Multi-disciplinary approach to sedimentary facies analysis of Messinian Salinity Crisis tectono-sequences (South-Mansoura Area, Nile Delta): Incised-valley fill geological model reconstruction and petroleum geology–reservoir element delineation

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Abstract
The quality of a hydrocarbon reservoir is strongly controlled by the depositional and diagenetic facies nature of the given rock. Therefore, building a precise geological/depositional model of the reservoir rock is critical to reducing risks while exploring for petroleum. Ultimate reservoir characterization for constructing an adequate geological model is still challenging due to the in general insufficiency of data; particularly integrating them through combined approaches. In this paper, we integrated seismic geomorphology, sequence stratigraphy, and sedimentology, to efficiently characterize the Upper Miocene, incised-valley fill, Abu Madi Formation at South Mansoura Area (Onshore Nile Delta, Egypt). Abu Madi Formation, in the study area, is a SW-NE trending reservoir fairway consisting of alternative sequences of shales and channel-fill sandstones, of the Messinian age, that were built as a result of the River Nile sediment supply upon the Messinian Salinity Crisis. Hence, it comprises a range of continental to coastal depositional facies. We utilized dataset including seismic data, complete set of well logs, and core samples. We performed seismic attribute analysis, particularly spectral decomposition, over stratal slices to outline the geometry of the incised-valley fill. Moreover, well log analysis was done to distinguish different facies and lithofacies associations, and define their paleo-depositional environments; a preceding further look was given to the well log-based sequence stratigraphic setting as well. Furthermore, mineralogical composition and post-depositional diagenesis were identified performing petrographical analysis of some thin sections adopted from the core samples. A linkage between such approaches, performed in this study, and their impact on reservoir quality determination was aimed to shed light on a successful integrated reservoir characterization, capable of giving a robust insight into the depositional facies, and the associated petroleum potential. The results show that MSC Abu Madi Formation constitutes a third-order depositional sequence of fluvial to estuarine units, infilling the Eonile-canyon, with five sedimentary facies associations; overbank mud, fluvial channel complex, estuarine mud, tidal channels, and tidal bars; trending SW-NE with a Y-shape channel geometry. The fluvial facies association (zone 1 and 3) enriches coarse-grained sandstones, deposited in subaerial setting, with significantly higher reservoir quality, acting as the best reservoir facies of the area. Although the dissolution of detrital components, mainly feldspars, enhanced a secondary porosity, improving reservoir quality of MSC Abu Madi sediments, continental fluvial channel facies represent the main fluid flow conduits, where marine influence is limited.

Keywords Sedimentary Facies Analysis · Depositional model · Reservoir Quality · Incised-valley fill · Abu Madi Formation · Onshore Nile Delta
Introduction

Reservoir characterization involves the work on depicting the reservoir heterogeneity [through analyzing and mapping depositional facies], and reservoir quality [through identifying post-depositional diagenetic processes effect on porosity and permeability], to efficiently predict the reservoir performance.

Today, reservoir characterization demands integrating various disciplines (e.g., seismic geomorphology, sequence stratigraphy, and sedimentology), comprehensively defining the reservoir characteristics, to obtain the best recoveries with fewest wells (Slatt 2013). Integrating different approaches to depicting the depositional environments/facies, and identify their effect on reservoir performance, gives a precise picture of the reservoir characteristics and improves the success rates of hydrocarbon exploration and development (Abdel-Fattah and Slatt 2013; Abdel-Fattah 2014; Pigott and Abdel-Fattah 2014; Abdel-Fattah and Tawfit 2015). Sediments of different depositional environments may be broadly grouped into continental, shoreline/transitional, and marine deposits. Each depositional system exhibits unique architectural features, with particular sedimentological patterns, caused by sediment transport processes and the subsequent deposition in various environments. Sizes, shapes, net-to-gross values, orientation, continuity, and other characteristics of the reservoir are a result of the sediment transport nature, depositional environment, basin configuration, tectonics, fluctuation of eustatic sea level, and climate (Slatt 2006). Therefore, building a precise geological/depositional model, capable of efficiently depicting the reservoir characteristics and controls on reservoir performance, is of utmost importance in reservoir management phases.

The Nile Delta of Egypt is considered a noteworthy depositional system, in which Nile River-Mediterranean complex interaction has been operating the geologic history for 35 million years (Said 1981; Sestini 1995; Guiraud and Cherif 1999). Being part of the North African plate, it was covered by the Jurassic Neotethys (Kerdany and Cherif 1999). In the few past decades, it became a major focus of exploring for hydrocarbons (EGPC 1994; Nashaat 1998; Abdel Aal et al. 2000, 2001; Dolson et al. 2000, 2001; Keshta et al. 2012; Abdel-Fattah 2014; Younis et al. 2015; Abd El-Gawad et al. 2019a, b). It occupies about 250,000 km² of the eastern Mediterranean (Kirschbaum et al. 2010). Recently, multitrillion cubic feet of gas have been discovered in the Nile Delta Basin (Barsoum et al. 2002; Niazi and Dahi 2004). Hence, it is considered an emerging area for gas (Samuel et al. 2003; Hanafy et al. 2016; El-Mowafy et al. 2018). It already gained the ultimate interest after locating the giant gas field, namely Zohr Field (Esestime et al. 2016).

The study area, South Mansoura (Fig. 1), is located within the onshore Nile Delta basin, approximately 6 km south El-Mansoura city; between latitudes 30° 95’ 00” and 31° 00’ 00” N, and longitudes 31° 18’ 00” and 31° 33’ 00” E. In onshore Nile Delta, sequences of Messinian age host main petroleum reservoirs of the Nile Delta Basin; Qawasim and Abu Madi formations (Dolson et al. 2001; Niazi and Dahi 2004; Leila et al. 2016). Tectonically, the Messinian age (of the Upper Miocene; 7.24–5.33 Ma) represents a critical time period in the Mediterranean Sea evolution; in which isolation from waters of the Atlantic Ocean (Garcia-Castellanos et al. 2009), upon Messinian Salinity Crisis (MSC) seal level fall (Barber 1981), led to the accumulation of evaporites in deep-sea sites and widespread erosion on land. During MSC lowering of sea level and upon recovery, transgression at the close of Messinian, sedimentary infills (e.g., Eonile canyon, Fig. 1) incised into, and buried beneath, the thick Plio-Pleistocene sediments; forming the canyon/incised valley fluviol-deltaic Abu Madi Formation (Hsu et al. 1973; Ryan et al. 1973; Said 1990; Salem et al. 2005; Leila and Moscariello 2019). Besides the episodes of widespread land erosion, the MSC incisions were accompanied by cyclic fluctuations of climate, from arid conditions to humid, resulting in huge changes in physiography of North African margin together with the Nile Delta Basin (Griffin 1999, 2002; Leila et al. 2018). Influences of such physiographic changes on the composition of syn-MSC sediments, in terms of type and rate of sediment supply, are poorly controlled.

After discovering the gas of Abu Madi Field, in 1960s, from these incised valleys, the MSC facies became a major focus for hydrocarbon exploration (Abdel Aal et al. 1994; Dalla et al. 1997; Dolson et al. 2001). Given the MSC Abu Madi sediments were being deposited under complex conditions of climate and depositional environments, the depositional and diagenetic facies were also certainly being affected. This, in turn, has a significant impact on the reservoir quality of Abu Madi facies (Salem et al. 2005; Leila et al. 2016, 2018, 2019); as a range of continental (fluvial) to estuarine (deltaic) facies constitute Abu Madi Formation (Sharaf et al. 2004; Salem et al. 2005; Leila and Moscariello 2019; Leila et al. 2020). Hence, the depositional setting, architecture, and diagenetic evolution of MSC Abu Madi facies still convey a big uncertainty for exploration and development strategies. Moreover, the Eonile infill models have not been yet totally established, in which questions about the genesis of the current incised valley model (Zaitlin et al. 1994; Shanley and McCabe 1994) still rise; whether or not it may apply to Messinian incised-valley context, where magnitude of incision, timing, and subsequent infill are not matching with the ones caused by global eustatic sea level changes (Breda et al. 2007). Although some recent investigations addressed El-Mansoura Concession (e.g., Leila and Moscariello 2017; Abu El-Ata et al. 2019; Leila 2019;
Fig. 1 Location map of South Mansoura area within Nile Delta Basin, with main structural elements (adopted and modified after Leila et al. 2019)
Hussein et al. 2020; Leila and Mohamed 2020), they were mainly concerned with geochemical and sedimentological patterns, far from South Mansoura Area; moreover, pre- and post-MSC rather than syn-MSC. Hence, ultimate characterization of South Mansoura MSC reservoir, particularly its paleoenvironmental settings and their impact on reservoir quality, has not been satisfactorily achieved. Furthermore, Said (1990) and Abdel Aal et al. (1994) interpreted MSC Abu Madi sediments as lateral onshore equivalent to MSC offshore evaporite facies (Rosetta Formation). Nonetheless, no detailed sedimentary facies analysis was carried out to reveal the paleoenvironmental conditions controlled the sediment deposition. In addition to this, a further uncertainty over stratigraphic relationships between pre-MSC and MSC facies still arises. In this study, we combined multiple facies-based disciplines; seismic geomorphology, sequence stratigraphy, and sedimentology; to efficiently depict the depositional and diagenetic setting of Messinian Abu Madi incised valley fill in the onshore Nile Delta. This study uses a considerable range of dataset (seismic data, well logs, borehole images, and core data) to provide an unequalled opportunity to delineate the paleoenvironmental depositional conditions of the MSC event, depicting the reservoir heterogeneity and quality that are significant key parameters in justifying further hydrocarbon exploration and development plans of the area.

Geologic setting

The Nile Delta of Egypt occupies the quite deformed northern edge of the African plate; interposing three major tectonic regions (Red Sea/Gulf of Suez rift, Syrian Arcing system, and African-Anatolian plate) (Said 1990; Sarhan and Hemdan 1994; Harms and Wray 1990). Its structural and stratigraphic setting went a subject of interest by several authors (Zaghloul 1976; Ross and Uchupi 1977; Sestini 1989; Loncke et al. 2002; Saleh 2012, 2013; SELIM 2016; Hanafy et al. 2017). Particular emphasis, addressing geometry, architecture, and associated petroleum potential, was given to the onshore Nile Delta (e.g., El Nady 2007; El-Din et al. 2013; Krott et al. 2015; Abd El-Wahed and Anan 2016; Ghassal et al. 2016; El Khadragy et al. 2017; Teama et al. 2018; Abu El-Ata et al. 2019).

Serious structural behavior has shaped the Nile Delta’s sedimentary patterns; hence divided it into many sub-basins (Ross and Uchupi 1977; Kamel et al. 1998; Gargani et al. 2008). An east–west faulted flexure, namely hinge, zone subdivides the Nile Delta Basin into northern and southern sub-basins (Fig. 1) (Abu El-Ella 1990; Kamel et al. 1998; Mohamed et al. 2013; Makled et al. 2017). The northern sub-basin features some listric extensional faults (Zaghloul 1976; Schlumberger 1984); while the southern one exhibits a number of asymmetrical folds belonging to the Syrian Arc folding system (Zaghloul 1976). The hinge zone is a consequence of the Jurassic southern Neo-Tethys break-up. It represents not just a tectono-structure boundary but also a facies boundary; Upper Cretaceous carbonate shelf edge (Leila and Moscariello 2019); (Leila et al. 2016). It imparts recognized impacts on tectonic evolution of the Nile Delta Basin, causing thickening of Tertiary sediments basinward (Sestini 1995). Besides, northeast-southwest Rosetta and northwest-southeast Temsah faults subdivide the northern Nile Delta into western, central, and eastern sub-basins (Lashin and Mogren 2012; Hanafy et al. 2018). Deep-seated faults that run parallel to the Hinge Zone serve as migration pathways to hydrocarbons from source rocks; Upper Cretaceous–Lower Paleogene, and Jurassic sediments; to reservoir ones; Miocene sediments (Shaaban et al. 2006; Vandré et al. 2007; Leila and Moscariello 2017).

The stratigraphic column of the Nile Delta ranges in age from Precambrian to Recent (Schlumberger 1984; Abu El-Ella 1990; El Diasty and Moldowan 2013). The penetrated sedimentary succession is ended at the Jurassic (Fig. 2). Despite that, the petroleum potential is broadly limited to Neogene-Quaternary clastics (Leila et al. 2016; Nabawy and Shehata 2015). Neogene-Quaternary sediments of the Nile Delta have been grouped into three sedimentary cycles; Miocene, Pliocene, and Pleistocene (Said 1962; Ross and Uchupi 1977; Rizzini et al. 1978; Kamel et al. 1998). The shallow marine carbonates, Upper Jurassic, represent the oldest rock units penetrated in the area (Fig. 2) (Abdel Aal et al. 1994). The Lower Cretaceous is dominated by shallow marine facies (Guiraud and Bosworth 1999). During the Upper Cretaceous, the environment of deposition changed from open-marine to marine-alluvial sediments; before returning back to marine conditions upon the end of Cretaceous (Said 1990; Guiraud and Bosworth 1999). The Late Cretaceous-Eocene sequences are relatively thin because of Syrian Arc folding (Harms and Wray 1990). The Oligocene deposits consist of relatively thick coarse-grained siliciclastic fluvial facies (Harms and Wray 1990; Said 1990). Two notable unconformities are recorded in Miocene-Pliocene sequences (Rizzini et al. 1978; Barber 1981; Harms and Wray 1990; Said 1990). The first one separates the Middle Miocene from strata of the Upper Miocene, while the second one corresponds to Messinian Salinity Crisis desiccation event; upon forming Abu Madi incisions (Leila and Moscariello 2019). During the Lower Pliocene, marine transgression occurred, covering the Nile Delta Basin with marine Kafr El-Sheikh sediments (Ross and Uchupi 1977; Said 1990; Gargani and Rigollet 2007).
Data and methodology

Dataset utilized in this work include post-stack seismic data (Fig. 1), time–depth relationships, well logs (e.g., gamma-ray, spontaneous potential, resistivity, sonic, neutron, density, and FMI/borehole image) with age-identified interpreted stratigraphic tops, and thin sections adopted from core samples. This work implemented a multi-disciplinary approach; integrating various sedimentary facies-depicting disciplines (e.g., attribute-based seismic geomorphology, sequence stratigraphy, and sedimentology); using software program tools such as Petrel, and Techlog.
The post-stack seismic data of this study are dominated by a frequency range of 0–60 Hz (Fig. 3), with an approximately 13, 20, and 30 Hz predominant frequency values at the zone of interest. Seismic to well tie, corresponding stratigraphic horizons to seismic reflectors, was a first required step for interpreting seismic profiles (Abdelwahhab and Raef 2020). Linking tops of stratigraphic horizons to the corresponding seismic reflectors was achieved, in this study, using the established one-dimensional synthetic seismograms; an example is shown in Fig. 4. Synthetic seismic traces were a result of the convolution of reflectivity series (produced from sonic and density logs) and extracted wavelets (White and Simm 2003). A preceding step of well-log QC (quality control) analysis, that fixes log spikes, was done for a better generation of synthetic seismic traces used in seismic well tie. Mis-ties are caused due to signal–noise ratio or when real seismic traces do not have the same wavelets of synthetic ones (Ziolkowski et al. 1998; HENRY 2000). The produced synthetic traces were then matched with real seismic data. Upon reaching a satisfying seismic to well tie, with about 0.7 correlation coefficient, stratigraphic tops were picked throughout the entire seismic data.

Methods of analyzing depositional and diagenetic facies used in this work include: (1) seismic attribute, particularly frequency spectral decomposition, analysis so as to depict the planer distribution/geomorphology of sedimentary facies; (2) sequence stratigraphic framework and depositional facies analysis based on well log data (e.g., gamma-ray log response, and borehole image interpretation); (3) reservoir properties (e.g., porosity, and permeability) determination based on conventional well log analysis, applying several equations and cross-plots; (4) thin section petrographic analysis, examining nineteen samples with conventional petrographic microscope, to determine the mineralogical composition and define the post-depositional diagenetic processes and their impact on reservoir quality. Mineralogical modal composition was obtained through whole rock XRD analysis and point counting technique (Gazzi 1966; Dickinson 1970). Sandstone classification was introduced following Folk (1980); (5) paleogeomorphologic configuration and filling model reconstruction to establish the paleo-depositional system controlled sediment/reservoir heterogeneity and quality, from source to sink.

Results and discusions

Seismic geomorphology

Seismic sedimentology is basically a seismic-based analysis of sedimentary rocks (rock and fluid property) and their paleo-depositional environments. It provides
litho-geomorphologic mapping of sedimentary facies, particularly when combined/calibrated with other related approaches (e.g., well-log analysis) (Zeng et al. 1998a; Zeng and Hentz 2004). Seismic geomorphology is a key component of seismic sedimentology. It reveals the litho-geomorphologic distribution of sedimentary facies. Stacked and time-migrated seismic data, and amplitude attributes, are of use as a starting point. Several advanced approaches exist (e.g., seismic attribute analysis (Chopra and Marfurt 2007), AVO analysis (Chopra and Castagna 2014), seismic inversion (Cooke and Schneider 1983; Russell and Hampson 1991), and multicomponent seismic (Hardage et al. 2011)) (Zeng et al. 2020). Such approaches are beyond our paper’s scope; except seismic attribute analysis, particularly spectral decomposition. Several seismic attribute related approaches were performed in this study; e.g., frequency spectral decomposition and fusion/blending, stratal slicing (horizon stacking), and relative acoustic impedance; so as to depict the planer litho-geomorphology of facies.

Spectral decomposition and fusion involve the process of partitioning the seismic traces, in the time domain, into various frequency bands and subsequently recombining the frequency panels so as to improve the visual effect of the sedimentary geometries (Zeng 2017); and delineate stratigraphic settings (e.g., channel sands) (Partyka et al. 1999). In fact, new seismic attributes are generated and can then be displayed in RGB (red–green–blue) color blending form. Choices of frequency panels are determined considering the desired thickness interval to visualize; with low frequency adjusted to thick sandstones and high frequency adjusted to thin beds. Frequency fusion/blending considerably reduces the thin-bed tuning effect through applying multiband tuning (tuning in expanded thickness), generating realistic view of lithostratigraphic geometries (Zeng et al. 2020). In this work, three frequency panels; at 13, 20, and 30 Hz (Fig. 5a);
were chosen in the process of amplitude spectrum frequency decomposition (Fig. 5b); applying short-time discrete Fourier transform (STDFT) spectral decomposition following Partyka et al. (1999). 13 Hz frequency is adjusted to thick beds (Fig. 6a), 20 Hz to moderate ones (Fig. 6b), and 30 Hz to thin ones (Fig. 6c).

Typically, depositional surfaces picked on seismic profiles follow geologic time. For geologic time-related seismic events, auto-tracking of seismic reflections may satisfy application purposes. However, for other certain events, stratal slicing (Zeng et al. 1998a, b) would be the proper choice. A stratal slice is a phantom slice generated following sediment-accumulation model and does not inevitably follow the same seismic phase. The stratal slicing removes structural influences on the horizontal seismic slices so as to analyze and interpret stratigraphic features (Zeng et al.
Fig. 6 Frequency panels, at 13, 20, and 30 Hz adjusted to thick, moderate, and thin beds
In this work, 300 stratal slices (horizon stacks) were generated between seismic reflections, at selected zone of interest over seismic data, preceded by geo-model grid construction. RGB blended frequency slices (Fig. 7a) are the principal displays of the seismic litho-geomorphologic facies depicted in this study.

Relative acoustic impedance attribute is calculated by integration of original seismic trace followed by passing a low cut filter (Latimer et al. 2000). It provides an indication of impedance change, boundaries of sequences, porosity content, unconformities, and discontinuities in reservoirs (Subrahmanyam and Rao 2008). In this study, relative acoustic impedance attribute was extracted to maximize capturing of the potential effect of channel incisions and lithofacies variations within the Messinian Salinity Crisis sequences.

Figure 8 is an interpreted seismic section for pre-, syn-, and post-Messinian sequences. It obviously shows the sequence of syn-MSC Abu Madi infills incision into pre-MSC Qawasim Formation. The bottom erosion surface of Abu Madi sequence dips basinward and displays an asymmetrical depression, about 7 km wide, (Eonile canyon). Abu Madi infills are traced between 2150 and 2430 ms TWT. They represent a channel-fill morphology where the MSC Abu Madi facies demonstrate bidirectional onlap terminations across channel walls. On well log data the top and bottom surfaces of MSC Abu Madi infills are marked by a sharp break in GR values; reflecting their erosional characteristics and noticeable change in depositional facies, due to different tectono-sediment supply abiding environments, between pre- and post-MSC facies. Abu Madi infills pinch-out towards margins of the Eonile canyon, where they reach about 35 ms TWT thickness; and thicken towards the depression center, where they reach 200 ms TWT thickness approximately. The RGB blended frequency slice (Fig. 7a) depicts the litho-morphologic facies distribution of Abu Madi incised valley fill.

Figure 7 Crossline 1680 seismic section, showing Abu Madi sediment infills onlapping on channel walls. IL and XL stand for seismic inlines and crosslines, respectively.

**Sequence stratigraphy and depositional facies analysis**

Lithostratigraphic correlation, displaying variation of thickness, may provide clues to areas of subsidence and others of uplifting. However, controls on sediments' temporal and spatial distribution can be adequately defined through sequence stratigraphic models (Braaksma et al. 2006). Sequence stratigraphic analyses divide stratigraphic records into depositional sequences with boundaries marked by subaerial erosion (unconformity) surfaces or their correlative conformities (Mitchum et al. 1977). A sequence boundary marks abrupt basinward shift in the deposition, and is therefore interpreted from the sharp shallowing of depositional facies (lowering of sea level) across erosion surfaces (H W Posamentier and Vail 1988). Fluvial to estuarine sediments, in the study area, are composed of...
Fig. 8 Stratal slices of a RGB frequency fusion, showing channel geomorphology, and b RAI map, showing higher values corresponding to channel geometry
sandstone and shale interbed cycles, seen on GR shaliness log (Fig. 9). Sequence stratigraphic analyses were guided by models and principles of fluvial sequence stratigraphy following Wright and Marriott (1993), Legarreta and Uliana (1998), and Catuneanu et al. (2006). The well log-based sequence and depositional facies correlation, as shown in Fig. 9, emphasized changes in relative sea level; marking third-order depositional sequences; and depositional systems and facies associations in the study area. We recognized one third-order depositional sequence, formed in a continental shelf setting, predominates Abu Madi Formation. It is built upon lateral and vertical shift between fluvial, and estuarine facies. Abu Madi sequence stratigraphic subdivision demonstrates the stacking patterns and stratigraphic framework of different lithologies/lithofacies preserved in the area of study, and helps define historical stages of change in base level which marks the evolution of Abu Madi Formation during the Messinian Salinity Crisis.

Conventional cores provide the most reliable evidence of depositional environment and facies. Lithology, grain size, color, and sedimentary structures point to fine-scale changes in bedforms, facies, and environments of deposition (Zeng et al. 2020). In this study, due to unavailability of conventional cores, gamma-ray (GR) log patterns were used, instead, to provide means of paleo-depositional environment and facies association interpretation. Five GR motifs (Fig. 9) were used to reveal the log facies; BL (blocky) for thick distributary channel fills, FU (fining upward) for moderately thick fluvial channel fills, FL (finger-like) for thin estuarine tidal channel sandstones, CU (coarsening upward) for moderately thick estuarine sand bars, SE (serrated) for overbank/floodplain (higher GR) and estuarine (lower GR) fines/mud; following Selley (1978), Cant (1992), Emery and Myers (1996), Chow et al. (2005), and Nazeer et al. (2016). Moreover, borehole image (FMI) logs (Figs. 10 and 11), were used to maximize the interpretation of lithofacies associations.

In the study area, Abu Madi Formation (Fig. 9) discloses fluvial to estuarine depositional systems, with five facies associations. From bottom upwards, overbank/flood plain muds and braided to meandering fluvial channel complex, followed by tidally influenced channels, then tidal channels, bars, and estuarine mud deposits at pure estuarine regime.

The overbank/flood plain mud facies association is composed of massive mudstone lithofacies with minor lamina-

consists of massive sandstone lithofacies subordinated with cross-bedded ones (Fig. 10), indicating high-energy sedimentation and erosion likely to fluvial channels (Miall 1977; Tucker 2001), followed by parallel and cross-laminated sandstones and mudstones (of estuarine setting). It lacks any bioturbation confirming continental freshwater setting. It lacks any mudstones indicating elevated hydrodynamic flow setting. It shows fining upward pattern of GR log, with coarse, medium, to fine grains upwards (graded bedding) (Figs. 11a, b, 12a, b, c, and d; Table 1). It is conglomeratic in parts (Fig. 11c), suggesting rapid sedimentation of bedload (Reineck and Singh 1980). Lower parts of the fluvial facies are characterized by uniform dipping suggesting unidirectional paleocurrent flow (of fluvial dominated systems). Multiple scour surfaces covered with conglomerates and existence of stacked units with deficiency of mudstones indicate repeated channel incisions and infill episodes (Miall 1996; Bridge 2011). It acts as the main hydrocarbon reservoir facies in the study area. It is characterized by an average effective porosity of 25% (Fig. 10). The fluvial sedimentation was confirmed by the moderate to high sinuosity fluvial channel geomorphology on the RGB spectral decomposition and extracted relative acoustic impedance mapping (Fig. 7a, b, respectively).

The estuarine tidal channel facies association includes cross-laminated sandstone and massive sandstone lithofacies (Fig. 10). It shows finger-like GR motif, reflecting waning charge regime in tidal dominated setting, with lenticular body appearance. The massive lithofacies may be due to the intense bioturbation dominated in the depositional system. The dominance of bioturbation supports the upward shift from continental to marginal marine setting.

The estuarine tidal bar facies association includes parallel lamination and cross-laminated sandstone lithofacies subordinated with massive sandstones (Fig. 10). It exhibits a coarsening upward pattern of the GR log, indicating the bar system. The existence of parallel and cross-lamination, with low dipping stratification, points to the fluctuation of deposition from upper to lower charge regime of tidal condition.

The estuarine mud facies association consists of laminated and massive mudstone lithofacies (Fig. 10), with local deformation. The existence of laminated and massive lithofacies reflects the suspension fall-out in calm flows. The local deformation may be a result of extensive bioturbation activity or micro-faults.

Petrography and post-depositional diagenesis

The studied samples, nineteen thin sections, of MSC Abu Madi Formation were subjected to detailed petrographic and post-depositional diagenetic analysis. Grain sizes were determined through measuring the longest axes of several grains per sample, calculating the mean value. Sorting and
Fig. 9 SW-NE stratigraphic correlation panel, revealing the depositional sequences and facies associations
Roundness of grains were defined using standards of Pettijohn et al. (1972); poorly sorted, moderately sorted, well-sorted, and very well-sorted. Roundness is displayed by the degree in which sharp edges of grains have been smoothed. Defining sorting and roundness provides means of rock textural maturity and transport history that could be key parameters for predicting reservoir quality. Table 1 shows that most of the samples are generally poorly to moderately sorted, with subangular to subrounded grain texture. Ternary plots (Fig. 12e), using QFL limits of Blatt and Tracy (1996), were used to define the framework composition, microscale heterogeneity, of MSC Abu Madi sediments. The compositional, textural, and diagenetic features of Abu Madi sediments are summarized in Table 2.

Depositional model and reservoir quality

Sediment dispersal in source-sink systems correspond to “sediment routing system” that is often described in regard to feedback mechanisms and dynamic processes between various forcing conditions, autogenic and allogenic, that control sediment distribution in erosional-depositional systems (Allen and Hovius 1998; Allen 2005, 2008a, b; Densmore et al. 2007; Sømme et al. 2009, 2013; Sømme and Jackson, 2013; Prizomwala et al. 2014). The evolution of depositional systems is indicated by morphological modifications within adjacent segments (Sømme et al. 2009). What a study area experienced; including depositional filling, structural deformation, differential compaction, and erosion; could be combined to form a composite response reflecting paleogeomorphology. Paleogeomorphology is an adequate method of understanding and predicting sedimentary facies dispersal patterns within depositional systems. During sedimentation, the paleogeomorphology and sediment charge, as well, control the spatial distribution of sediments within different depositional systems operating the basin (Martin 1966; Richards et al. 1998; Zeng and Hentz 2004; Posamentier 2004; Posamentier et al. 2007; Seidel et al. 2007; Masrouhi et al. 2008; Masini et al. 2011; Dumont et al. 2012; Zhu et al. 2014). Therefore, paleogeomorphologic restoration is a crucial approach in reconstructing depositional systems/models and predicting reservoir-quality rock distribution (Liu et al. 2016).

Paleogeomorphological architecture of the study area is dominated by the incised valley channel geometry. Positive topographic units controlled the dispersal direction of incised valleys. The channel incisions gradually converged from source to sink. Appropriate geological/depositional models of channel reservoir distribution may guide the appropriate exploration and development strategies in the area. Based on the different approaches performed in this study, conceptual depositional models (Fig. 13) of MSC Abu Madi sediments have been established so as to show sediment dispersal patterns and their depositional evolution under different depositional systems. As revealed from seismic geomorphology and sedimentary facies analyses, syn-MSC Abu Madi canyon infills represent prograding fluvial to estuarine depositional systems. From bottom upwards, the sediments display a sequence changing from fluvial channel incisions, passing through estuarine tidal bars and channels, to estuarine mud. The fluvial facies association (Fig. 13a) enriches coarse-grained sandstones, deposited in subaerial distributary channels. Therefore, it has considerably high reservoir quality, in terms of porosity and permeability, relative to the estuarine facies associations, in which reservoir quality is decreased with subsequent increase in marine influence. This is quite consistent with the extracted relative acoustic impedance stratigraphic slice.
map and well log-derived porosity. A transgressive surface/event marks the boundary between the fluvial unit and the upper estuarine unit. The fluvial channel infills is followed by tidal sand bar facies, representing the onset of transgressive deposition (Fig. 13b).

The petrographic analysis maximized capturing the impact of depositional and diagenetic facies on reservoir quality. MSC Abu Madi Formation, deposited within fluvio-estuarine setting, reveals quite high degree of heterogeneity at various scales, from fieldwide to microscopic scale. Depositional
facies heterogeneity is considered one of the chief controlling factors on reservoir porosity and permeability (Yassin et al. 2018). Diagenetic processes, such as compaction, cementation, and dissolution, are another factor affecting reservoir quality (Bloch 1991). Generally, the fieldwide and macroscopic (inter-well) scale heterogeneity is mainly controlled by depositional
Table 1 Petrographic analysis of Abu Madi Formation

| Sample No | Depth (feet) | Grain size (mm) | Sorting                     | Roundness          | Qtz  | Fsp  | Lith | Mica | Hem | Py | Cc | Glauconite | Detrital Clay | Illite/Smec- | Kaolinite | Chlorite |
|-----------|--------------|----------------|----------------------------|--------------------|------|------|------|------|-----|----|----|-------------|---------------|--------------|-----------|----------|
| 1         | 8630         | 1              | Poorly sorted              | Subangular to subrounded | 88.3 | 1.5  | 0    | 0    | 0   | 0  | 2  | 2           | 6.2           | 0            | 0         | TR       |
| 2         | 8612         | 0.52           | Moderately sorted          | Subangular to subrounded | 88.8 | 1.4  | 0    | TR   | 0   | TR | 7.3| 1           | 1.5           | 0            | 0         | TR       |
| 3         | 8602         | 0.27           | Poorly sorted              | Subangular to subrounded | 86.2 | 1.9  | 0    | 0    | 0   | 4.9| 2.5| 4.5         | 0             | 0            | 0         | TR       |
| 4         | 8584         | 0.125          | Moderately sorted          | Subangular to subrounded | 80.5 | 3.2  | 1.1  | 1.1  | 0   | 5.4| 5.7| 3           | 0             | 0            | 0         | TR       |
| 5         | 8568         | 0.195          | Moderately sorted          | Subangular to subrounded | 68   | 7    | 0.5  | 2.5  | 1   | 0.5| 3.5| 10          | 7             | 0            | 0         | TR       |
| 6         | 8532         | 0.25           | Poorly to moderately sorted| Subangular to subrounded | 84.3 | 3.7  | 1.1  | 1.1  | 0   | 2.8| 4.5| 2.5         | 0             | 0            | 0         | TR       |
| 7         | 8522         | 0.23           | Moderately sorted          | Subangular to subrounded | 93   | 2.8  | 0    | 0    | TR  | 0  | 2.2| 1.25        | 0.75          | 0            | 0         | TR       |
| 8         | 8516         | 0.175          | Poorly to moderately sorted| Subangular to subrounded | 64.5 | 7    | 1.5  | 0.5  | 1   | 0  | 4  | 8           | 13.5          | 0            | 0         | TR       |
| 9         | 8506         | 0.19           | Moderately sorted          | Subangular to subrounded | 70   | 6    | 1.5  | 2.5  | TR  | 0  | 3.5| 5.5         | 9.5           | 0            | TR        | 1.5      |
| 10        | 8474         | 0.26           | Poorly to moderately sorted| Subangular to subrounded | 87.3 | 1.1  | 1    | 1    | 0   | 2.3| 2.3| 3           | 0             | 0            | 0         | 2        |
| 11        | 8468         | 0.32           | Poorly sorted              | Subangular to subrounded | 69   | 4.5  | 0.5  | 2    | 0.5 | 0  | 6.5| 4.5         | 12            | 0            | 0         | TR       |
| 12        | 8451         | 0.325          | Moderately sorted          | Subangular to subrounded | 66   | 4    | 3.5  | 3    | TR  | 0  | 4.5| 8           | 11            | 0            | 0         | TR       |
| 13        | 8214         | 2              | Very poorly sorted         | Subrounded to subangular | 65.5 | 5.5  | 6    | 1    | 0.5| 1  | 5.5| 3.5         | 11.5          | 0            | 0         | TR       |
| 14        | 8162         | 2.25           | Poorly sorted              | Subrounded to subangular | 80.1 | 2.8  | 0.7  | 0    | 0.5| 0  | 10.9        | 5             | 0            | 0         | TR       |
| 15        | 8116         | 1              | Poorly sorted              | Subangular to subangular | 87   | 5.5  | 0.5  | 0.5  | 0.5| 1  | 5    | 3.5         | 0             | TR           | 0         | 0        |
| 16        | 8110         | 1.05           | Poorly sorted              | Subrounded to subangular | 90.8 | 2    | 0    | TR   | TR  | 0  | 2.3| 1.2         | 3.7           | 0            | TR        | 0        |
| 17        | 8066         | 2.05           | Poorly sorted              | Subrounded to subangular | 85   | 4.5  | 1    | 0.5  | 1   | 0  | 2  | 0.1         | 0             | 4.5          | 1.4       | 0        |
| 18        | 8059         | 0.65           | Poorly to moderately sorted| Subrounded to subangular | 91.2 | 1.7  | 0.1  | 0    | 0   | 2.3| 0  | 2.5         | 0             | 2.2          | 0         | 0        |
| 19        | 8046         | 2              | Poorly to moderately sorted| Subrounded to subangular | 64.5 | 1.4  | 1.9  | TR   | 1   | 0  | 25.3| 2          | 3.9           | 0            | 0         | 0        |

Qtz: Quartz, Fsp: Feldspar, Lith: Lithic, Hem: Hematite, Py: Pyrite, Cc: Calcite cement
### Table 2 Abu Madi sediments texture and diagenesis

| Facies associations            | Sediment textures                                                                 | Detrital grains                                                                 | Diagenetic processes                                                                 |
|-------------------------------|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Fluvial channel complex       | Medium to coarse-grained (Fig. 11a, b), poorly to moderately sorted, subangular to subrounded, arkosic arenite to subarkose arenite sandstone microfacies (Fig. 12). Dispersed pore-filling clay matrix is commonly observed | **Quartz** predominates all sections of Abu Madi sandstones (up to 93%), and mostly occur as monocrystalline grains (Fig. 12a). **Feldspars**: constitute 3.7%, approximately, of the whole framework and mostly of k-feldspar type (Fig. 12b). Few lithic fragments: mostly bioclasts, carbonaceous fragments with minor cherts, claystones, and granitic fragments; are existed and may reach about 1.1% (Fig. 12c). **Detrital clays**: recorded mostly in all samples, ranging from 2% to 8.7%. They are detrital and digenetic in origin | Textural features of the studied samples provide evidence for the occurrence of mechanical and chemical compaction, depending on the depth of burial. Grain contact types exhibit point to concavo-convex types, reflecting a moderate degree of compaction. Minor occurrences of stylolites (Fig. 12a) reflect pressure solution, proving chemical compaction. Most diagenetic minerals identified are quartz; in which minor occurrences of quartz overgrowths are noticed (Fig. 12b) due to pressure solution; calcite, and iron oxide cements. Authigenic clay minerals are also identified. Dissolution of grains may develop a secondary porosity (Schmidt and Mcdonald 1979; Ehrenberg 1990; Shalaby et al. 2014). Secondary porosity locally occurs in Abu Madi sandstones as a result of dissolution, partial to complete, of detrital grains (feldspars and glauconite pellets). Evidences for the dissolution include intra-particle porosity resulted from dissolution of k-feldspars (Fig. 12a). Some of glauconite pellets exhibit reddish-brown color, because of the oxidation to iron oxides (Fig. 12a) |
| Estuarine/tidal channels and bars | Fine-grained, moderately sorted facies. Glauconitic fine to very fine grained, green to brownish, pellets are commonly observed |                                                                                           |                                                                                       |

*Note*: This table lists the sediment textures, detrital grains, and diagenetic processes associated with different facies associations in the Abu Madi sediments.
facies, architecture, and geometry (Miall 2010). In contrast, the microscopic scale heterogeneity is chiefly controlled by grain texture and diagenetic processes (Aigner et al. 1990). In the study area the lowstand systems tract fluvial facies are interpreted to have higher quality reservoirs due to efficient textures and non-marine influence. Moreover, diagenetic processes, in the study area, have affected the reservoir quality; in terms of porosity and permeability, acting as the best reservoir facies of the area.

Conclusions

(1) The RGB frequency fusion stratal slices depict the litho-morphological facies distribution of MSC Abu Madi incisions, showing a SW-NE trending reservoir fairway, with a Y-shape channel geometry.

(2) MSC Abu Madi Formation constitutes third-order sequence of fluvial to estuarine units infilling the Eonile-canyon, with five sedimentary facies associations (overbank muds, fluvial channel complex, tidal bars, tidal channels, and estuarine muds).

(3) The fluvial facies association is enriched with coarse-grained sandstones, deposited in subaerial setting, with considerably higher reservoir quality, in terms of porosity and permeability, acting as the best reservoir facies of the area.

(4) Depositional facies heterogeneity and diagenetic processes are the main factors controlling reservoir quality in the area. Although it is noticed that dissolution of feldspars has developed a secondary porosity of Abu Madi sediments, continental fluvial facies are the chief fluid flow conduits, where marine influence is limited.

(5) Consequently, adequately depicting the heterogeneity/architecture, along with reservoir quality, of syn-MSC Abu Madi sediments, pointing to best sedimentary facies (fluvial channels), would give a robust insight into significant key parameters for future exploration and development strategies in the area.

(6) Furthermore, it is recommended to perform a further petroleum system-based approach, and sealing analysis, so as to define the entrapment and charge timing coincidence, along with identifying the migration pathways and best sites for hydrocarbon accumulation.

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Declarations

Conflict of Interest

There are no conflicts of interest.

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