Cent. Eur. J. Geosci. • 5(4) • 2013 • 497-507
DOI: 10.2478/s13533-012-0144-5

VERSITA

Central European Journal of **Geosciences**

Sequence Stratigraphic Controls on Reservoir Characterization and Architecture: Case study of the Messinian Abu Madi Incised-Valley Fill, Egypt

Research Article

Mohamed I. Abdel-Fattah[1*], Roger M. Slatt[2†]

1 Geology Department, Faculty of Science, Suez Canal University, Ismailia, Egypt

2 Institute of Reservoir Characterization and ConocoPhillips School of Geology and Geophysics, University of Oklahoma, Norman, USA

Received 18 April 2013; accepted 4 August 2013

Abstract: Understanding sequence stratigraphy architecture in the incised-valley is a crucial step to understanding the effect of relative sea level changes on reservoir characterization and architecture. This paper presents a sequence stratigraphic framework of the incised-valley strata within the late Messinian Abu Madi Formation based on seismic and borehole data. Analysis of sand-body distribution reveals that fluvial channel sandstones in the Abu Madi Formation in the Baltim Fields, offshore Nile Delta, Egypt, are not randomly distributed but are predictable in their spatial and stratigraphic position. Elucidation of the distribution of sandstones in the Abu Madi incised-valley fill within a sequence stratigraphic framework allows a better understanding of their characterization and architecture during burial.

Strata of the Abu Madi Formation are interpreted to comprise two sequences, which are the most complex stratigraphically; their deposits comprise a complex incised valley fill. The lower sequence (SQ1) consists of a thick incised valley-fill of a Lowstand Systems Tract (LST1)) overlain by a Transgressive Systems Tract (TST1) and Highstand Systems Tract (HST1). The upper sequence (SQ2) contains channel-fill and is interpreted as a LST2 which has a thin sandstone channel deposits. Above this, channel-fill sandstone and related strata with tidal influence delineates the base of TST2, which is overlain by a HST2. Gas reservoirs of the Abu Madi Formation (present-day depth ~3552 m), the Baltim Fields, Egypt, consist of fluvial lowstand systems tract (LST) sandstones deposited in an incised valley. LST sandstones have a wide range of porosity (15 to 28%) and permeability (1 to 5080mD), which reflect both depositional facies and diagenetic controls.

This work demonstrates the value of constraining and evaluating the impact of sequence stratigraphic distribution on reservoir characterization and architecture in incised-valley deposits, and thus has an important impact on reservoir quality evolution in hydrocarbon exploration in such settings.

Keywords: Sequence Stratigraphic • Reservoir Characterization and Architecture • Messinian • Abu Madi Incised-Valley • Baltim Fields

*E-mail: mohamed_ibrahim@science.suez.edu.eg

†E-mail: rslatt@ou.edu

1. Introduction

Sequence stratigraphy provides a deterministic framework for understanding the relationships in time and space between rock layers, depositional environments and facies in terms of relative sea level changes, and a structured scheme to define reservoir architecture and reservoir quality [1]. Changes in the relative sea level allow constraining the quality as well as the spatial and temporal distribution of reservoir rocks within the context of sequence stratigraphy [2–4].

Incised valleys are considered important hydrocarbon reservoir targets because they may be filled with coarse-grained and, thus, porous and permeable fluvial deposits, that are commonly covered by sealing mud rocks [4]. Valley incision occurs as a consequence of rapid fall in relative sea level below the shelf edge, and consequent subaerial exposure of the continental shelf [4]. At an early, erosional stage, sediment bypasses the shelf to be deposited in deep-water environments. Termination of incision and overall onset of valley infilling with fluvial and estuarine sediments occurs when the relative sea level is stable at a lowstand position and/or begins to rise, i.e., during deposition of late lowstand and transgressive systems tracts [2].

Owing to their economic importance, incised valleys have been studied in great detail, with most works focused on the stratigraphy and architecture of incised-valley deposits [5–9]. Conversely, the reservoir-quality evolution pathways of incised-valley deposits have begun to be explored only recently [10, 11]. [10] demonstrated that important diagenetic factors controlling the reservoir quality evolution of incised-valley sandstones include content of ductile grains and volume of quartz cement, which are more extensive in TST incised-valley fill estuarine sandstones, resulting in a greater permeability reduction during burial diagenesis than in LST fluvial incised-valley sandstones [10]. [12, 13] also recognized better reservoir quality sandstones in fluvial incised valley fill deposits than in overlying, late-stage estuarine valley fill.

Additional case studies on sequence stratigraphy are thus needed to improve our ability to predict the reservoir quality and architecture of incised-valley sandstones. Therefore, the aim of this paper is to elucidate and discuss the sequence stratigraphy and related reservoir quality and architecture pathways of fluvial systems tracts sandstones that have been deposited in an incised-valley (Abu Madi Formation, late Messinian). Also, this characterization provides the opportunity to obtain a better understanding of the internal complexity of the Abu Madi deposits based on seismic and borehole data.

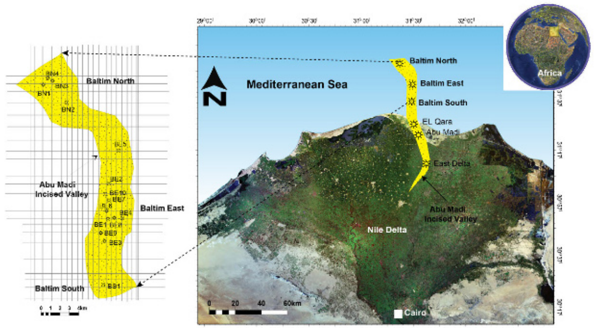

Figure 1. Study area showing the location of the available 2D seismic line profiles and wells on the offshore Nile Delta, Egypt.

The study area comprises the Baltim gas fields in the Nile Delta Basin, northern Egypt (Fig. 1).

2. Exploration History

Early stage (1966-1989). After the discovery of the gas-bearing sandstones of Abu Madi 1 well (1966), the late Messinian Abu Madi Formation represented one of the main targets in the present onshore area (Fig. 1). The discovery area was related to an elongate and faulted anticline, but the presence of different reservoir levels and the drilling of some dry wells suggested both structural and stratigraphic controls on reservoir distribution. The Tertiary stratigraphy of the Nile Delta Basin was defined in these years (Sidi Salim, Qawasim, Abu Madi, and Kafr el Sheikh formations were described in exploratory wells of the area), and the first sedimentological interpretation referred the Abu Madi Formation to a continental/deltaic depositional environment [14, 15] (Fig. 2). Several wells were drilled and the Abu Madi Field, now connected to the new discoveries of El Qar'a, started to reveal its present geometry and internal reservoir complexity [16].

Second stage (1990-1993). The southward extension of the Abu Madi incised-valley confirmed the hydrocarbon potential of the late Messinian succession. More sophisticated seismic acquisition and processing were carried out in the East Delta Concession where, in 1990, the East Delta 1 well (Fig. 1) was successfully drilled, 25 km south of the Abu Madi Field. This and the other wells drilled in those years, either positive or dry, confirmed the strict relationships between gas accumulations and the Messinian drainage system, an ancestor of the present Nile River. An increasing amount of well data, the elaboration of a sequence stratigraphic model, and an effective technological improvement in seismic acquisition and processing,

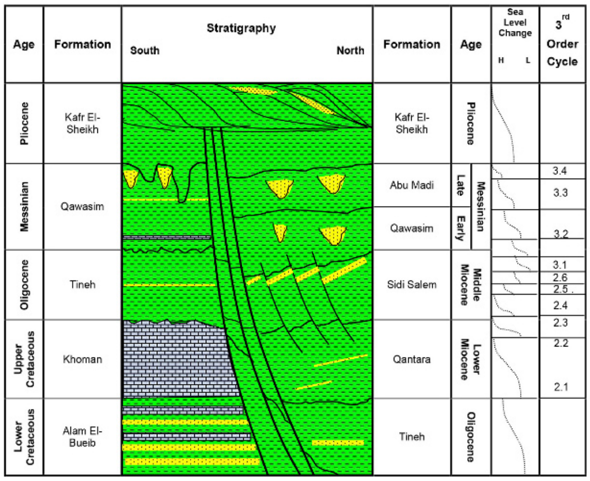

Figure 2. Stratigraphic column of the Nile Delta, Egypt (modified after [12, 13]).

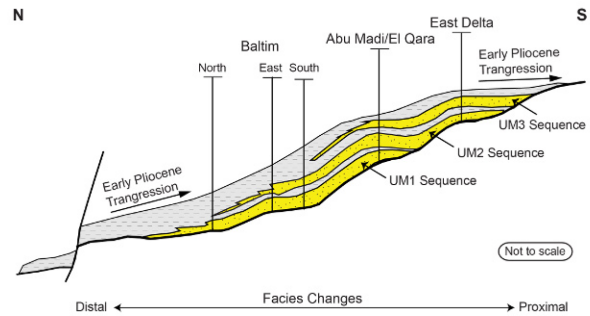

Figure 3. Sequence stratigraphy of the Abu Madi Formation from East Delta to Baltim. Location and nature of the main reservoir intervals within the Abu Madi incised-valley follow the regional transgression of the area in the late Messinian [16].

allowed to verify the regional geologic framework and to recognize more and more subtle traps [16].

Third stage (1993-1996). The comprehensive multidisciplinary effort resulted in the projection of the Messinian targets into the offshore area and in the acquisition of a 3D seismic volume in the newly acquired concession of Baltim. After the discovery of gas, in 1993 [17] in Baltim East 1 (Fig. 1), seven other wells were successfully drilled by the partnership IEOC/Amoco, delineating three fields in the area (Baltim North, East, and South Fields, Fig. 1). The Baltim exploratory phase represented not only the confirmation of a geologic stratigraphic model, but also a significant change in the geophysical interpretation as some combinations of seismic attributes showed a good correlation with lithological and petrophysical properties within Abu Madi deposits [16].

Also the regional picture became clearer and more reliable. Three different sequences, named UM1, UM2, and UM3, were defined and regionally correlated from East Delta to Baltim. All of them have shown a similar internal organization and evolution [18]. The only major difference was related to the more prospective fluvial to fluvio-deltaic facies: sequence by sequence they were progressively deposited in a paleo-landward direction, i.e., backstepping during the late Messinian transgression (Fig. 3). All the fields were correlated at the regional scale, and the existing relationships among the different productive levels were highlighted, either by longitudinal continuity or gross facies distribution (Fig. 3).

3. Database and Methods

Our dataset from the Baltim fields consists of a set of 15 wells and 40 2D seismic line profiles provided by Petrobel, Inc., covering an area of 572 km^2 (Fig. 1). The majority of the work was done by using normalized gamma-ray (GR), deep resistivity (ILD), sonic (DT), neutron (CNL) and bulk density (RHOB) logs. The proportions of each type of lithology for the Abu Madi reservoirs "Level III Main" and "Level III Lower" were determined by means of various well-logs. The well-log data was processed using Interactive Petrophysics software. The well-log analysis defined "clean" and shale baselines on the GR logs, and identified "clean" zones containing hydrocarbons. Shale volume (V_{sh}) was determined using both single curve indicators such as the gamma ray or deep Resistivity responses and double curve indictors (Density and Acoustic – Neutron and Density). Minimum values of these methods were considered to be representative of the shale volume. Shale volume (VCL GR), calculated from the GR log, was used to indicate the amount of shale in each reservoir interval. The work included identification and correlation of sequence stratigraphic surfaces, litho-saturation (lithology and fluid saturation) analysis, and construction of a subsurface cross-section of the Abu Madi Formation in the Baltim area.

The pressure data obtained from RFTs are very useful as they enable judgments to be made about the position of the gas-water contact (GWC) in the Abu Madi reservoirs. Additionally, information is provided about compartmentalization, or whether the various fluids in a reservoir are separated physically by an impermeable barrier. The contacts between fluids (gas and water) were interpreted based on resistivity logs (gas/water) and formation pressure data (RFT).

Depending on the type of data available for analysis, the correct identification of the various types of stratigraphic surfaces is key to the success of the sequence stratigraphic approach, and the criteria used for such identifications in this study are based on well logs and seismic data. Stratigraphic surfaces may be identified based on a number of criteria, including the nature of contact (conformable or unconformable), the nature of facies which are in contact across the surface, depositional trends recorded by the strata below and above the contact (forced regressive, normal regressive, or transgressive), and stratal terminations associated with each particular surface. It can be noted that most of these criteria involve preliminary facies analyses and an understanding of the environments in which the stratigraphic contact and the juxtaposed facies that it separates, originated. The reconstruction of the depositional setting therefore enables us to apply objective criteria for the recognition and correlation of stratigraphic surfaces. Integration of 2D, 3D seismic and well logs provides additional constraints on depositional setting and the genesis of stratal termination in an environmental context, thus allowing for a proper identification of the stratigraphic contacts under investigation. A sequence stratigraphic framework was first established for the BE1 discovery well. This well contains the most comprehensive well database for the analyzed late Messinian stratigraphic targets, thus it was the reference well to build a well log sequence stratigraphic framework and then to extend it to the remaining area for the integrated interpretation. Once the key surfaces for stratigraphic correlation were identified, the well log signatures were extrapolated to the nearby wells through well log cross section correlations. Finally, the well log data and key surfaces were tied to the seismic data for seismic stratigraphic correlation and interpretation. Several loops between seismic and well log data were performed to assure agreement of interpretations. After the preliminary framework was established, seismic sequence interpretation was employed to more accurately delineate the reservoir intervals. This analysis formed the basis for identifying new opportunities in the study area and to plan a development strategy for Baltim fields.

Well logs allow the identification of key surfaces for sequence stratigraphic interpretation and for correlation of these surfaces between adjacent wells. Well log sequence stratigraphic analysis provides a first understanding of the relationships between the depositional environment and how it was affected by sea level changes. The gamma ray curve was used to identify log patterns and candidates for sequence boundaries, maximum flooding surfaces and other regional marker horizons were identified on seismic profiles. The quality of the available seismic allowed us to associate abrupt changes of reflection character with the lateral extension limits of the stratigraphic sequences. The use of complex trace analysis on 2D and 3D seismic data allowed a better characterization of the geometric relationships among the reflectors, and the delineation of an Abu Madi incised-valley became possible. The Abu Madi Formation was interpreted as the sedimentary filling of this intra-Messinian erosional feature.

In the Abu Madi Formation of Baltim wells, sequence stratigraphic surfaces, markers, thickness trends, and lithology units were correlated using well logs and seismic data. Flooding surfaces within the Abu Madi shale and recognizable and widespread sequence boundaries at the top and bottom of the Abu Madi Formation were correlated and used to constrain the correlation of the sequence stratigraphic surfaces.

Litho-saturation analysis and petrophysical core information were also integrated within this framework. Pressure tests from two wells were analyzed to test connectivity between the sequence stratigraphic intervals and verify the stratigraphic correlation.

4. Results

4.1. Identification and correlation of sequence stratigraphic surfaces

Well logs (especially GR logs) and seismic responses have respectable recognition criteria for sequence stratigraphy framework (sequence boundaries, stratigraphic surfaces, facies and depositional systems). Criteria for the recognition of subaerial unconformities as sequence bounding surfaces have been identified by top either gradationally based (highstand or earliest forced regressive) or sharp-based (forced regressive) shoreface deposits. Stratigraphic surfaces have been recognized by the entire range of GR log motifs which includes 'blocky' (also referred to as 'cylindrical'), 'jagged' (also referred to as 'irregular' or 'serrated'), 'fining-upward' (also referred to as 'bell-shaped') and 'coarsening-upward' (also known as 'funnel-shaped'). Continuous character of seismic data have a major advantage relative to well-log data, which only provide stratigraphic information from discrete locations in the basin, so the integration of all these techniques with previous sedimentological studies in the study area is critical for mutual calibration and the development of reliable facies and a depositional environment model. The amplitude of the seismic reflection is usually proportional to the contrast in acoustic impedance across the geological 'contact'. Thus, high negative anomalies at the top of reservoir facies are commonly seen as a good 'sign' for petroleum

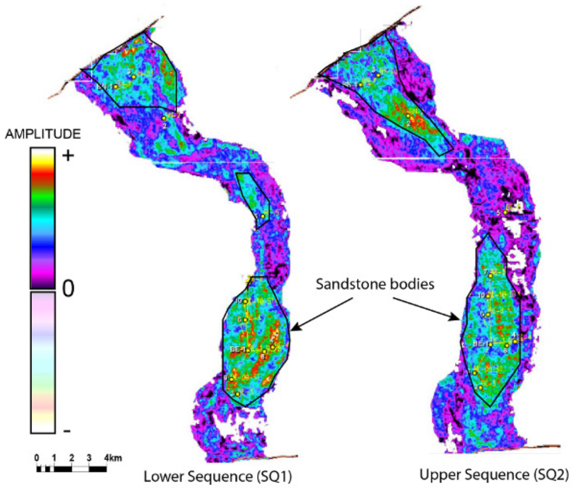

Figure 4. Seismic amplitude anomalies show the locations of sandstone bodies in lower and upper sequence of the lowstand stystems tract (LST).

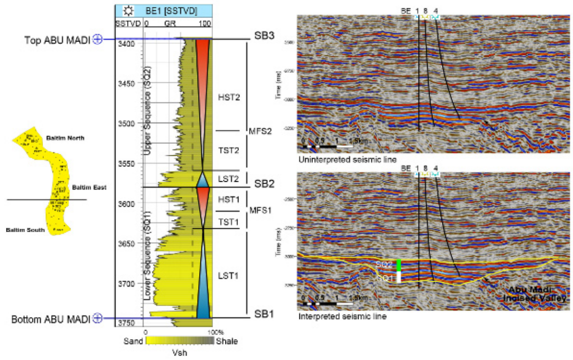

Figure 5. Sequence stratigraphic surfaces of the Abu Madi Formation based on BE1 well which integrated with seismic data.

exploration (Fig. 4), as they suggest a sudden decrease in acoustic impedance inside the reservoir, which may potentially be related to the presence of porosity and low density fluids (i.e., hydrocarbons) in a good sandstone body. Within fluvial successions, low accommodation conditions result in an incised-valley-fill type of stratigraphic architecture dominated by multi-storey channel fills and a general lack of floodplain deposits. The depositional style is progradational, accompanied by low rates of aggradation, often influenced by the underlying incised-valley topography, similar to what is expected from a lowstand systems tract. Deposition of lowstand systems tract within the incised-valley occurred subsequent to stabilization of sea level at lowstand or an incipient rise, which favored the deposition of braided river and later meandering-river sediments. The low-accommodation systems tract generally includes the coarsest sediment fraction of a fluvial depositional sequence, which may in part be related to rejuvenated sediment source areas and also to the higher energy fluvial systems that commonly build up the lower portion of a sequence. These features give the low-accommodation systems tract some equivalence with the lowstand systems tract, reflecting early and slow base-level rise conditions (or low rates of creation of fluvial accommodation, in the absence of marine influences) that lead to a restriction of accommodation for floodplain deposition. High accommodation conditions (attributed to higher rates of creation of fluvial accommodation) result in a simpler fluvial stratigraphic architecture that includes a higher percentage of finer-grained overbank deposits, similar in style to the transgressive and high- stand systems tracts. Transgressive systems tracts are characterized by a mixture of bedload and suspension-load deposits arranged as upward-fining and upward-thinning bed sets. The depositional style is aggradational, with less influence from the underlying topography or structure.

Based on borehole and seismic data, the strata of Abu Madi Formation are interpreted to comprise two sequences, which are the most complex stratigraphically; their deposits comprise a complex incised valley (Fig. 5). The lower sequence (SQ1) consists of a thick incised valley-fill Lowstand Systems Tract (LST1)) overlain by a Transgressive Systems Tract (TST1) and Highstand Systems Tract (HST1). The upper sequence (SQ2) contains channel-fill and is interpreted as a LST2 which has a thin sandstone channel-fill. Above this, channel-fill sandstone and related tidally-influenced strata delineates the base of TST2 and overlain by a HST2. The main sequence stratigraphic surfaces that were identified and correlated (Fig. 5 and 6) are the sequence boundary (SB1) at the base of the LST1 sandstone (i.e. the bottom of Abu Madi Formation), the sequence boundary (SB2) at the base of the LST2 sandstone, and the sequence boundary (SB3) at the base of the top of the HST2 (i.e. the top of Abu Madi Formation). The major valley direction in the study area is north-south (Fig. 6). Baltim South field is separated from Baltim East and North by a west-east directed normal fault. Valley incisions generally thin toward down-dip and thicken towards the up-dip directions. The thinning and thickening trends down-dip and up-dip can be observed in both subsurface well-logs and seismic profiles (Figs. 6 and 7) in the study area.

4.2. Litho-saturation analysis

The vertical distribution, in a form of litho-saturation (lithology and hydrocarbon saturation) plots, shows ir-

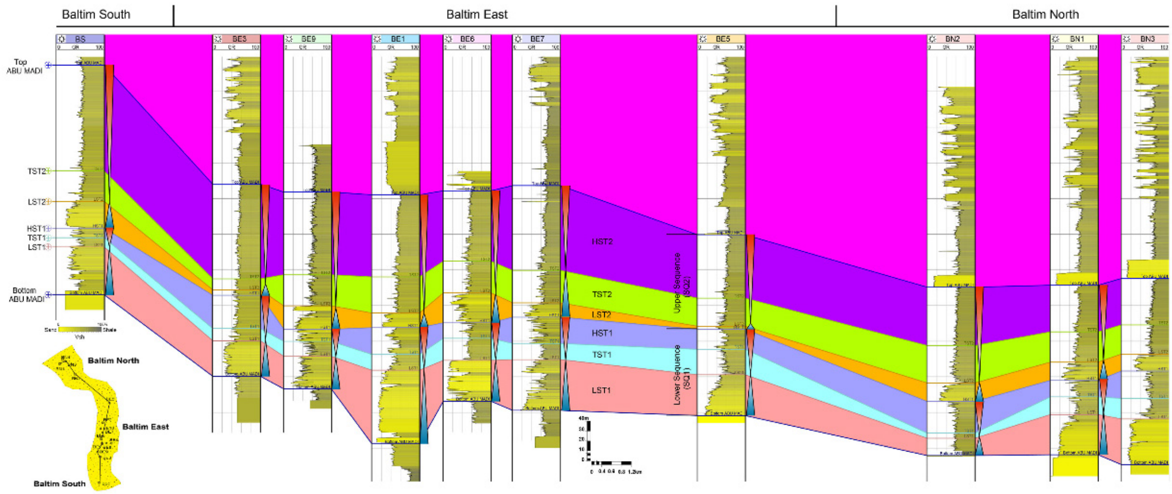

Figure 6. Well correlation showing the sequence stratigraphic surfaces of the Abu Madi Formation in Baltim fields (South, East and North).

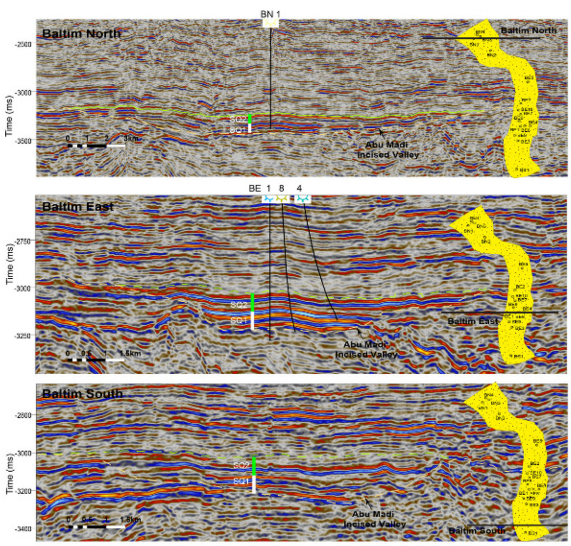

Figure 7. West-East seismic lines across the Baltim fields that illustrate the sequence stratigraphic surfaces and the Abu Madi incised-valley boundary.

regular vertical variations throughout the system tracts, in lithology, and water and gas contents (Figs. 8 and 9). Petrophysical parameters of the Abu Madi reservoirs, including shale volume, porosity and water saturation, vary from well to well in the Baltim fields. Figs. 8 and 9 show vertical variations for these parameters in wells BE1 and BN1, over the systems tracts of interest, The lithology of the Abu Madi reservoirs appears to be dominated by sandstone with more minor siltstone and shale, which are represented in LST intervals in each SQ1 and SQ2. Two different gas-water contacts were recognized in each well. In well BE1, GWC1 occurs at a structural depth of 3636 m while GWC2 occurs at a depth of 3700. In well BN1, GWC1 occurs at a depth of 3685 m while GWC2 occurs at a depth of 3778.3 m (Fig. 8 and 9).

4.3. Porosity and permeability

Regardless of the quantity of wireline log data, numerous trials were done to understand the effect of porosity on permeability in the study area by constructing linear correlation cross plots of core porosity vs core permeability, and from this correlation, determining the permeability values for lower sequence (SQ1) and upper sequence (SQ2) in the Abu Madi Formation (Table 1). LST sandstones have a wide range of porosity (15 to 28%) and permeability (2 to 5080mD). TST shows lower porosity and permeability values than HST in each sequence. In lower sequence (SQ1), the data of the correlation between

Table 1. Porosity and permeability values of systems tracts in lower sequence (SQ1) and upper sequence (SQ2) in the Abu Madi Formation.

Sequence	Systems Tract	Porosity (%)	Permeability (mD)
Upper (SQ2)	HST2	11 – 21	1.2 – 6.9
	TST2	0.8 – 15	0.03 – 0.85
	LST2	17 – 28	2 – 2873
Lower (SQ1)	HST1	12 – 16	1.8 – 33
	TST1	2 – 10	0.04 – 1.02
	LST1	15 – 28	20 – 5080

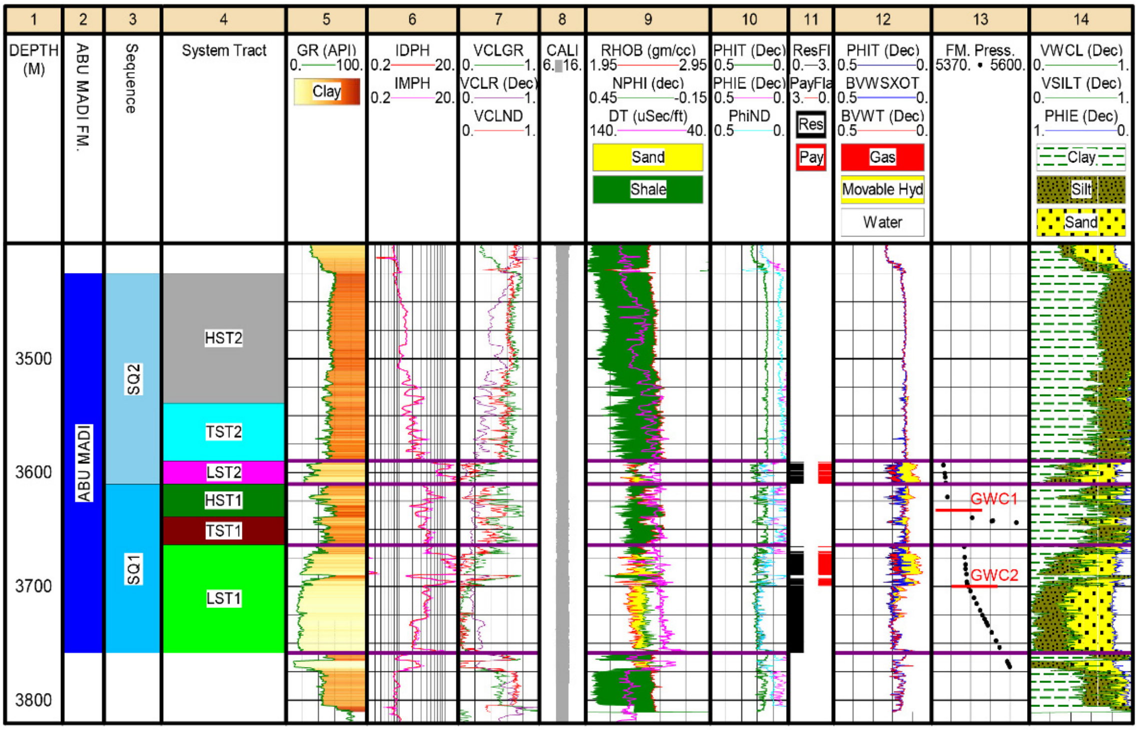

Figure 8. Litho-saturation plot illustrating vertical variations in the lithology, GWC, fluid saturation, and petrophysical characteristics of the stratigraphic system tract of the Abu Madi Formation in BE1 well.

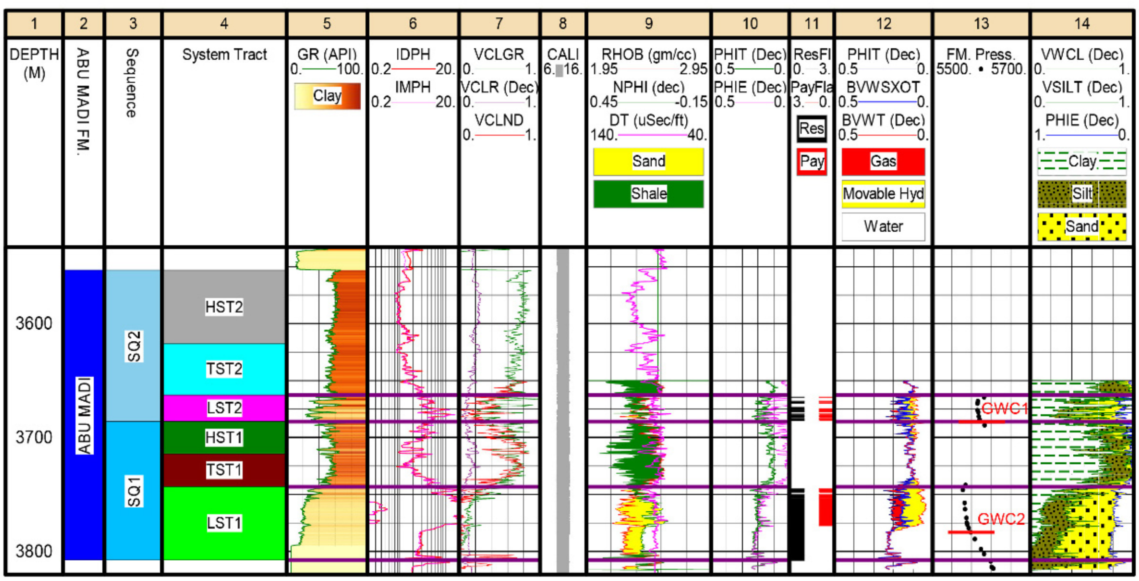

Figure 9. Litho-saturation plot illustrating vertical variations in the lithology, GWC, fluid saturation, and petrophysical characteristics of the stratigraphic system tract of the Abu Madi Formation in BE1 well.

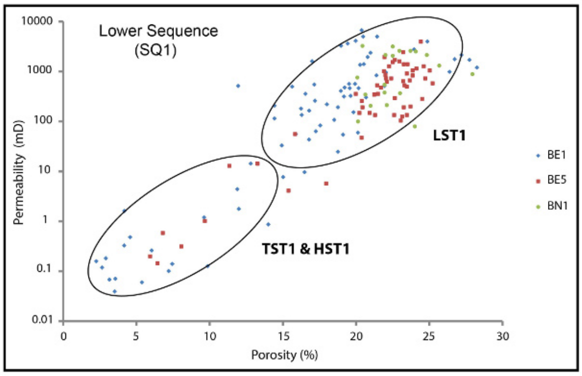

Figure 10. Poro-perm relationship for measured values of SQ1 in cored intervals of wells BE1, BE5 and BN5. The correlation between porosity and permeability from the cores showing that there is homogeneity between all wells data and have the same trend.

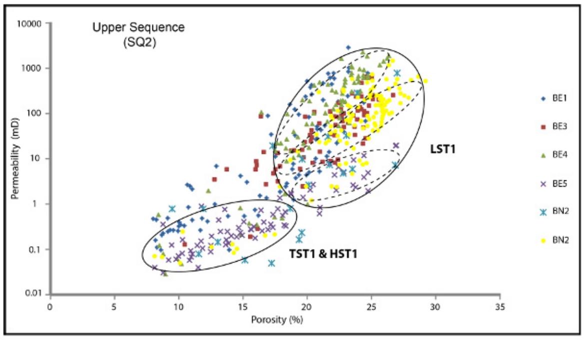

Figure 11. Poro-perm relationship for measured values of SQ2 in cored intervals of wells BE1, BE3, BE4, BE5, BN2 and BN5. The correlation between porosity and permeability from the cores show that there is no homogeneity between all well data, especially in LST2. LST2, which shows three different trends.

porosity and permeability from the cores (Fig. 10) reveals a systematic positive trend with LST1 sandstone having higher values of porosity and permeability than TST1 and HST1. Unlike upper sequence (SQ2), there is no homogeneity in the LST2 sandstone (Fig. 11) and there may be three trends. Green data points of well BE4 exhibit a positive porosity-permeability trend in the middle of the thick LST2 channel facies. The second trend with yellow and brown colored points, from wells BN5 and BE3 respectively, exhibits a good porosity and permeability relationship, but the values are lower than the previous points. This trend is located near the periphery of the sandstone channel fill. The third trend with violet colored data points shows low values for both porosity and permeability in the BE5 well, which lies outside the channels.

5. Discussions

Reservoir characterization as a discipline grew out of the recognition that more oil and gas could be extracted from reservoirs if the geology of the reservoir was understood [19]. In fluvial reservoirs, when only sparse data is examined, oversimplification and questionable correlations of stratigraphic architecture are more likely. One of the means to constrain correlation involves using dimensional databases e.g., [20–22]. Data suggest that systematic changes in fluvial architecture and channel geometries may occur within sequences and systems tracts [23–26] showed clear changes in the width and thickness of fluvial channel sandstones in different systems tracts within sequences.

The overall incised-valley filling pattern of the Abu Madi Formation is consistent with an abrupt relative sea level fall followed by a stillstand, then a progressive rise, as described for other valley fill sequences [24, 27, 28]. The initial rapid relative sea level fall had an important tectonic-uplift component in the area [29], and caused valley incision and the formation of a regional unconformity at the base of the valley. The valley cut into the Messinian marine mudstones of the Qawasim Formation (Fig. 5).

Deposition of lowstand systems tract within the incised-valley occurred subsequent to stabilization of sea level at lowstand or an incipient rise, which favored the deposition of braided river and later meandering-river sediments. Sediment deposition occurred mainly along the axis of the valley, with some contribution from alluvial fans from the valley walls. The LST is a really? The LST is a really restricted and laps out against the basin flanks. The internal architecture of the systems tract is characterized by sandy bedload deposits organized as amalgamated, upward-fining and thickening channel-fill complexes. Eventually, high-frequency and high-amplitude fluctuations in base level, induced by relative sea-level changes, rapidly changed accommodation space within the valley. Transgressive systems tracts are characterized by a mixture of bedload and suspension-load deposits arranged as upward-fining and upward-thinning bed sets. These strata have a wider areal extent than the lowstand deposits and are interpreted to reflect increased accommodation during periods of stratigraphic base-level rise. Periods of accommodation-space creation favored the development of meandering fluvial systems with widespread deposition of floodplain siltstones and mudstones [30] that now form reservoir seals at the field scale in the LST (Fig. 12). Recurrence of braided-river deposits suggests that accommodation space and/or sediment supply oscillated through time [30]. When the rate of relative sea-level rise and accommodation-space creation finally outstripped

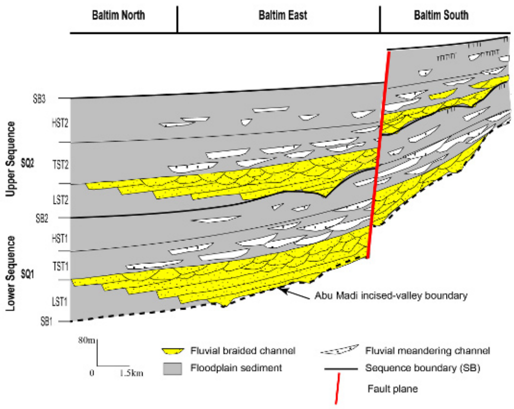

Figure 12. Schematic cross section illustrating the sequence stratigraphic framework of the Abu Madi Formation in Baltim fields, offshore Nile Delta, Egypt.

the rate of sediment supply, the system started to retrograde and the incised-valley was flooded with marine water and was transformed into an estuary [14, 15, 31]. Consequently, the fluvial deposits were subjected to reworking by tidal processes. The tidal influence in incised-valley fluvial deposits has been used as a criterion to determine the beginning of overall shoreline transgression [1, 24, 27] and thus marks the beginning of the TST in the Abu Madi incised-valley fill (Figs. 5 and 6). Deposition during early stages of the TST, within the valley limits, is dominated by siltstones and mudstones. These fine-grained deposits, which can reach up to 30m in thickness, constitute a stratigraphic marker and a reservoir seal. At this time, when the parasequences change from retrogradational to aggradational, the maximum flooding surface (MFS) is deposited [32, 33]. As transgression continued, tidal influence on the fluvial deposits increased until the time when the incised-valley was completely filled with sediments, marine conditions were established, and deposition of shelf mudstones took place. These mudstones (up to 150m thick) constitute the HST deposit and form an important stratigraphic marker in the basin (Fig. 12).

Characterizing reservoir heterogeneity is significant for the understanding and optimization of the hydrocarbon potential accumulations in the Abu Madi Formation. Abu Madi reservoirs contain impermeable lithologic units and heterogeneous distributions of porosity/permeability (Figs. 10 and 11), especially in the TST and HST, which are further affected by structural complexities that significantly can affect the fluid paths in the reservoir. Reservoir characterization is needed in effective petroleum production since reservoir heterogeneities are closely related to the pressure of trapped fluids. Floodplain deposits in each TST and HST represent a good seal separating LST gas reservoirs of lower sequence (SQ1) and upper sequence (SQ2) from two different gas-water contacts in each well in the Baltim fields (Figs. 7 and 8). Baltim South field is separated from Baltim East and North by a west-east directed normal fault. This fault is called the Baltim trend (Figs. 6 and 12). The Abu Madi incised-valley fill of this trend is complexly layered, with multiple stacked point-bar and estuarine deposits, which form structural and stratigraphic traps within the incised-valley fill [17].

6. Conclusions

In the exploration and development activity, an effective geologic/geophysical interaction with a real methodological improvement, permits a continuous updating and improved understanding of the target reservoir. The mutual integration between a sequence stratigraphy interpretation of well data and seismic line profiles with semi-quantitative inferences, eventually resulted in a clearer and more precise picture of the Messinian Abu Madi Formation, and consequently, improved the success ratio of this subtle gas play in the Baltim fields. The information contained in this paper clearly demonstrates the importance of building a sequence stratigraphic framework for an improved understanding of the depositional model and physical distribution of reservoir properties in the Baltim gas fields of offshore Nile Delta, Egypt.

On the basis of extended bottom borehole logging and detailed well correlations, it was possible to recognize and describe fluvial to estuarine/shelfal facies, vertically arranged in an overall fining and thinning upward trend. The presence of sandstone bodies at different stratigraphic levels was related to smaller-scale regressive transgressive cycles, and/or possibly avulsions within the regional transgressive trend of the late Messinian time. According to abrupt vertical facies changes and detailed seismic interpretation, different stratigraphic sequences were defined and traced over more than 572 km_2. Due to the lack of enough comprehensive well data at the Messinian stratigraphic levels in the study area, the BE1 well provided the base for extrapolating geological and geophysical conditions away from the well site. The sequence stratigraphic framework developed for BE1 well was extended to 14 additional nearby wells taking into account the gamma ray pattern of the key surfaces and shale marker as datum. Once the key surfaces for stratigraphic correlation were identified, they were transferred to the seismic data to extrapolate them to nearby wells. Several loops between seismic and well log data were performed to assure agreement of interpretations.

Three sequence boundaries which bracket two depositional sequences SQ1 (lower sequence) and SQ2 (upper sequence), as well as two maximum flooding surfaces, were interpreted from the well sequence stratigraphy and extrapolated to nearby wells through well log and seismic correlation. Retrogradational parasequences sitting atop major sequence boundaries that are mappable both seismically and from well logs provides an important new play concept in the Baltim area.

Reservoir facies were deposited in incised-valley environments. In such environments, reservoir quality is driven by the amount of sand within the channel fill. As the sand content increases and the shale content decreases the porosity and permeability increase. LST fluvial channels fill represent the main reservoirs in Baltim area. Pressure data indicate that these reservoirs are mutually separated by TST and HST shale deposits. The geological model established here, as well as the nature and physical distribution of reservoir properties, was based on the sparse information available at the time this paper was initiated. Therefore, new knowledge should be included and the model regularly updated as new wells are drilled and new G&G data is acquired for Messinian objectives in this area.

The knowledge gained from this research is an important contribution to the petroleum geology of Baltim and the Nile Delta basin, which confirms the petroleum system for this Messinian play, defines a new play concept, establishes a sequence stratigraphic model for reservoir characterization and architecture if analogous projects are undertaken in the future, and defines the basis for further research in the study area.

Acknowledgements

We wish to express our gratitude to the Egyptian General Petroleum Corporation (EGPC) and Belayim Petroleum Company (Petrobel), Cairo, Egypt, for their approval and permission to use the material for study.

References

[1] Catuneanu O., Principles of sequence stratigraphy, (1st ed.) Elsevier, Amsterdam, 2006

[2] Van Wagoner J.C., Mitchum R. M., Campion K. M. and Rahmanian V. D., Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facie. Am. Assoc. Petr. Geol., 1990, Methods in Exploration Series 7, 1-55

[3] Posamentier H. W. and James D. P., An overview of sequence-stratigraphic concepts: uses and abuses, in Posamentier H. W., Summerhayes C. P., Haq B. U. and Allen G. P., eds., Sequence Stratigraphy and Facies Association. Int. Assoc. Sedimentol., 1993, Special Publication 18, 3-18

[4] Posamentier H. W. and Allen G. P., Siliciclastic sequence stratigraphy: concepts and applications. SEPM (Society for Sedimentary Geology), Tulsa, 1999

[5] Dalrympl, R. W. and Zaitlin B. A., High-resolution sequence stratigraphy of a complex, incised valley succession, Cobequid Bay–Salmon River estuary, Bay of Fundy, Canada. Sedimentology, 1994, 41, 1069–1091.

[6] Zaitlin B. A., Dalrymple R. W. and Boyd R., The stratigraphic organization of incised valley systems associated with relative sea-level change, in Dalrymple R. W., Boyd R. and Zaitlin B. A., eds., Incised-Valley Systems; Origin and Sedimentary Sequences. SEPM, 1994, Special Publication 51, 45–60

[7] Willis B. J., Architecture of fluvial-dominated valley-fill deposits in the Cretaceous Fall River Formation. Sedimentology, 1997, 44, 735–757

[8] Hou B., Frakes L. A., Alley N. F. and Clarke J. D. A., Characteristics and evolution of the Tertiary palaeovalleys in the northwest Gawler Craton, South Australia. Aust. J. Earth Sci., 2003, 50, no. 6, 983–999

[9] Plint P. A. and Wadsworth J. A., Spatial variability of Palaeosols across Cretaceous interfluences in the Dunvegan Formation, NE British Columbia, Canada; palaeohydrological, palaeogeomorphological and stratigraphic implications. Sedimentology, 2003, 50, 1187–1220

[10] Dutton S. P. and Willis B. J., Comparison of outcrop and subsurface sandstone permeability distribution, Lower Cretaceous Fall River Formation, South Dakota and Wyoming. J. Sediment. Res., 1998, A68, 890–900

[11] Ketzer J. M., Morad S., Evans R. and Al-Aasm I. S., Distribution of diagenetic alteration in fluvial, deltaic, and shallow marine sandstones within a sequence stratigraphic framework: evidence from the Mullaghmore Formation (Carboniferous), NW Ireland. J. Sediment. Res, 2002, 72, 760–774

[12] Mark S. M., Reservoir compartmentalization of the Morrow Sandstone at Sorrento Field, southeastern Colorado. In R.M. Slatt (ed.) Compartmentalized reservoirs in Rocky Mountain basins, Rocky Mtn. Assoc. Geol. (RMAG) Publ., 1998, 99-130

[13] Tillman R. W. and Pittman E.D., Reservoir heterogeneity in valley-fill sandstone reservoirs, southwest Stockholm Field, Kansas. In: W. Linville (ed.) Reservoir Characterization III, Proc. 3rd Inter. Reservoir Char. Tech. Conf. Tulsa, 1993, 51-105

[14] El Heiny I., Rizk R. and Hassan M., Sedimentological model for Abu Madi sand reservoir, Abu Madi field, Nile Delta, Egypt. EGPC 10th, Exploration and Production conference, Cairo, Egypt, 1990, 1-38

[15] Wornardt Jr W., Revision of sequence boundaries and maximum flooding surfaces: Jurassic to Recent. Offshore Technology Conference, Texas, OTC, 1999, 1-18

[16] Dalla S., Harby H. and Serazzi M., Hydrocarbon exploration in a complex incised valley fill: an example from the late Messinian Abu Madi Formation (Nile Delta Basin, Egypt). The Leading Edge, 1997, 16, 1819–1824

[17] Dolson J. C., Shann M. V., Matbouly S., Harwood C., Rashed R. and Hammouda H., 2001, Chapter 23: The Petroleum Potential of Egypt, Am. Assoc. Petr. Geol., Memoir 74, 453-482

[18] Palmieri G., Harby H., Marini J. A., Hashem F., Dalla S. and Shash M., Baltim fields complex: An outstanding example of hydrocarbon accumulations in a fluvial Messinian incised valley, in M. Youssef, ed., Proceedings of the 13th Petroleum Conference: Cairo, Egypt, Egyptian General Petroleum Corporation, 1996, 256–269

[19] Slatt Roger M., Stratigraphic reservoir characterization for petroleum geologists, geophysicists, and engineers. Elsevier Science Limited, Amsterdam, 2006

[20] Reynolds A. D., Dimensions of paralic sandstone bodies. Am. Assoc. Petr. Geol., 83, 1999, 211–229

[21] Gibling M. R., Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. J. Sediment. Res., 2006, 76, 731–770

[22] Pranter M. J. and Sommer N. K., Static connectivity of fluvial sandstones in a lower coastal-plain setting: An example from the Upper Cretaceous lower Williams Fork Formation, Piceance Basin, Colorado. Am. Assoc. Petr. Geol., 2011, 95, 899-923

[23] Shanley K. W., McCabe P. J. and Hettinger R. D., Significance of tidal influence in fluvial deposits for interpreting sequence stratigraphy. Sedimentology, 1992, 39, 905–930

[24] Shanley K. W. and P. J. McCabe, P.J., Alluvial architecture in a sequence stratigraphic framework: a case history from the Upper Cretaceous of southern Utah, U.S.A., in S. Flint and I. Bryant, eds., Quantitative modelling of clastic hydrocarbon reservoirs and outcrop analogues. Int. Assoc. Sedimentol., 1993, Special Publication 15, 21– 55

[25] Shanley K. W. and P. J. McCabe, P.J., Perspectives on the sequence stratigraphy of continental strata. Am. Assoc. Petr. Geol., 1994, 78, 544–568

[26] Van Wagoner J. C., Sequence Stratigraphy and Marine to Nonmarine Facies Architecture of Foreland Basin Strata, Book Cliffs, Utah, U.S.A.. Am. Assoc. Petr. Geol.: 1995, Memoir 64, 137-223

[27] Posamentier H. W. and Allen G. P., Siliciclastic sequence stratigraphy: concepts and applications. SEPM (Society for Sedimentary Geology), Tulsa, 1999

[28] Catuneanu O., Abreu V., Bhattacharya J. P., Blum M. D., Dalrymple R. W., Eriksson P. G., Fielding C. R., Fisher W. L., Galloway W. E., and Gibling M. R., Towards the standardization of sequence stratigraphy. Earth Sci. Rev., 2009, 92, 1-33

[29] Sestini G., Nile Delta, a review of depositional environments and geological history, in Whately, M.K.G., and Pickering, K.T., eds., Deltas: Sites and Traps for Fossil Fuels. Geological Society of London, 1989, Special Publication 41, 99–127

[30] Wright V. P. and Marriott S. B., The sequence stratigraphy of fluvial depositional systems: the role of floodplain sediment storage. Sediment. Geol., 1993, 86, 203–210

[31] Salem A. M., Ketzer J. M., Morad S., Rizk R. R. and Al-Aasm I. S., Diagenesis and reservoir-quality evolution of incised-valley sandstones: evidence from the Abu Madi gas reservoirs (Upper Miocene), The Nile Delta Basin, Egypt. Journal of Sedimentary Research, 2005, 75, 572-584

[32] Emery D. and Myers K. J., Sequence Stratigraphy. Blackwell Science, Oxford, 1996

[33] Catuneanu O., Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. J. Afr. Earth Sci., 2002, 35, 1-43