Integration of Sequence Stratigraphic Analysis and 3D Geostatistical Modeling of Pliocene–Pleistocene Delta, F3 Block, Netherlands

Haris Ahmed KHAN[1], Ali Asghar SHAHID[2], Muhammad Jahangir KHAN[3, *], Taher ZOUAGHI[4, 5], Maria Dolores ALVAREZ[6] and Syed Danial Mehdi NAQVI[3]

[1] *Hydrocarbon Development Institute of Pakistan, Plot# 18, Street # 6, H-9/1, Islamabad, Pakistan*
[2] *Department of Geoscience, University of Oslo, Sem Sælands vei 1, 0371 Oslo, Norway*
[3] *Department of Earth and Environmental Sciences, Bahria University, Karachi Campus, 13 National Stadium Road, Karachi-75260, Pakistan*
[4] *Department of Geoexploration, Faculty of Earth Sciences, King Abdulaziz University, 21589 Jeddah, Saudi Arabia*
[5] *Laboratoire de Géoressources, CERTE, Pôle Technologique de Borj Cédria, 8020 Soliman, Tunisia.*
[6] *Argentina's Geological and Mining Survey, Aveneida General Paz 5445, Edificio 25, INTI, General San Martin, Argentina*

Abstract: This research is focused on the analysis of the sequence stratigraphic units of F3 Block, within a wave-dominated delta of Plio–Pleistocene age. Three wells of F3 block and a 3D seismic data, are utilized in this research. The conventional techniques of 3D seismic interpretation were utilized to mark the 11 surfaces on the seismic section. Integration of seismic sequence stratigraphic interpretation, using well logs, and subsequent 3D geostatistical modeling, using seismic data, aided to evaluate the shallow hydrocarbon traps. The resulting models were obtained using System Tract and Facies models, which were generated by using sequential stimulation method and their variograms made by spherical method, moreover, these models are validated via histograms. The CDF curve generated from upscaling of well logs using geometric method, shows a good relation with less percentage of errors (1 to 2 for Facies and 3 to 4 for System Tract models) between upscaled and raw data that complements the resulted models. These approaches help us to delineate the best possible reservoir, lateral extent of system tracts (LST and/or HST) in the respective surface, and distribution of sand and shale in the delta. The clinoform break points alteration observed on seismic sections, also validates the sequence stratigraphic interpretation. The GR log-based Facies model and sequence stratigraphy-based System Tract model of SU-04-2 showed the reservoir characteristics, presence of sand bodies and majorly LST, respectively, mainly adjacent to the main fault of the studied area. Moreover, on the seismic section, SU-04-2 exhibits the presence of gas pockets at the same location that also complements the generated Facies and System Tract models. The generated models can be utilized for any similar kind of study and for the further research in the F3 block reservoir characterization.

Key words: sequence stratigraphy, facies modeling, system tract modeling, F3 block, North Sea

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1 Introduction

The Netherlands is situated on the Western Europe, between 52°23'N latitudes and 4°55'E longitudes. It spreads over 33,893 km^2 of land and 7,650 km^2 of water, with a transition zone of 41,543 km^2. The Netherlands is bounded, northward, by the North Sea basin in which lies our study region. The portion of the North Sea that falls into the territory of the Netherlands is also known as the Dutch Offshore, whereas the North Sea F3 block falls in the southern part of North Sea Dutch Central Graben. The North Sea basin is situated at North Atlantic inland edge that covers zone around 625,000 km^2. It is bounded southward by the Netherlands, eastward by Norway, Sweden and Denmark, and westward by England (Fig. 1a).

North Sea Dutch Central Graben remains analysts' focal point of interest in confirming the sedimentary sequences connection. Due to the difference of opinion between oil organizations and academic experts, the stratigraphy of this area should be reanalyzed (Heybroek, 1975; Herngreen and Wong, 1989). Following research is to bring about the consequences of sequence stratigraphic conception on F3 Block which is a wave-dominated delta of Plio–Pleistocene. Sequence stratigraphic analysis is a solid parameter, for associating regional and local scales, to understand the stratigraphic development by coordinating numerous arrangements of information for creating chronostratigraphic system (Catuneanu et al., 2009; Lacaze et al., 2011). The depositional geometry and process (erosion, truncation, basin filling, reservoir spatial circulation, source, seal and traps), environmental settings (system tracts) and lithology prediction is dealt by

* Corresponding author. E-mail: jahangir.khan99@gmail.com

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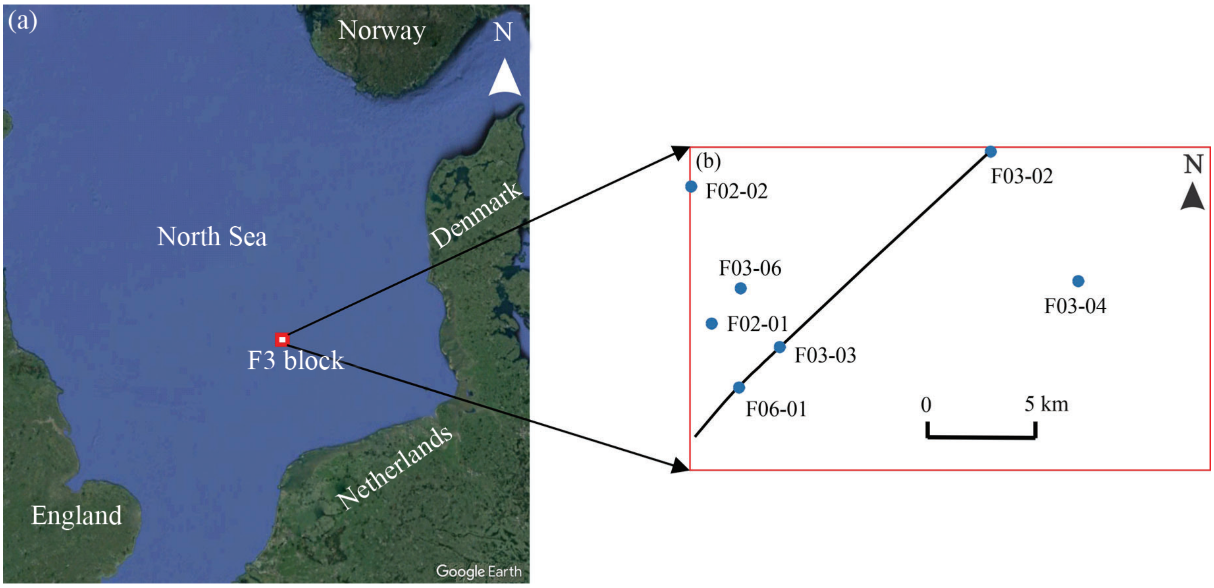

Fig. 1. (a) The above map is the location map of Dutch offshore North Sea, where small red square marks the boundary of F3 Block (modified after Google Earth); (b) base map of F3 Block, Blue dots showing available wells location and black line shows cross-section of wells for this study.

sequence stratigraphy (Vail, 1987).

The sequence stratigraphic analysis plays a vital role in the reservoirs modeling and enhances the understanding in predicting the depositional setting and properties of the complex reservoirs (Bijlsma 1981; Rohrman et al., 1996; Overeem et al., 2001). Moreover, enhancing hydrocarbon recovery requires point by point and precise details of reservoir properties (Ma, 2011). Complex reservoirs modeling requires a blend of reasonable stratigraphic models and geostatistical recreations (Edigbue et al., 2015). The basic connection between seismic interpretation and reservoir simulation is reservoir modelling. The incorporated ways without reservoir modelling deal with exploration and production arrangement and precise reservoir assessment, are practically unthinkable (Ma, 2011). The reservoir model is most widely recognized and utilized, to give a 3D numeric contribution to reservoir simulation. The reservoir modeling and simulation give a foundation to amplifying economic value for field advancement and operational choices; it can likewise be utilized for value assurance, reserve confirmation, or support for subsidizing projects (Ma, 2011). Reservoir modeling and simulation give forceful tools used for reservoir depiction and hydrocarbon generation determination (Dubrule, 1989), and can help reservoir management and field improvement (Khan et al., 2019). The approaches for the complex reservoir modeling comprise of foreseeing the general reservoir geometry and their expansion with a stochastic conceptual model (Edigbue et al., 2015). At the reservoir scale these methodologies, give a stratigraphic framework that may decrease the risk of miss-ties between various genetic units (Edigbue et al., 2015). Stochastic methodologies are presently more as often as possible connected to reproduce the spread of small-scale sedimentary bodies and inside reservoir heterogeneity (Alabert and Corre 1991; McDonald et al., 1992; Massonnat et al., 1993; Shanor et al., 1993). The geostatistical approaches, additionally, give equiprobable acknowledge of the heterogeneity dispersion.

This study introduces a consolidation of both stratigraphic and geostatistical approaches. The sequence stratigraphic examination was performed, and this brought about the characterization of reservoir layering. Inside this system, geostatistical simulations give distinctive acknowledge of the small-scale geological heterogeneities (Edigbue et al., 2015). The sequence stratigraphy identifies system tracts by using surfaces stacking patterns and stratal geometries. The depositional sequence consists of three main system tracts which are Lowstand system tract (LST), Transgressive system tract (TST) and Highstand system tract (HST). Boundaries of system tracts correspond to depositional boundaries of onlap, downlap, toplap, etc. Lowstand system tract (LST) is the term used for the deposits of low sea level time period, whereas, Transgressive system tract (TST) are the deposits deposited on the shelf within the time of relative sea level rising quicker than the rate of sediments supply, and the Highstand system tract (HST) are the beds deposited during the time of high sea level. In this study clinoform break point analysis aid to understand the patterns of sequences on seismic section (Catuneanu et al., 2009).

2 Geological Setting

In the North Atlantic region including North Sea, deformations are related to Variscan orogeny originated in Late Carboniferous and persisted up to Early Triassic (Haszeldine and Russell, 1987; Lyngsie and Thybo, 2007; Anell et al., 2010). This orogeny has controlled the

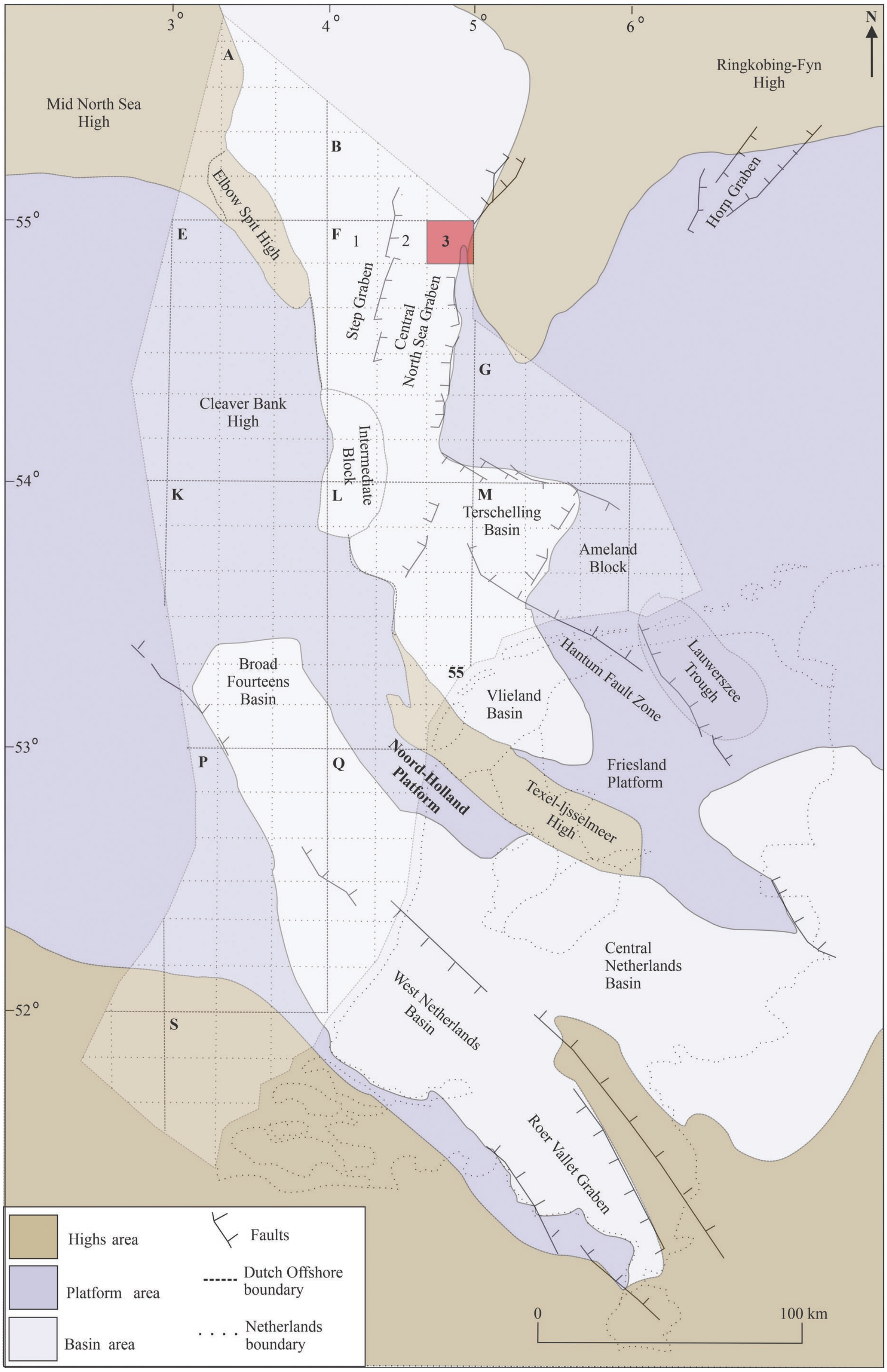

Fig. 2. The structural map of North Sea Dutch Offshore, where F3 block (represented by red box). The highs are represented by brown color, platform by purple color and basin by white color (modified after Schroot and Schuttenhelm, 2003; and Nelskamp et al., 2012).

evolution of the Central European Basin system during Paleozoic time. Variscan orogeny shows Ringkobing-Fyn high (Fig. 2) that causes the breakage of the basin into two separate parts, which are titled as Northern and Southern Permian basins (Khan et al., 2019).

Throughout the Cenozoic time and the periods of Alpine orogeny, anti-clockwise movement of African plate occurred which conveyed transpressional stress on North Sea basins (Rasser et al., 2008) that came about into periodic inversion (turned around the basin bounding faults) of the basins (Ziegler, 1987, 1988, 1990; Van Wijhe, 1987; Dronkers and Mrozek, 1991; Ziegler et al., 1995; Marotta et al., 2002; Knox et al., 2010).

Grabens/sub-basins in the North Sea area are the resultants of periodic phases of Variscan orogeny and Mesozoic failed rift system (Van Wijhe, 1987). Ringkobing-Fyn high of Permian age reactivated during Miocene to Pliocene times and sub-divided the North Sea Basin into two embayment. The northern embayment (covers Norwegian-Danish Basin and northern part of Central Graben) and southern embayment (covers North German Basin and southern part of Central Graben Basin) (Sørensen and Michelsen, 1995). These embayments were linked and depocenter were found within them, in the west of deep seaway of Dutch Central Graben Basin (Sørensen et al., 1997). Through late Miocene and early Pliocene rate of uplifting increases (Ghazi, 1992; Jordt et al., 1995), due to which the drainage system shifted from northeast and east to south (Spjeldnaes, 1975), throughout this time basin shallowing occurred due to low rate of subsidence than the (high) rate of sedimentation.

Neogene and Pleistocene sediments within the southern North Sea basin deposited by the westward flowing North German River (Zagwijn, 1974). The enormous inflow of coarse sediments into the North Sea, has been caused by the regression that triggered as the result of the Pliocene uplift of Scandinavia (Gregersen et al., 1997; Eidvin and Rundberg, 2001; Rasmussen and Dybkjaer, 2005). The deltaic system of Pleistocene age, which falls under the Upper North Sea Group, progrades mainly towards west-southwest (Tigrek, 1998).

The sedimentation rate severely expanded during the Quaternary time and about half of the aggregate thickness was deposited in 2% of Cenozoic deposition time. The sediments were deposited in shallow marine and fluvial conditions with quickened subsidence during the glacial time (De Gans, 2007). Cenozoic North Sea sediments mainly consist of marine clay and sands (Fig. 3). These Groups unconformably overly Late Cretaceous Chalk Group. The Upper North Sea Group, consists of clays and silts, the Middle North Sea Group consists mainly of shale, the Lower North Sea Group consist of mainly marine shale lithology and little portion of marl at it's top (Winthaegen and Verweij, 2003).

The Mid-Miocene unconformity separates the Cenozoic succession into two packages (Anell et al., 2010; Tetyukhina et al., 2010; Mojeddifar et al., 2015). The Paleogene sediments are predominantly within the lower package (middle North Sea and lower North Sea Groups), are relatively fine-grained (Steeghs et al., 2000) compared to the upper package of Neogene sediments (Upper North Sea Group), about 700 m thick. Within the Upper North Sea Group (Mojeddifar et al., 2015), deltaic coarser sandy-clay stone and sand are present and reveal complex geometries. This study shows the stratigraphic units being interpreted using the GR logs by which system tract and facies models were generated. GR enables us to identify the system tracts with seismic sub-units and its boundaries. The system tract model shows the presence of LST, TST and HST, whereas the facies model shows the presence and lateral extent of sand and shale bodies and marked clinoform break points reaffirms the sequence stratigraphy of (Khan et al., 2019).

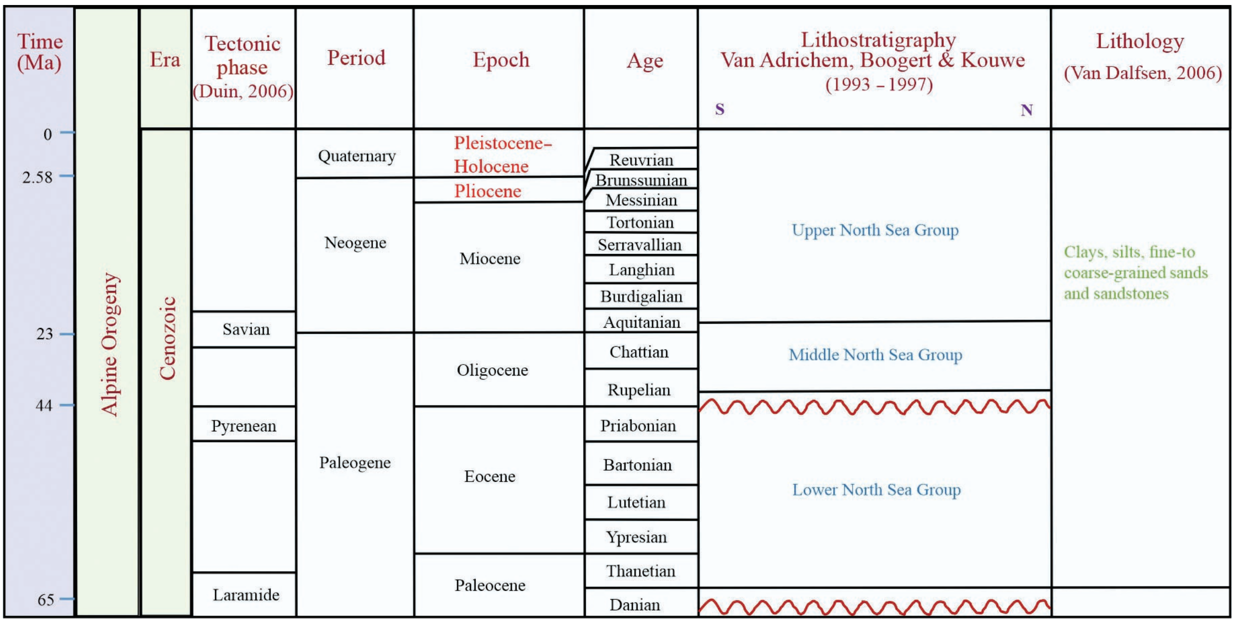

Fig. 3. Generalized Cenozoic Era stratigraphic map of Dutch offshore (modified after Duin et al., 2006; Van Dalfsen et al., 2006).

Table 1 The available well and well logs

Wells	Cali	GR	RHOB	NPHI	DT	PHIE	LLD	LLS	MSFL	SP	SN
F06-01	-	X	X	-	X	X	-	-	-	-	-
F03-06	X	X	X	X	X	-	X	X	X	X	-
F03-04	-	X	X	-	X	X	-	-	-	-	-
F03-03	X	X	X	X	X	-	X	X	X	X	X
F03-02	-	X	X	-	X	X	-	-	-	-	-
F02-02	-	X	X	-	X	-	-	-	-	-	-
F02-01	-	X	X	-	X	X	-	-	-	-	-

3 Data Set and Methodology

3D seismic data in time, covering area about 380 km², were used in this study. The seismic cube consists of 646 Inlines and 947 Xlines with the sampling rate 4 ms and 25 m sampling interval in both directions. There were 7 available wells (Fig. 1b; Table 1), with the limited data utilized for this research. In all wells, only gamma ray log was accessible for the correlation and distinguish sand and shale inside the investigated zone.

Three wells (F03-02, F03-03 and F06-01) were chosen to illuminate the interpretation of stratigraphic units. In order to get the basic interpretation rule of the gamma ray log, Luthi (2001) recommended that the higher values of gamma ray related to the shale/dirt layers and conversely lower values to the sandy layers (Khan et al., 2018). The other four wells, along with the chosen three wells, were used in making the system tract and facies models but in the delta direction. A cross section was drawn in which the respective three chosen wells were involved.

Inside three seismic units over the Mid Miocene unconformity and interpret two sorts of lithology (shale and sand) (Mojeddifar et al., 2015). Greater than 70 API value of the gamma ray log, compare to the shale rich sediments, basically has a place with the seismic units 1 and 3. In any case, lower than 70 API value of the gamma ray log, relate to the sand rich sediments, regularly has a place with the seismic unit 2. Additionally, in this research, seismic unit 2 subdivided into additional 11 seismic units and classified the lithologies, into four types on the basis of the range of the gamma ray log (Mojeddifar et al., 2015).

The gamma ray log value above 70 API corresponds to shale, within the range of 45 and 70 API represents finer sand whereas in the range of 20 and 45 API is sand and below 20 API GR log value indicates coarser sand. To understand the depositional and stacking patterns of the area, seismic data and well logs have been integrated. For creating a time-depth relation a number of techniques are present (White and Walden, 1984; White, 1998; White and Simm, 2003; Edgar and van der Baan, 2011; Duchesne and Gaillot, 2011).

Furthermore, 3D System Tract and 3D Facies models were established with the help of well data. Variograms of all surfaces using spherical method were made, and a statistical relation was occurred, which generated a geostatistical model later, by using sequential stimulation method. Variogram plotting can be defined by the following parameters; separation distance “h”, sill (C), range (a) and nugget effect (C_0) for the further details please follow Pawar (2003). Equations (1) and (2) utilized for the generation of spherical variograms.

If $h \le a$

$$g(h) = C_1\,[1 - \exp(-3h/a)] \tag{1}$$

otherwise

$$g(h) = C_1 \tag{2}$$

where the model variogram by Equations (1) and (2) produce linear behavior at shorter separation distance “h” and reaches the spatially structured component of Sill ($C_1 = C_1 - C_1$) at the range “a”.

4 Sequence Stratigraphy

4.1 Well logs

Three representative wells were selected (F06-01, F03-03, F03-02) in NE–SW direction (Fig. 4), in which the responses of GR log reveal presence of shale and sand bodies. Similar cutoff ratio of facies interpretation via GR log has been applied as followed by Khan et al. (2019). The system tracts in each well are marked by different color and also by their respective arrows, LST is being represented by yellow color, TST with maroon color and HST with pink color (Fig. 4).

The black broad lines are showing the main seismic unit boundaries in the three wells, where at the bottom it is showing the SU-01 and at top it is marked with SU-05-2. The red lines are indicating the sub-unit boundaries in all the three wells, some of the sub-unit boundaries doesn’t occur throughout the three wells. In the sequence boundaries, GR log maximum value is inferred maximum flooding surfaces (MFS). Khan et al. (2019) highlighted five seismic super units (SSU-01 to SSU-05) of Plio–Pleistocene age in the F3 block.

The low and high fluctuations of gamma ray (GR) response was corresponded by seismic reflections high and low amplitudes of all the intervals, of the wells F06-01, F03-03 and F03-02 (Fig. 4). During TST, sand to shale (GR bell shape) shows retrogradation of parasequences and during HST, shale to coarse sand (GR funnel shape) was deposited due to prograding parasequences. The delta front as the thickest part, identified in each unit, changes its direction with respect to the source of sediment supply from northeast to east-west. The light blue thin line is showing us the Maximum Flooding Surface boundaries (MFS) in all three chosen wells.

4.2 Seismic stratigraphy

The seismic interpretation was done in order to mark

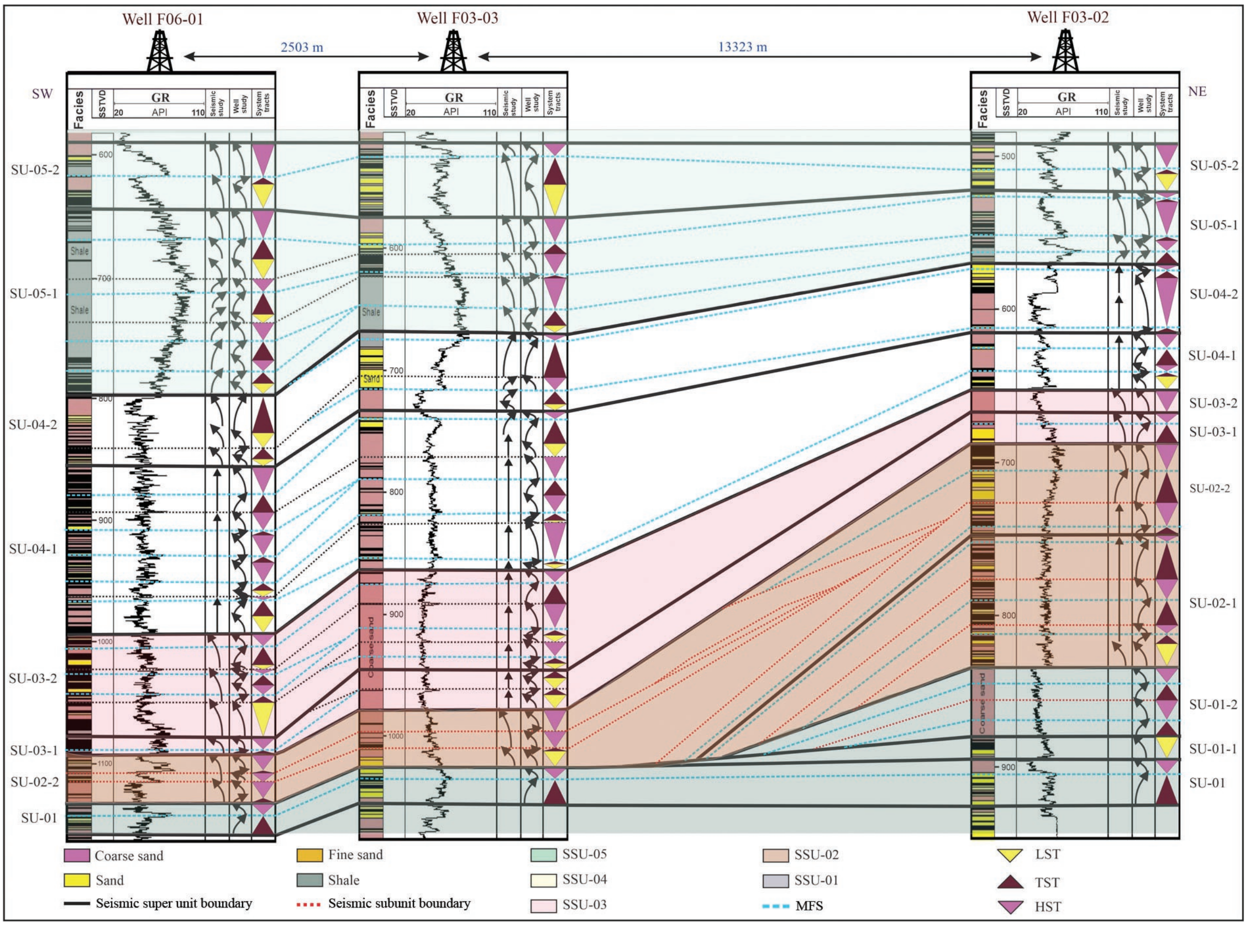

Fig. 4. Shows well log section with system tracts, seismic unit boundaries, subunit boundaries and MFS.
Well log section through NE to SW, correlate the Plio–Pleistocene delta seismic subunits enclosed within the seismic units. Distinct background colors representing the seismic super units, solid black lines representing the seismic units, seismic subunits boundaries are marked by the doted red color lines and maximum flooding surfaces are marked by blue dashed lines. However, LST symbolized by yellow color inverted triangle, TST by maroon color triangle and HST by pink color inverted triangle.

the parasequences and sequences within the studied package with the help of well logs available, across the entire field F3 block. Horizons were marked in the seismic section, the interpreted seismic section was then converted to time structural maps and afterwards it was converted to depth contoured map. To generate synthetic seismogram (time to depth relation) wavelet has been extracted (Fig. 5) with the following parameters: Ricker wavelet of 40 Hz at zero-phase, 2 m sampling rate and normal polarity to achieve best seismic to well tie.

4.3 Base level cycle events (clinoforms)

The sequence stratigraphic surfaces and system tracts interpretation is not established with the concluded correlations of global or local cycle graphs, but with the observations of facies relationships and stratal stacking trends from well logs, seismic data, cores, and outcrops of the concerned area (Van Wagoner et al., 1987, 1990; Posamentier and Allen, 1999; Catuneanu, 2006), for developing that chronostratigraphic framework (Lacaze et al., 2011). When highlighted on the basis of such data, the system tracts and sequence stratigraphic surfaces relative formation timing can be interpreted in terms of a base level cycle specific events (Catuneanu et al., 2009). The interpretation of the main reflection packages and additional subdivision of these reflection packages into seismic sequences and systems tracts is dealt by Seismic sequence stratigraphy. Following schematic diagram shows the prograding delta succession (delta top and clinoform break) (Fig. 6a). The base level cycle four main events (onset of forced regression, end of forced regression, end of regression and end of transgression), mark the changes in the shoreline trajectory type, and discreetly changes in the stratal stacking trends in rock record. The base level cycle all four events, holds the control of the formation timing of all system tracts and sequence stratigraphic surfaces (Catuneanu, 2006).

The lowstand normal regression, in which the progradation rate with the time decreases, whereas, on the other hand the aggradation rate increases with the time and, moreover, it records a change in depositional pattern from being dominantly progradational to dominantly aggradational and it shows the shoreline trajectory (Fig. 6b) as ‘Concave Up’. However, in the highstand normal regression (Fig. 6c), the progradation rate with the time increases, whereas the aggradation rate

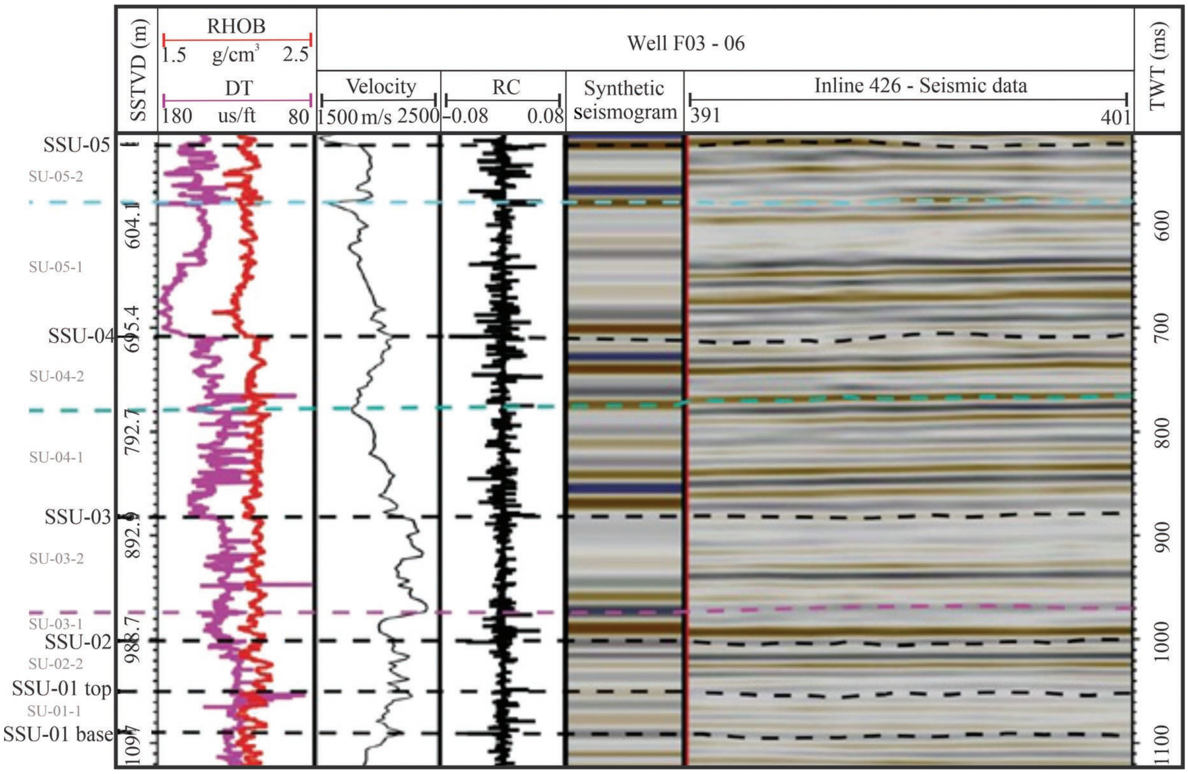

Fig. 5. Best fit time to depth relation has been generated via synthetic seismogram.

Starting from left, depth displayed in first track, second track representing the density (RHOB) and sonic (DT) displayed by red and pink color respectively, third track represents the derived velocity (*V*p) curve displayed by thin black solid line. Fourth track representing reflection coefficient (RC). Fifth track representing the synthetic traces generated by extracted wavelet has been tied with the Inline 426 displayed in sixth track and two-way travel (TWT) time displayed within the seventh track (Khan et al., 2020).

decreases, and it registers a change from being aggradation to progradation and it shows shoreline trajectory as ‘Convex Up’ (Catuneanu, 2006). Figure 7 is the interpreted seismic section along NE–SW direction, with the wells F06-01, F03-03, F03-02 and their GR log responses. The red lines are marking sequences which are sub-unit boundaries of the main seismic boundaries from bottom SU-01 to top SU-05-2. These shoreline trajectories were marked by the clinoform break points in the seismic section and it is the continuation of our previous F3 block interpretation (Khan et al., 2019), in which sequence stratigraphic analysis was interpreted on the basis of well logs and it was then collaborated with the seismic. In this research, sequence stratigraphy interpreted on the seismic with the help of clinoform break points and validated by well logs.

4.4 Upscaling of well logs

The relation of upscaled and raw data model can be seen on a CDF curve (Cumulative Distribution Function) Fig. 8. However, if in the CDF curve there is no large gap present between raw and upscaled data, then the upscaling of well logs is accepted for the further processes.

5 3D Geostatistical Modeling

The results of this study are comprehended in Zones Model, System Tract Model, Facies Model and Variogram. The 3D models are the result of Sequential Simulation method. Figure 9 showing all three models and zone model is the result of structural modeling. The zone model is showing the delta progradation in the best view, it is also showing a disruption and a gap in the beds from top to bottom, which is the main fault in the study area. The zone model surfaces are also being shown in a separated manner, through which identification of lateral extent of all the surfaces becomes feasible, as the zone modeling was carried out in order to know the lateral extend of all the surfaces in the study area, which helps later in facies modeling in order to see whether the surfaces are being laterally extended identically as in the structural model and this evidence complements the facies model. In the Fig. 9, system tract and facies models are also present, they were generated in order to know how they laterally behave in the zone model.

The variogram has been generated using geostatistics methods, utilizing well data to established statistical relation, through this relation models (System Tract and Facies Models) were generated and which are validated via histograms (Figs. 10, 11). The generation of variogram model is essential prior to the 3D geomodel. For that purpose, spherical type variogram model chosen to acquire the best fitting between the model curve and experimental/sample curve. The fitting procedure of model variogram consist of determining accurate anisotropy direction.

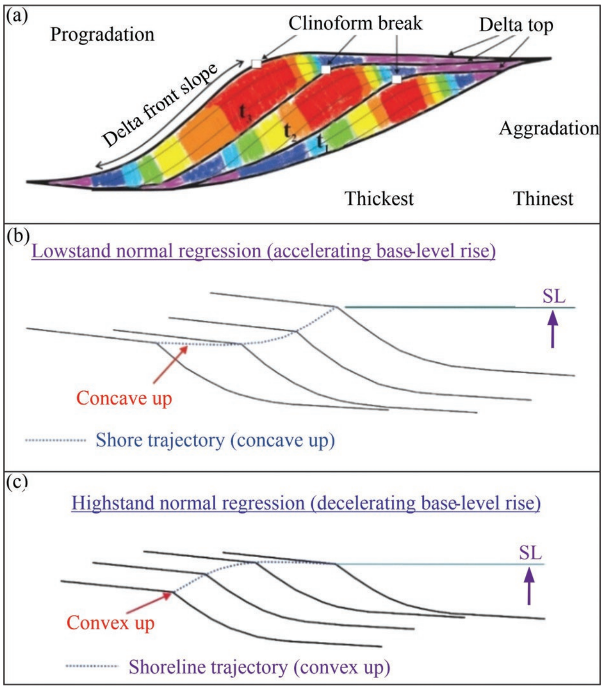

Fig. 6. Schematic diagram of clinoform geometry showing (a) seismic units' thickness variation in progarding deltaic succession, where white square represents clinoform break and delta front is shown by the thickest red section (modified after Khan et al., 2019); (b) Shoreline Trajectory with Concave Up pattern in Lowstand Normal Regression; (c) Shoreline Trajectory with Convex Up pattern in Highstand Normal Regression (modified after Catuneanu et al., 2009).

5.1 3D system tract model

With the help of System Tract modeling the presence and lateral extent of system tracts (LST, TST, HST) in an area can be visualized. The result of System Tract modeling (Fig. 10), showing the model for all surfaces from SU-01 to SU-05-2. The reason SU-04-2 is being chosen because this is the only package, which is showing the best possible reservoir characteristics in the study area. The SU-04-2 surface (Fig. 10), where it clearly exhibits the presence and lateral extent of LST, TST, and HST which are in yellow, maroon and pink color respectively, as well as in the same package, present in the well log (Fig. 4). Moreover, it is showing histogram of the System Tract model, in which the model, upscaled and well log blocks are nearly equal to each other and having 3 to 4 percentage of error, this is the evidence that System Tract model is accurately generated.

5.2 3D facies model

Facies model shows the presence and extent of different types of facies encountered in the wells of an area. The result of Facies modeling (Fig. 11), showing the model for surfaces from SU-01 to SU-05-2 and also showing, particularly the model of SU-04-2 surface. Figure 11 shows the presence and lateral extent of the sand bodies and shale, which are in yellow and gray color respectively. SU-04-2 model is the only model which is showing the best possible reservoir characteristics in the study area. Similar to the system tract model, the facies model also shows a histogram in which the model, upscaled and well log blocks are nearly equal to each other and having 1 to 2 percentage of error, this is the confirmation that facies model is generated accurately.

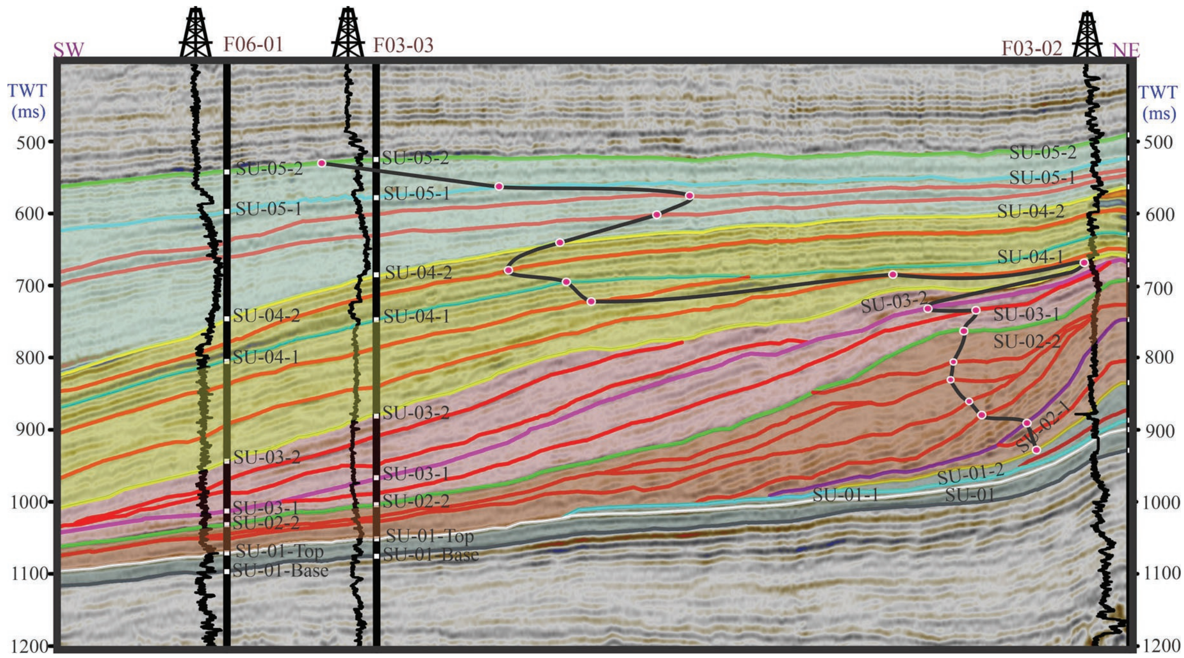

Fig. 7. Interpretation of seismic parasequences in NE to SW direction passing across the representative wells.
It is showing SSU-01- to SSU-05 sequences (oldest to youngest) depositional pattern. The distinct background color represents the boundaries of seismic super units. However, the solid red color lines representing the seismic subunits boundaries. The pink circles are marked on the clinoforms break points for only second order parasequences, from the top of SU-05-2 till base of SU-02-1.

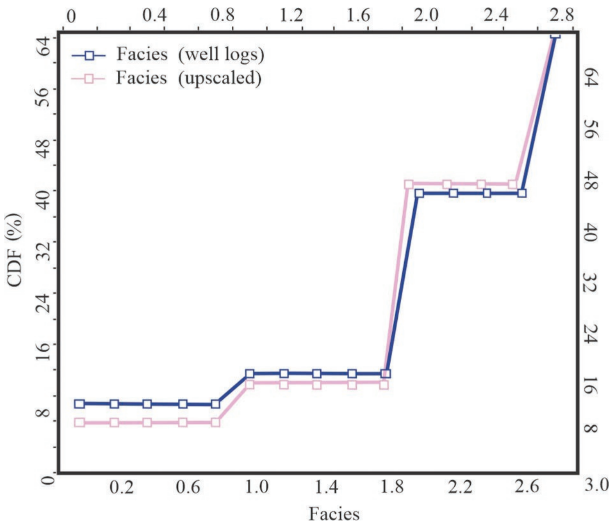

Fig. 8. CDF curve of raw well data (blue curve) and upscaled well log data values (pink curve).

6 Discussion

This research was carried out with the help of sequence stratigraphy of F3 block Paleocene–Pleistocene delta, the 3D modeling was done with its integration of sequence stratigraphy in order to identify the shallow depth surfaces which contains properties of a probable reservoir. One of the example of similar kind of study that supports presence of reservoir through 3D geostatistical modeling can be seen in a research article written by (Edigbue et al., 2015) named as "Integration of sequence stratigraphy and geostatistics in 3D reservoir modeling: a case study of Otumara field, onshore Niger Delta" in which several reservoirs models were generated from geostatistical simulation, moreover, variogram models, geostatistical analysis and the stochastic simulation showed geological heterogeneity in the identified reservoirs.

This method can be followed, to generate 3D models of an area in order to locate the presence of reservoir, however, in our study due to the limited data it was very difficult to identify the exact reservoir. However, the best possible reservoir presence marked in the area with the help of the available data and generating both System Tract and Facies models. The variograms were made with spherical methods and Sequential stimulator was used in making variograms, as it was generating models correctly with perfect histograms and providing desired results for the study. The similar approach can be seen in the (Edigbue et al., 2015) research article, where they generated models for several reservoir units with an integrated approach of geostatistical modeling and sequence stratigraphic analysis that gave a more insight to the reservoir characterization in the study area of Niger delta.

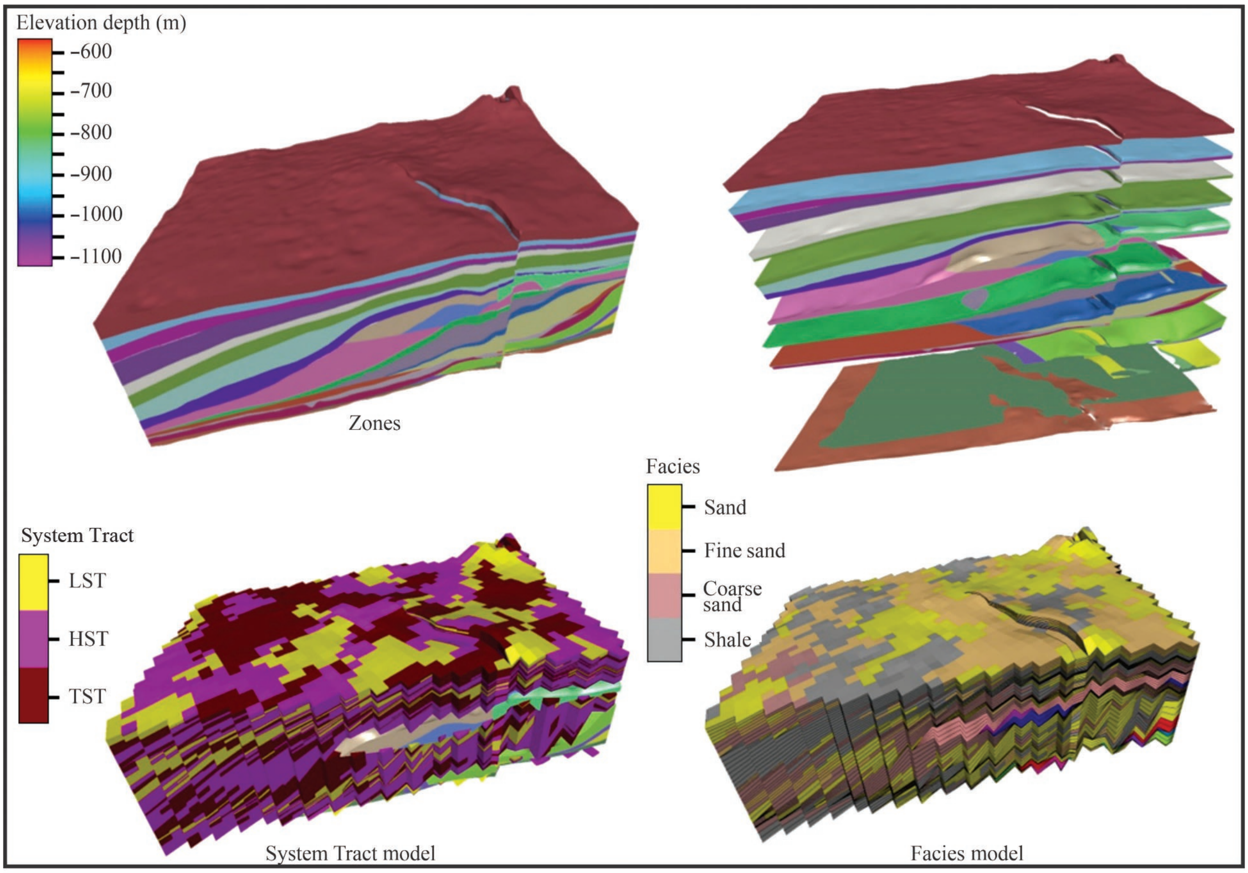

Fig. 9. A figure of all zones with their lateral continuity, System Tract model and Facies model.

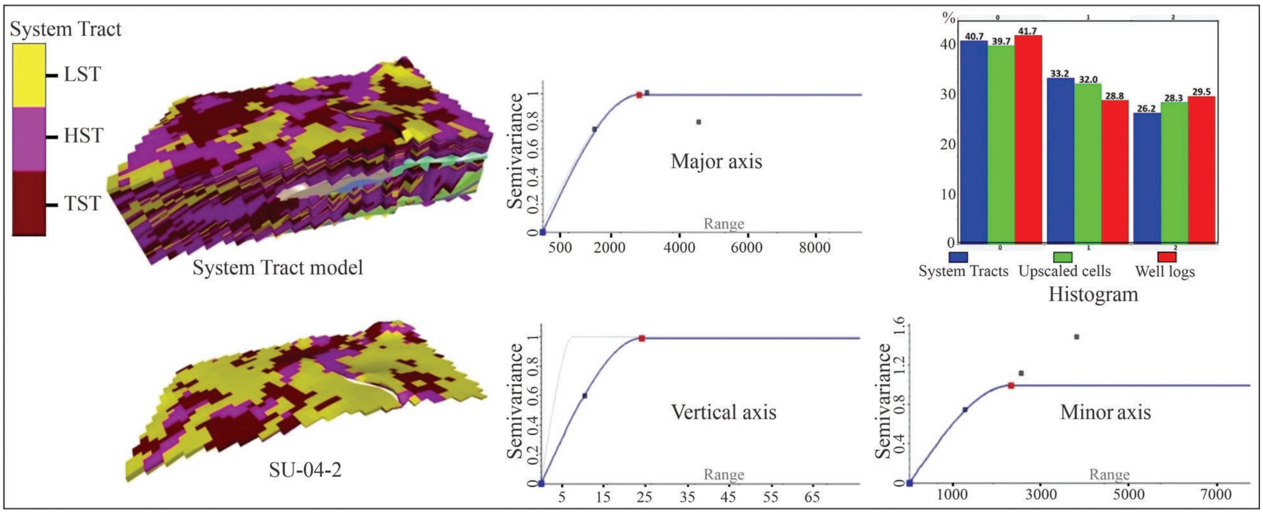

Fig. 10. System tract model of all surfaces and its histogram and also showing SU-04-2 of system tract model with its major, minor and vertical axis.

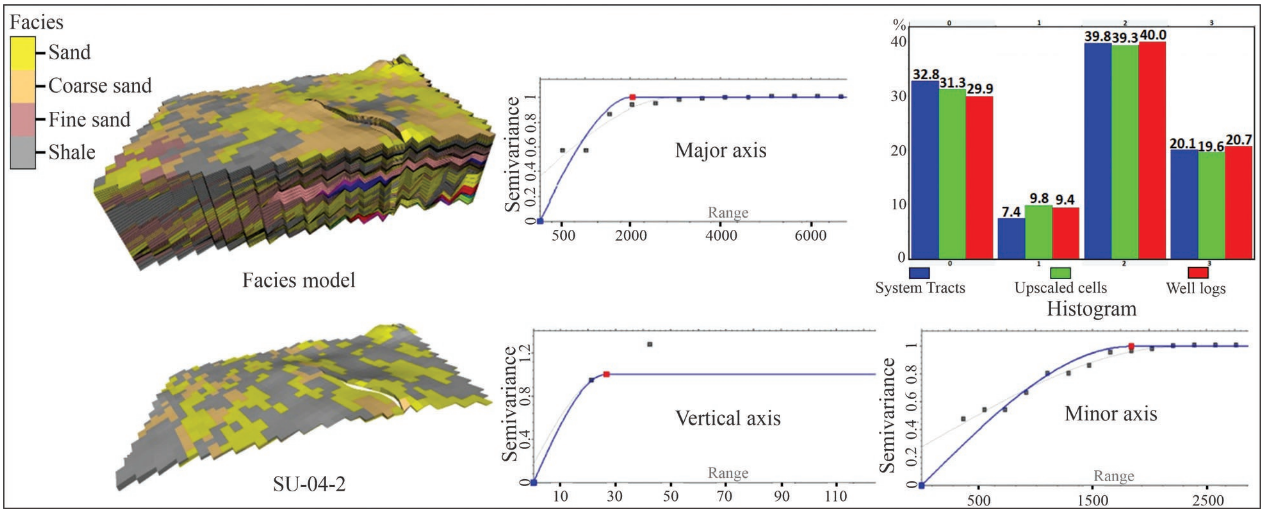

Fig. 11. Facies model of all surfaces and its histogram and also showing SU-04-2 of facies model with its major, minor and vertical axis.

For the upscaling of well logs, geometric method was used as it is the simplest method and minimum percentage of error can occur with this method, the upscaling well logs is correctly done can be seen on the CDF curve (Fig. 8) where the relation of raw well data and upscaled data nearly overlies each other and give evidence of its correctness. The 3D model results of this research are very clearly indicating the probabilities of reservoir characteristics available in the study area. The results generated for this research started with the generation of 3D model for zones (Fig. 9), in order to see the lateral extent of all surfaces as it is helpful in complementing the Facies model, therefore, the lateral extent of all the surfaces in zone should coincide with the surfaces in facies model, hence, if the lateral extent coincide this shows the facies model is sufficiently well generated with minimum acceptable error but if the surfaces are not corresponding in both Zone and Facies models, this establishes the fact that either Facies or Zone model is incorrectly generated.

The System Tract model is representing the LST, TST and HST presence in the Pleistocene delta in the F3 block of Dutch offshore basin, it also indicates the lateral extent of the LST, TST and HST packages in the delta which helps us to locate the presence of sand bodies and shales where the possible reservoir packages with seal can be accumulated. In our research, SU-04-2 is the only model out of all models in the System Tract model, which is showing the presence and lateral extent of LST and HST with laterally presence of TST packages, on both sides of the main fault (Fig. 10), this shows the possibility of reservoir characteristics can be present in the SU-04-2 model. This possibility of having reservoir characteristics in the SU-04-2 model can be confirmed by collaborating it with the Facies model, that is, if the SU-04-2 model of Facies modeling is containing sand bodies on the exact location where the LST and HST are present in the SU-04-2 System Tract model.

The Facies model (Fig. 11), shows the distribution of all types of facies. The facies were present in the area that were encountered in the wells, variograms properly distributed them in the 3D Facies modeling. In the Facies model, SU-04-2 is the surface within the model, which is showing the presence and lateral extent of sand bodies and also the lateral presence of shale body, at the same location where System Tract model showed the presence and lateral extent of LST, HST, and TST on both sides of the main fault.

7 Conclusions

This study of the Plio-Pleistocene Delta of F3 block (Dutch Offshore Basin) has given a 3D geospatial distribution arrangement of different facies and set up the nearness of positive system tracts abnormalities in the research area. Through this study, it is compared and analyzed the chances of reliability and accuracy of interpreting sequence stratigraphy only on the basis of seismic data with the help of clinoform break points and validated it with the well log interpretation of sequence stratigraphy of our previous publication. The integration of sequence stratigraphy with 3D geostatistical modeling shows the presence and lateral extend of the LST, HST and sand bodies on both sides of the main fault and laterally presence of the shale body within TST in the area. Our study affirms that the study area is consisting of gas chimneys and showing gas pockets in the SU-04-2 surface, which shows lateral extent of LST, HST and TST packages on both sides of the main fault. Moreover, in the Facies model of SU-04-2 that shows lateral extent of sand and as well as shale bodies on both sides of the main fault, this perhaps utilized to infer the reservoir characteristics in the SU-04-2 surface. This methodology can effectively be applied on different areas to evaluate multi-dimensional studies of vertical and lateral facies changes (mainly reservoir packages).

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References

Alabert, F.G., and Corre, B., 1991. Heterogeneity in a complex turbiditic reservoir: Impact on field development. In: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.

Anell, I., Thybo, H., and Stratford, W., 2010. Relating Cenozoic North Sea sediments to topography in southern Norway: The interplay between tectonics and climate. Earth and Planetary Science Letters, 300(1): 19–32.

Bijlsma, S., 1981. Fluvial sedimentation from the Fennoscandian area into the north-west European Basin during the Late Cenozoic. Geologie en Mijnbouw, 60(4): 337–345.

Catuneanu, O., 2006. Stratigraphic surfaces in principles of sequence stratigraphy. Elsevier: 105–164. ISBN: 0080473989.

Catuneanu, O., Abreu, V., Bhattacharya, J., Blum, M., Dalrymple, R., Eriksson, P., Fielding, C.R., Fisher, W., Galloway, W., and Gibling, M., 2009. Towards the standardization of sequence stratigraphy. Earth-Science Reviews, 92(1): 1–33.

Clausen, O., Nielsen, S., Egholm, D., and Gołędowski, B., 2012. Cenozoic structures in the eastern North Sea Basin—A case for salt tectonics. Tectonophysics, 514: 156–167.

Clausen, O., Nielsen, S., Egholm, D., and Goledowski, B., 2013. Reply to Rasmussen (this volume): Cenozoic structures in the eastern North Sea Basin—A case for salt tectonics: Discussion. Tectonophysics, (601): 234–235.

Cloetingh, S., Reemst, P., Kooi, H., and Fanavoll, S., 1992. Intraplate stresses and the post-Cretaceous uplift and subsidence in northern Atlantic basins. Norsk Geologisk Tidsskrift, 72(3): 229–235.

De Gans, W., 2007. Quaternary. The geology of the Netherlands, 173–196.

Deagan, C., and Scull, B., 1977. A proposed standard lithostratigraphic nomenclature for the Central and Northern Sea. Reports Institute of the Geological Sciences, 77: 25.

Dronkers, A., and Mrozek, F., 1991. Inverted basins of the Netherlands. First Break, 9(9): 409–425.

Dubrule, O., 1989. A review of stochastic models for petroleum reservoirs. In: Geostatistics. Springer, Dordrecht, 493–506.

Duchesne, M.J., and Gaillot, P., 2011. Did you smooth your well logs the right way for seismic interpretation? Journal of Geophysics and Engineering, 8(4): 514–523.

Duin, E.J.T., Doornenbal, J.C., Rijkers, R.H.B., Verbeek, J.W., and Wong, T.E., 2006. Subsurface structure of the Netherlands-results of recent onshore and offshore mapping. Netherlands Journal of Geosciences, 85(4): 245.

Edgar, J.A., and Van der Baan, M., 2011. How reliable is statistical wavelet estimation? Geophysics, 76(4): 59–68.

Edigbue, P., Olowokere, M.T., Adetokunbo, P., and Jegede, E., 2015. Integration of sequence stratigraphy and geostatistics in 3-D reservoir modeling: A case study of Otumara field, onshore Niger Delta. Arabian Journal of Geosciences, 8(10): 8615–8631.

Eidvin, T., and Rundberg, Y., 2001. Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. Norwegian Journal of Geology/Norsk Geologisk Forening, 81(2): 119–160.

Faleide, J.I., Kyrkjebø, R., Kjennerud, T., Gabrielsen, R.H., Jordt, H., Fanavoll, S., and Bjerke, M.D., 2002. Tectonic impact on sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas. Geological Society of London, Special Publications, 196(1): 235–269.

Ghazi, S., 1992. Cenozoic uplift in the Stord Basin area and its consequences for exploration. Norsk Geologisk Tidsskrift, 72 (3): 285–290.

Gregersen, U., Michelsen, O., and Sørensen, J.C., 1997. Stratigraphy and facies distribution of the Utsira Formation and the Pliocene sequences in the northern North Sea. Marine and Petroleum Geology, 14(7): 893–914.

Harding, R., and Huuse, M., 2015. Salt on the move: Multi stage evolution of salt diapirs in the Netherlands North Sea. Marine and Petroleum Geology, 61: 39–55.
Haszeldine, R., and Russell, M., 1987. The Late Carboniferous northern North Atlantic Ocean: Implications for hydrocarbon exploration from Britain to the Arctic. Petroleum Geology of North West Europe, 2: 1163–1175.
Herngreen, G., and Wong, T.E., 1989. Revision of the 'Late Jurassic'stratigraphy of the Dutch Central North Sea Graben. In: Coastal Lowlands. Springer, 73–105.
Heybroek, P., 1975. On the structure of the Dutch part of the Central North Sea Graben. In: Woodland, A.W. (ed.), Petroleum and the Continental Shelf of NW Europe. 1 Geology, Applied Science Publishers, Barking, 339–352.
Jordt, H., Faleide, J.I., Bjørlykke, K., and Ibrahim, M.T., 1995. Cenozoic sequence stratigraphy of the central and northern North Sea Basin: Tectonic development, sediment distribution and provenance areas. Marine and Petroleum Geology, 12(8): 845–879.
Khan, H.A., Zouaghi, T., Iftekhar, S., Khan, M.J., and Irfan, M., 2019. Plio–Pleistocene stratigraphic sequences and depositional model using 3D seismic interpretation constrained by well logs in Central Graben, North Sea. Journal of Earth System Science, 128(4): 85.
Khan, M., Khan, M.J., Kakar, M.I., and Mehmud, K., 2018. Geology and tectonic setting of Nal Ophiolite, District Khuzdar, Balochistan, Pakistan. American Journal of Earth and Environmental Sciences, 1(3): 115–123.
Knox, R.W.O.B., Bosch, J.H.A., Rasmussen, E.S., Heilmann-Clausen, C., Hiss, M., De Lugt, I.R., Kasinski, J., King, C., Köthe, A., Slodkowska, B., and Standke, G., 2010. Cenozoic. In: Petroleum Geological Atlas of the Southern Permian Basin Area. Publisher: European Association of Geoscientists and Engineers (EAGE) Publications b.v.; Houten - The Netherlands: 211–224.
Kooi, H., Hettema, M., and Cloetingh, S., 1991. Lithospheric dynamics and the rapid Pliocene–Quaternary subsidence phase in the southern North Sea basin. Tectonophysics, 192 (3): 245–259.
Lacaze, S., Pauget, F., Lopez, M., Gay, A., and Mangue, M., 2011. Seismic stratigraphic interpretation from a geological model-A North Sea case study. In: 2011 SEG Annual Meeting. Society of Exploration Geophysicists, 1134–1139.
Luthi, S., 2001. Geological well logs: Their use in reservoir modeling. Springer Science and Business Media.
Lyngsie, S.B., and Thybo, H., 2007. A new tectonic model for the Laurentia−Avalonia−Baltica sutures in the North Sea: A case study along MONA LISA profile 3. Tectonophysics, 429 (3): 201–227.
Ma, Y.Z., and La Pointe, P.R., 2011. Uncertainty analysis and reservoir modeling: Developing and managing assets in an uncertain world. American Association of Petroleum Geologists Memoir 96.
MacDonald, A.C., Høye, T.H., Lowry, P., Jacobsen, T., Aasen, J.O., and Grindheim, A.O., 1992. Stochastic flow unit modelling of a North Sea coastal-deltaic reservoir. First Break, 10(4): 124–133.
Marotta, A., Bayer, U., Thybo, H., and Scheck, M., 2002. Origin of the regional stress in the North German basin: Results from numerical modelling. Tectonophysics, 360(1): 245264.
Massonnat, G.J., Norris, R.J., and Chalmette, J.C., 1993. Well test interpretation in geologically complex channelized reservoirs. In: SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers.
Mojeddifar, S., Kamali, G., and Ranjbar, H., 2015. Porosity prediction from seismic inversion of a similarity attribute based on a pseudo-forward equation (PFE): A case study from the North Sea Basin, Netherlands. Petroleum Science, 12(3): 428–442.
Nelskamp, S., Verweij, J., and Witmans, N., 2012. The role of salt tectonics and overburden in the generation of overpressure in the Dutch North Sea area. Netherlands Journal of Geosciences, 91: 517–534.
Overeem, I., Weltje, G.J., Bishop-Kay, C., and Kroonenberg, S., 2001. The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: A climate signal in sediment supply? Basin Research, 13(3): 293–312.
Pawar, R.J., 2003. Introduction to geostatistics. In: Developments in Petroleum Science. Los Alamos National Laboratories, Los Alamos, NM, USA. Elsevier, 51: 85–95.
Posamentier, H., and Allen, G., 1999. Siliciclastic sequence stratigraphy. Concepts Applications: SEPM, Concepts in Sedimentology Paleontology, 7: 210.
Qayyum, F., Hemstra, N., and Singh, R., 2013. A modern approach to build 3D sequence stratigraphic framework. Oil and Gas Journal, 111(10): 46–46.
Rasmussen, E.S., and Dybkjaer, K., 2005. Sequence stratigraphy of the Upper Oligocene–Lower Miocene of eastern Jylland, Denmark: Role of structural relief and variable sediment supply in controlling sequence development. Sedimentology, 52(1): 25–63.
Rasser, M.W., Harzhauser, M., and Anistratenko, O., 2008. Palaeogene and Neogene. The Geology of Central Europe, 2: 1031–1139.
Rohrman, M., Andriessen, P., and Beek, P., 1996. The relationship between basin and margin thermal evolution assessed by fission track thermochronology: An application to offshore southern Norway. Basin Research, 8(1): 45–63.
Rohrman, M., Beek, P., Andriessen, P., and Cloetingh, S., 1995. Meso–Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferred from apatite fission track thermochronology. Tectonics, 14(3): 704–718.
Sales, J., 1992. Uplift and subsidence do northwestern Europe: Possible causes and influence on hydrocarbon productivity. Norsk Geologisk Tidsskrift, 72(3): 253–258.
Schroot, B., and Schüttenhelm, R., 2003. Expressions of shallow gas in the Netherlands North Sea. Netherlands Journal of Geosciences, 82: 91–105.
Sclater, J.G., and Christie, P.A., 1980. Continental stretching: An explanation of the post-Mid-Cretaceous subsidence of the central North Sea Basin. Journal of Geophysical Research: Solid Earth, 85(B7): 3711–3739.
Shanor, G.G., Samimi, B., Bagherpour, H., Karakas, M., Buck, S., Carnegie, A., Crossouard, P.A., and Nasta, V., 1993. An integrated reservoir characterization study of a Giant Middle East Oil Field: Part 1-Geological modelling. In: Middle East Oil Show, Society of Petroleum Engineers.
Sørensen, J., and Michelsen, O., 1995. Upper Cenozoic sequences in the southeastern North sea basin. Bulletin of the Geological Society of Denmark, 42(1): 74–95.
Sørensen, J.C., Gregersen, U., Breiner, M., and Michelsen, O., 1997. High-frequency sequence stratigraphy of Upper Cenozoic deposits in the central and southeastern North Sea areas. Marine and Petroleum Geology, 14(2): 99–123.
Spjeldnæs, N., 1975. Paleogeography and facies distribution in the Tertiary of Denkmark and surrounding areas. Norges Geologiska Undersøkels, 316: 289–311.
Steeghs, P., Overeem, I., and Tigrek, S., 2000. Seismic volume attribute analysis of the Cenozoic succession in the L08 block (Southern North Sea). Global and Planetary Change, 27(1): 245–262.
Stollhofen, H., Bachmann, G., Barnasch, J., Bayer, U., Beutler, G., Franz, M., Kästner, M., Legler, B., Mutterlose, J., and Radies, D., 2008. Upper Rotliegend to early Cretaceous basin development. In Dynamics of complex intracontinental basins. The central European basin system, Springer: 181–210.
Tetyukhina, D., van Vliet, L.J., Luthi, S.M., and Wapenaar, K., 2010. High-resolution reservoir characterization by an acoustic impedance inversion of a Tertiary deltaic clinoform system in the North Sea. Geophysics, 75(6): 57–67.
Tigrek, S., 1998. 3D seismic interpretation and attribute analysis of the L08 block, southern North Sea Basin (M.Sc. thesis). Netherlands: Delft University of Technology.
Vail, P.R., 1987. Seismic stratigraphy interpretation using sequence stratigraphy: Part 1: Seismic stratigraphy interpretation procedure. In: Bally, A.W. (ed.), AAPG Studies in Geology #27, Atlas of Seismic Stratigraphy, 1: 1–10.
Van Dalfsen, W., Doornenbal, J., Dortland, S., and Gunnink, J., 2006. A comprehensive seismic velocity model for the Netherlands based on lithostratigraphic layers. Netherlands

Journal of Geosciences, 85(4): 277–292.
Van Wagoner, J., Mitchum Jr, R., Posamentier, H., and Vail, P., 1987. Seismic stratigraphy interpretation using sequence stratigraphy: Part 2: Key definitions of sequence stratigraphy: 11–14.
Van Wagoner, J., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops. AAPG Methods in Exploration Series, 7: 8–17.
Walden, A.T., and White, R.E., 1984. On errors of fit and accuracy in matching synthetic seismograms and seismic traces. Geophysical Prospecting, 32(5): 871–891.
Warren, J., 2008. Salt as sediment in the Central European Basin system as seen from a deep time perspective. In: Dynamics of complex intracontinental basins. Springer, Berlin, Heidelberg: 249–276.
White, R.E., and Hu, T., 1998. How accurate can a well tie be? The Leading Edge, 17(8): 1065–1071.
White, R.E., and Simm, R., 2003. Tutorial: Good practice in well ties. EAGE Publications BV, First Break, 21(10). DOI: 10.3997/1365-2397.21.10.25640
Winthaegen, P., and Verweij, J., 2003. Estimating regional pore pressure distribution using 3D seismicvelocities in the Dutch Central North Sea Graben. Journal of Geochemical Exploration, 78: 203–207.
Zagwijn, W., 1974. The paleogeographic evolution of the Netherlands during the Quaternary. Geologie en Mijnbouw, 53(6): 369–385.
Ziegler, P., 1987. Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine foreland—A geodynamic model. Tectonophysics, 137(1): 389–420.
Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe, Shell International Petroleum Maatschappij. BV, The Hague: 239.
Ziegler, P.A., 1988. Evolution of the Arctic-North Atlantic and the Western Tethys—A visual presentation of a series of paleogeographic-paleotectonic maps. AAPG Memoir, 43: 164–196.
Ziegler, P.A., Cloetingh, S., and van Wees, J.D., 1995. Dynamics of intra-plate compressional deformation: The Alpine foreland and other examples. Tectonophysics, 252(1): 7–59.

About the first author

Dr. Haris Ahmed KHAN, male; born in 1984 in Karachi City, Sindh Province; currently working as a Principal Petroleum Geologist at Hydrocarbon Development Institute of Pakistan (Ministry of Energy – Petroleum Division). He holds Ph.D. from King Abdulaziz University, in petroleum geology with bachelor and master from University of Karachi, in the same subject. His main fields of interest are geomodeling, 3D seismic geomorphology and reservoir characterization. Dr. Haris have strong geological background and good command on Schlumberger state-of-the-art packages Petrel, PetroMod and Techlog. He offered teaching services in B.Sc., M.Sc. and Ph.D. programs at Bahria University for 4.5 years. He also worked as a mud logger for almost 3.7 years with Petroservices GmbH. E-mail: harisahmed@hdip.com.pk.

About the corresponding author

Dr. Muhammad Jahangir KHAN, male, born in 1987 in Burewala City, Punjab Province (Pakistan); currently working as an assistant professor of geophysics at Bahria University, Karachi. He has earned master's degree in geophysics from Quaid-i-Azam University (Islamabad). He has been participated in series of International Workshops-cum-Seminars on marine geological and geophysical surveys, held at Beijing and Qingdao, organized by China Geological Survey. He is now interested in integrated studies emphasizing on earthquake and geospatial data analysis. E-mail: mjahangir.bukc@bahria.edu.pk.