Madi Formation represents a part of the Upper Miocene syn-rift megasequence of Sarhan et al. (2014).

Consequently, the expected subsidence and uplifting within the Upper Miocene time (during the deposition of the Abu Madi Formation) in the study area led to the non-homogeneous deposition of the Abu Madi Formation. Generally in rift basins, the tectonic setting and the structural elements have the major impact on stratal geometry and facies stacking patterns as the tectonic factor controls the accommodation space and the structural elements affect the sediment supply (Gawthorpe et al., 1994). Also the syn-rift sedimentary succession is characterized by lateral variation in

accommodation development according to the tectonic subsidence or uplift (Collier and Gawthorpe, 1995).

Accordingly, in the sequence stratigraphic approach, the present work concluded that the major factor affected the deposition of Abu Madi Formation was the Late Miocene tectonic phases rather than the eustatic sea level changes which act as a second factor. Regarding the hydrocarbon aspects of the Abu Madi Formation, it is observable in the present work analysis that the gas–water contacts lie within the sandy facies of the interpreted LST, TST and HST in level III. So it can be concluded that the sandy facies of the different systems tracts (LST, TST and HST) within each 4th order depositional cycles in the Abu Madi Formation (especially in the lower part of the formation as the sand percentage increases downward) have a specific importance and most probable to be gas bearing intervals so it is recommended from this study to direct the efforts to examine the facies of LST, TST and HST all over the Nile Delta basin. This is matching with Catuneanu (2006) who considered the fluvial deposits related to the incisions in all LST, TST and HST has good reservoir aspects.

## 7. Recommendations

For further development of the gas occurrences in the Abu Madi Formation in order to explore new targets in the study area and its surroundings, it is recommended to direct the drilling efforts to the expected stratigraphic traps representing the sandy intervals of the whole 4th order interpreted depositional sequences (i.e. the sandy intervals of the LST, TST and HST) because all of the entire systems tract within each interpreted sequence deposited as incision valley fill which have good reservoir aspects in the Messinian age especially in both level II and level III in the basal part of the Abu Madi Formation as the sandy facies increase downward in this formation.

## Acknowledgments

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