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3D static reservoir modelling to evaluate petroleum potential of Goru C-Interval sands in Sawan Gas Field, Pakistan

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This study is aimed at building a 3D static model of the C-Interval horizon within the Lower Goru Formation of the Sawan gas field, Pakistan. The C-Interval horizon is a proven gas reservoir with considerable potential for further development. Sequence stratigraphic interpretation reveals that C-Interval horizon was deposited under transgressive-regressive conditions, with forced regression resulting in deposition of sand bodies in a deltaic environment. Well logs and core analysis reveal different lithological facies. Thin interbedded shales induced extreme heterogeneity in C-Interval reservoir properties. Sequential Indicator Simulation (SIS) and Sequential Gaussian Simulation (SGS) have been applied to spatially map the heterogeneities of the reservoir properties such as water saturation (S_w), porosity (ϕ), facies, etc. The models indicate thick reservoir quality sand facies are present in the northeastern half with high effective porosity (ϕ_e) being consistent with the high sand content near the paleo-coast line. However, the shale content (V_{sh}) increases towards the southwestern half consistent with more basinward settings. The lithologies in the southwestern half exhibit low ϕ_e with an increase in S_w . The techniques utilized in this study have implications for other producing hydrocarbon fields with complex reservoir properties and similar geological settings.

Introduction

The world's growing population will see increasing demand for energy resources in order to sustain an improved quality of life. Advancements in computational technology has resulted in increasing success for the search of hydrocarbon resources within geological basins (Adeoti et al., 2014; Osinowo et al., 2018). Three-dimensional reservoir modelling is now more commonly performed for exploitation of hydrocarbon fields (Godwill and Waburoko, 2016; Chongwain et al., 2019) and has been extensively applied in the hydrocarbon industry for improved visualization of reservoir properties (Patrick et

al., 2002; Singh et al., 2013; Soleimani et al., 2016; Abeer et al., 2019). Utilizing a time and cost-effective solution in the determination and visualization of reservoir properties is an essential requirement of reservoir studies. In order to develop or explore a new hydrocarbon field, detailed reservoir modelling is required in addition to conventional studies such as structure, stratigraphy and formation evaluation (Benetatos et al., 2010; Adelu et al., 2019).

The stratigraphy and structure of the reservoir should be well understood in order to develop an accurate and detailed reservoir model. High resolution seismic (HRS) reflection data provides an effective approach in delineating the structure, stratigraphy and depositional setting of the reservoir (Ahmed et al., 2004; Zeng and Hentz, 2004; Li et al., 2017). Delineation of the depositional setting of the formation is required as reservoir properties such as porosity (ϕ), permeability (δ), shale content (V_{sh}) and water saturation (S_w) depend upon lithologies present (Jafarzadeh et al., 2019). Hence the type of lithology and its depositional setting help to understand the variation in petrophysical properties (Haldorsen and Damsleth, 1990). Geophysical well logs such as gamma ray (GR) and self potential in addition to reservoir core logs are key to interpret the lithological variation in the reservoir. Geophysical logs are then compared with corresponding core logs (where available) to identify relationships between measured logs and actual lithologies. In addition, geophysical logs provide the reservoir parameters such as ϕ , δ and S_w at well locations (Baouche et al., 2020).

Drilling a large number of wells for the calculation of formation properties is prohibitively expensive in both time and cost. A three-dimensional (3D) HRS survey provides an effective approach to mapping variations of properties in clastic reservoirs (Zhao et al., 2020). Seismic sequence stratigraphy techniques aid in establishing the depositional setting of a particular formation for a basin while assisting the prediction of lithologies (Vail et al., 1987; Ahmed et al., 2004; Munir et al., 2011). Key lithologic horizons identified on seismic reflection data are correlated to well data either by generating synthetic seismograms, check shot surveys or by a vertical seismic profiling (Cubizolle et al., 2015; Ali and Farid, 2016; Wu and Caumon, 2017). Utilizing the results of studies from well data to predict and map reservoir properties over large areas can provide a guide for the reservoir modelling procedure (Ali et al., 2018, 2019).

A reservoir model (both static and dynamic) is a digital depiction of

subsurface content and conditions (Doyen, 2007; Visser and Viota, 2017). Modelling improves the subsurface reservoir characterization through integration of all geophysical (seismic, well logs), geological (well cores, lithologies), petrophysical and production data (Mode and Anyiam, 2007; Aizebeokhai and Olayinka, 2011; Adelu et al., 2016). The development of an existing hydrocarbon field requires a 3D reservoir model be constructed typically in two phases, i.e., first construct a static model which describe the geological architecture of the reservoir and second, build a dynamic model to describe the fluid distribution within the reservoir (Visser and Viota, 2017; Adelu et al., 2019). Reservoir modelling can be calibrated through historical field data (including geophysical, geological, petrophysical and production data) to describe the future development of the reservoir.

The Lower Indus Basin holds a significant economic position due

to its existing hydrocarbon reserves including many oil and gas fields (Quadri, 1986; Zaigham and Mallick, 2000). The Sawan gas field lies on the Jacobabad-Khairpur High (as highlighted in Fig. 1). Currently, it is producing from the sandstone (C-Interval) of the Lower Goru Formation that accumulates several commercial hydrocarbons resources (Ahmed et al., 2004; Berger et al., 2009; Yasin et al., 2019). Most recent studies are focused on evaluating the reservoir properties of the Lower Goru Formation (Anwer et al., 2017; Azeem et al., 2017; Toqeer and Ali, 2017; Ali et al., 2018).

The current study aims to develop a static model of the C-Interval of the Lower Goru Formation utilizing 3D seismic reflection data and techniques with existing well data (geophysical logs, core description and formation tops). Emphasis is on evaluating the depositional settings, identifying the prolific sand zones and determining the properties

Figure 1. Regional location of Sawan gas field on Jacobabad-Khairpur High area in Pakistan (modified after Kadri, 1995) as highlighted by blue square.

of C-Interval in a 3D domain. The C-Interval horizon was identified by establishing a time-depth (T-D) relationship between the wells and 3D seismic data. The seismic horizons were mapped and a structural model was established. Key facies and formation property interpretation from the wells acted as a constraint for 3D seismic mapping. Post-stack seismic inversion identified further potential prospect zones within the reservoir.

Geological Settings

The study area lies within the Sukkur Rift zone along the south eastern margin of Jacobabad-Khairpur High (Kadri, 1995; Kazmi and Jan, 1997; Zaigham and Mallick, 2000; Ahmed et al., 2004) as shown in Fig. 2. Geologically, the Punjab Platform lies towards the northeast of the study area, the Sulaiman Fold Belt to the north and northwest, the Kirthar Fold Belt towards the west and the Rajasthan Shelf and Indian Shield to the east (Kadri, 1995) as shown in Figs. 1 and 2. The sedimentary succession over the basement is approximately 4000 m thick within the Sukkur Rift Zone with significant amounts of hydrocarbons trapped within the Mesozoic and Tertiary formations (Kazmi and Jan, 1997). The structure and stratigraphy of the area are controlled by three major tectonic events: uplift and erosion of stratum during the Late Cretaceous, Late Paleocene tear faulting, and uplift of the Jacobabad-Khairpur high in the Late Tertiary (Ahmed et al., 2013; Azeem et al., 2016).

The first uplifting episode happened in Late Cretaceous time near to the Cretaceous-Tertiary (K-T) boundary, which was evidenced by thinning of the Ranikot Formation towards paleo highs (Ahmed et al., 2004). The occurrence of volcanic rocks which include basaltic flows, tuffs and volcanic boulder conglomerates in the lower part of the Bibai

Formation further west of the study area suggest the existence of volcanism due to the collision of the Indian and Eurasian plates in the Late Cretaceous. The unconformities existing within the Late Cretaceous sequences indicate the variable tectonic and stratigraphic conditions of the basin (Kazmi and Jan, 1997). Later, anticlockwise rotation of the Indian plate and its collision with the Eurasian plate induced wrench faulting (Zaigham and Mallick, 2000; Ahmed et al., 2004). Basement induced NNW to SSE wrench faults cut the whole sedimentary section till Cretaceous (Kazmi, 1979; Kazmi and Rana, 1982). These faults form as a single rooted system within the basement and changes character to a multiple fault system (making negative flower structures) near the Upper Goru formation until terminating against the tertiary unconformity (Azeem et al., 2018). Uplifting of Jacobabad-Khairpur high happened in the Late Tertiary which controlled the sedimentation of the reservoir units of Lower Goru Formation (Berger et al., 2009; Azeem et al., 2016; Khan and Khan, 2018). The tectonic activity of the western axial belts formed the foreland bulges which initiated the formations of traps within the Lower Indus Basin (Ahmed et al., 2013).

The stratigraphic succession of the study area is presented in Fig. 3. The oldest rocks belong to the Wulgai Formation which is the only exposed Triassic strata in the region. This formation was deposited in an open marine environment and consists of limestone. The Jurassic rocks in the region include the thick clastic sequences of Shirinab Formation (Kazmi and Jan, 1997). The deposition of thick-bedded Chiltan Limestone followed the deposition of the Shirinab Formation with a conformable contact (Kazmi and Jan, 1997). An unconformity separates the Chiltan Limestone and the Cretaceous Sembar Formation (Williams, 1959; Kazmi and Jan, 1997). Sembar Formation consist of black shale, sandstone and nodular limestone (Quadri and Shuaib, 1986; Kadri, 1995). Goru Formation follows the Sembar Formation and is comprised of

Figure 2. Basemap of study area including geological structure, locations of oil and gas fields, 3D seismic boundary and well locations (modified after Kadri, 1995).

Figure 3. Stratigraphy of the study area developed from well data and modified after Kadri (1995).

limestone, shale, sandstone and siltstone. Goru Formation is divided into Upper and Lower Goru Formations depending on lithological settings. Lower Goru Formation consists of interlayered sandstone and shale horizons (Krois et al., 1998). The sandstone horizons are divided into A-Interval, B-Interval, C-Interval and D-Interval (Ahmed et al., 2004; Berger et al., 2009; Munir et al., 2011; Yasin, 2019).

Data Sets and Methods

The details of seismic and well data sets are presented in Table 1. The current study makes use of 3D seismic reflection data which was acquired and processed using standard industry processing algorithms. The post stack seismic reflection 3D cube represents a subsurface image of 4.5 sec two-way time. Complete data sets of six wells from the Sawan gas field including wireline logs, formation tops, lithological information were available for the current study. The data sets were georeferenced in Universal Transverse Mercator (UTM-43N) projection system.

The work flow for the static modelling of the C-Interval horizon is presented in Fig. 4. This process includes horizon identification, seismic stratigraphy, petrophysical interpretation, sequential gaussian and indicator simulations, facies and property modelling.

In order to delineate the sand horizons of Lower Goru Formation, well to seismic tie was performed by generating synthetic seismograms with the help of density and sonic logs. The seismic wavelet was extracted from the 3D seismic cube which was later convolved with the reflectivity series generated by density and sonic logs from W-5. The resulting synthetic seismogram was correlated for coherency with the seismic data to identify the major subsurface horizons in addition to the sands of Lower Goru Formation as shown in Fig. 5.

Reservoir Parameters and Well Correlation

The reservoirs parameters have been estimated through the analysis of well logs. The calculated parameters include the volume of shale (V_{sh}) effective porosity (ϕ_e) and water saturation (S_w). Initially, facies were identified at the well locations referencing borehole logs predominantly using GR logs calibrated into GR zones. GR > 80 API were used to identify 'Shale Facies', GR 50 to 80 API correspond to 'Shaly Sand Facies' and GR < 50 API identifies the 'Sand Facies'. The interpreted lithologies (facies) are presented in Fig. 6.

Table 1. Details of data sets used in the current study

Well Data				
Well	Total Depth TD (m)	TD Formation	TD Horizon	Geophysical Logs
W-1	3587	Lower Goru	C-Sand	GR, DT, RHOB, LN, NPHI, PEF
W-2	3489	Lower Goru	B-Sand	GR, DT, RHOB, LN, NPHI, PEF
W-3	3380	Lower Goru	C-Sand	GR, DT, RHOB, LN, NPHI, PEF
W-4	3370	Lower Goru	C-Sand	GR, DT, RHOB, LN, NPHI, PEF
W-5	3400	Lower Goru	B-Sand	GR, DT, RHOB, LN, NPHI, PEF
W-6	3430	Lower Goru	C-Sand	GR, DT, RHOB, LN, NPHI, PEF
Seismic Data				
Type	Total Time	Sampling Interval	Inlines	Crosslines
3D	4.5 sec	4ms	394	158

The ϕ_e was calculated using the formula presented by Asquith et al., (2004)

$$\phi_e = \phi_{avg}(1 - V_{sh}) \quad (1)$$

where ϕ_{avg} is the average porosity and can be calculated as

$$\phi_{avg} = \sqrt{\frac{\phi_{density} + \phi_{NPHI}}{2}} \quad (2)$$

where $\phi_{density}$ is density porosity and ϕ_{NPHI} is neutron porosity. The ϕ_{NPHI} is determined directly from neutron log and generalized formula for $\phi_{density}$ is represented as

$$\phi_{density} = \frac{\rho_{matrix} - \rho_{log}}{\rho_{matrix} - \rho_{fluid}} \quad (3)$$

where ρ_{log} is the density of the respective formation obtained directly from density logs, ρ_{matrix} is the matrix density equal to 2.65 g/cm³ in the case of sands and ρ_{fluid} is the fluid density normally assumed as 1 g/cm³.

For petrophysical analysis, differentiation between formation fluids is a key parameter (Tiab and Donaldson, 2004). The S_w refers to pore volume occupied by water. Different models for calculating S_w such as Archie's equation for clean sand, the Indonesian equation for 'dirty formation' as well as the Dual water are based on the lithology. Thin interbedded shales degrade the quality of C-Interval sand. Therefore, S_w is estimated through the Indonesian equation.

$$S_w = \left\{ \frac{\sqrt{\frac{1}{R_t}}}{\left(\frac{V_{sh}^{(1-0.5V_{sh})}}{\sqrt{R_{sh}}} \right) + \sqrt{\frac{\phi_e^m}{aR_w}}} \right\} \quad (4)$$

where S_w is water saturation, R_t , R_{sh} and R_w are the true, shale and water resistivity of the respective formation obtained from resistivity logs, m and a are the cementation and tortuosity factors normally taken equal to 2 and 1 for sandstones (Guéguen and Palciauskas, 1994).

Seismic Stratigraphy of C-Interval Horizon

Major horizons are identified using synthetic seismograms which also include the prolific sand interval horizons of the Lower Goru Formation. Three major sand interval horizons namely B-Interval, C-

Figure 4. Flow chart diagram of the static modeling procedure in the current study.

Interval, and D-Interval are identified and interpreted in addition to top Lower Goru on the seismic section. The C-Interval horizon was interpreted on the whole seismic 3D cube using horizon mapping. The 2D seismic sections were extracted from the 3D seismic cube at key locations.

Static Models

Static modelling initiated with detailed seismic interpretation of Sawan field in order to delineate the stratigraphy of C-Interval. Two horizons, i.e., Top C-Interval and Top B-Interval were picked and interpreted on the whole 3D seismic cube as a pre-requisite for the reservoir model (Casentino, 2001; Barclay et al., 2008). The initial model is built by adding the interpreted horizons as layers. These layers are carefully designed as they determine the orientation and cell thicknesses of the resulting grids. These grid cells determine the property variation within the grid system and display the results spatially along these layers.

Building a sound structural model is the foundation for a static model. This model was built with standard procedures including, generation of a depth contour map, fault modeling, insertion of well tops

(such as top and base of reservoir) and layering between top and base of the reservoir. Upscaling is a process of averaging attribute values and then assigning a value to each grid cell at the well locations. Each grid cell with assigned value then acts as a starting point for property modeling. Before spatially populating the reservoir properties, or entering into the 3D grid system, it is necessary to scale up the well log properties in order to bridge the gap between resolution of both data-sets. There are different methods typically used for averaging (scaling up) such as the arithmetic mean, harmonic mean and geometric mean methods. Most commonly the, arithmetic mean method is used for scaling up the ϕ and S_w parameters (Baldawi and Buraq, 2015).

The Sequential Simulation Indicator (SIS) is a geostatistical simulation technique applied to a widespread range of data sets and relies on an indicator (variogram aided kriging). When working in a gridding system, SIS computes or estimates a value at a free grid cell by using both input and simulated data. Multiple realizations of a property are generated, which are then assessed for uncertainty with the most appropriate realization. SIS geostatistical simulation is widely used in reservoir modeling to predict variables such as facies (Zhou et al., 2018). The first stage of the process involves the 'Binary Indicator Transform' which transforms all original well data into indicator variables describing

Lithology:

Clastic Rocks Carbonate Rocks

Figure 5. Well-Seismic tie and T-D relationship for well W-5 identifying key seismic horizons and unconformities.

Figure 6. Well correlation between W-4, W-3, W-1, W-5, W-6 and W-2 for facies, S_w and ϕ_c in addition to basic depositional setting.

the probability values. This transformed data is assigned into a simulation grid and random search paths are generated through grid nodes. Kriging and variogram analysis are applied to estimate mean values for the indicator variables at each node. This analysis relies on the values of surrounding data points for each node, the distance of each node to the surrounding data points, variogram parameters, search parameters and property variations (facies variation in this case). The process is repeated

until all the nodes in the grid obtains a value.

The procedure for initiating the Sequential Gaussian Simulation (SGS) process requires the univariate stochastic property values be assigned, then a score transformation to normal distribution is executed assuming the multinormality of the normal scores (Musawi and Jawad, 2019). The multinormal supposition confirms that the provisional spreading at a given site is with standard mean and vari-

ance provided by kriging. Reproduction of normal score values at grid nodes is performed sequentially with kriging using the standard score variogram and zero mean (Isaaks, 1991; Goovaerts, 1997; Deutsch and Journel, 1998). Once all standard scores are simulated, they are back-transformed to their original values. Two reservoir properties, i.e., φ_c and S_w were modelled using this simulation method in a 3D domain.

Variogram Modelling

The variogram is calculated using the following equation (Cressie, 1993; Khan et al., 2016).

$$\gamma(h) = 0.5E[Z(X+h) - Z(X)]^2 \quad (5)$$

where the semi-variance is denoted by $\gamma(h)$, expectation by E , location by X , sampling distance or distance of separation by h , and observed value by Z . The relationship amongst the experimental values and their scatter is measured by the expression in equation (5).

Since the variogram shows the variability between sample pairs with respect to h the distance therefore leads to zero (i.e., $h > 0$) and the variability should also be zero. If the variability value is greater than zero (i.e., $\gamma(h) > 0$) then the remaining value is known as the nugget effect (C_0). The Sill (S) is defined as, $C + C_0$, where, C is treated as S provided C_0 is zero.

Numerous possible variogram model types can be applied to these data sets; the most basic and common types are the spherical, linear and exponential models (Gringarten et al., 1999; Shamo et al., 2012). For the majority of this data, any one of the basic models (spherical, linear and exponential) will produce an acceptable result. As such, the spherical model has been selected for this study.

The expression for the spherical type model is given below,

$$\gamma(h) = C_0 + (C - C_0) \left[\frac{1.5h}{\alpha - 0.5\left(\frac{h}{\alpha}\right)} \right] \quad (6)$$

where α is the range, C_0 is the nugget effect and C is the sill of the variogram.

Nearly all the gridding techniques require a weighted average approach to intelligently predict values at the grid nodes between the sample locations. In this study, a weighted linear average is used and is given below with the expression for T .

$$T = w_1g_1 + w_2g_2 + w_3g_3 + \dots + w_mg_m \quad (7)$$

where T is the estimator, $w_1, w_2, w_3, \dots, w_m$ are the weighting factors and $g_1, g_2, g_3, \dots, g_m$ are the property values at the well locations. The weighting factors were estimated using the kriging technique. Kriging is based on interpolation by estimating the property at unknown location within a grid taking into consideration the spatial variability in the property. Therefore, it requires use of a variogram model to estimate the variability within the data set in order to determine the weight factors.

The kriging matrix is defined below as,

$$\begin{pmatrix} \gamma_{(1,1)} & \dots & \gamma_{(1,X)} & \lambda \\ \cdot & \dots & \cdot & \lambda \\ \cdot & \dots & \cdot & \lambda \\ \cdot & \dots & \cdot & \lambda \\ \gamma_{(N,1)} & \dots & \gamma_{(N,X)} & \lambda \\ 1 & \dots & 1 & 0 \end{pmatrix} \begin{pmatrix} w_1 \\ \cdot \\ \cdot \\ \cdot \\ w_N \\ 1 \end{pmatrix} = \begin{pmatrix} \gamma_{(1,X)} \\ \cdot \\ \cdot \\ \cdot \\ \gamma_{(N,X)} \\ 1 \end{pmatrix} \quad (8)$$

In above expression, γ stands for spherical variogram model, λ for Lagrange multiplier so that the sum of weights is equal to one ($\sum w_m = 1$), N is the number of data points, and X is the location, where the property value is required.

Multiple realizations are made for the current work (facies distribution, φ_c and S_w distribution) where variograms were generated for use in interpolation using the kriging method. Variograms were constructed in major, minor and vertical directions as shown in Figs. 7a and 7b for φ_c and S_w respectively and used in kriging method for interpolation through the 3D network. The variogram parameters used are shown in Table 2.

Acoustic Impedance Inversion

Seismic inversion plays a significant role for the petroleum sector to reduce the uncertainties inherent in exploration for oil and gas. Most of the exploration and production sector rely on seismic inversion methods to generate a detailed view of subsurface geology. Seismic inversion techniques convert reflectivity data that represents an interface property into a layer property of a rock (Barclay et al., 2008). Inversion is a method for prediction, calculation and inferencing physical parameters from real data (Sen, 2006). The model-based inversion is a robust way of estimating impedance from seismic. It uses a 'Generalized Linear Inversion' algorithm that modifies the initial geological model until the calculated trace model matches the observed seismic within some acceptable limits (Gavotti et al., 2013). In order to build an accurate initial model, the interpreter must have a good geological knowledge of the study area. The generalized linear inversion algorithm is based on an objective function that calculates misfit error between the predicted model and the observed seismic traces.

$$j = w_a(C - WT) + w_b(G - HT) \quad (9)$$

where C represents seismic data, W is the extracted wavelet, G is initial guess model, H is an integration operator and w_a, w_b are weights. The statistical wavelet has been derived from seismic data within a defined window ranging from 1,900 to 2,400 ms with a wavelength measuring 200 ms and zero phase.

Results and Discussion

As a first step in the development of 3D static models, the top and bottom of the reservoir should be positively identified on the seismic data. In the next step, the reservoir parameters obtained from well data analysis will be used as a constraint for the static models prepared from 3D seismic data. Time-depth relationship has been developed by generating a synthetic seismogram as shown in Fig. 5. The well tops were displayed on the seismic section to identify individual horizons for interpretation.

Figure 7. (a) Variogram models in both major and minor directions for ϕ_e ; (b) Variogram models in both major and minor directions for S_w .

Table 2. Petrophysical properties of the C-Interval Sand utilizing the available well log data

Water Saturation				
Direction	Type Variogram	Nugget	Sill	Range
Major direction	Spherical	0	0.998	2748
Minor Direction	Spherical	0	0.998	2143
Vertical	Spherical	0.043	0.951	63
Effective Porosity				
Direction	Type Variogram	Nugget	Sill	Range
Major direction	Spherical	0	0.998	2936
Minor Direction	Spherical	0	0.998	2539
Vertical	Spherical	0.046	0.953	65

Well Logs Data Analysis

Wireline log analysis is typically used to evaluate subsurface geological conditions and to estimate reservoir characteristics while in this study they also facilitate the identification and quantification of reservoir fluids (Ali et al., 2018). The estimation of petrophysical properties from wireline logs assist in the interpretation of a reservoir's lithology and improves the study of reservoir characterization (Fitch et al., 2015). A comprehensive petrophysical analysis for the Sawan field were performed to estimate key petrophysical properties such as V_{sh} , ϕ , S_w etc. and to identify individual reservoir compartments. The averaged results of the well logs analysis are presented in Table 3. Potential gas zones can be identified by triple combo wire-

Table 3. Variogram parameters for the simulation

Well Name	Depth (m)	V_{sh} (%)	ϕ_e (%)	S_w (%)
W-1	3252 – 3319	17	13	47
W-2	3280 – 3305	24	10	55
W-3	3240 – 3260	21	9	60
W-4	3260 – 3290	20	10	50
W-5	3267 – 3323	9	12	45
W-6	3263 – 3325	9	13	47

line logs response such as low-medium values of GR, high resistivity values, low ρ and ϕ_{NPHI} values. The petrophysical properties of the C-Interval sands are delineated from the available wireline logs in W-1, W-2, W-3, W-4, W-5 and W-6 as shown in Fig. 6.

Table 3 shows the various calculated parameters from the suite of well-log data. The prolific C-Interval sand encountered at different wells within the study area show good effective reservoir properties. In well W-1, the C-Interval sand is encountered with maximum thickness of 199 m (Fig. 6). Based on our petrophysical analysis a 67 m thick net pay zone of clean sand can be delineated, with depth ranging between 3,252 and 3,319 m. This sandy zone exhibits a smaller percentage of V_{sh} (17%), ϕ_e (13%), and an economic percentage of pores filled with hydrocarbons (53%). This highly porous (total porosity 18%) thick pay zone has a substantial hydrocarbon saturation and qualifies as an excellent reservoir (Rider, 2002). Well log analysis results of other wells such as W-2, W-3, W-4, W-5 and W-6 also shows a presence of significant sand bodies having ϕ_e ranges from 9 to 13% and S_w at reservoir interval are 45 to 60%.

In addition, the well correlation presented in Fig. 6 provides insight on the depositional trends of the C-Interval. The base of the C-Interval is dominated by shales and shaly sands whereas its upper section appears to be sand prone as seen in Fig 6. Indications are that the C-Interval is deposited in a regressive environment where the litholo-

Figure 8. Core and lithologies description for well W-7.

gies moves seaward (both sand and shale). It is also observed that the lithologies shale out towards the west and southwest, thus confirming the east to west depositional direction. The sand horizons are attributed to the shale content increasing towards southwest with decreasing ϕ_c . The decrease in shale content with an increase in ϕ_c is observed in the northeast direction. The available core description from well W-7 suggest different lithologic properties as shown in Fig. 8. The top of C-Interval (between depths 3,405 and 3,470 m) is characterized by very coarse to medium grained, poorly to moderately sorted clean sandstone (referred as Sand facies in Fig. 6). Below the clean sandstone (between depths 3,470 and 3,538 m), very fine to medium grained moderately hard to very hard, highly carbonaceous sandstone is interlayered with moderately hard, platy, sub fissile, carbonaceous and micaceous shale and moderately hard to hard, slightly calcareous and carbonaceous siltstone (collectively these lithologies termed as shaly sand facies). Below depth 3,538 m, siltstone is interlayered with soft to firm, glauconitic shales (these lithologies are termed as shale facies; Fig. 8).

Seismic Characteristics of C-Interval

The key seismic horizons including C-Interval are identified through synthetic seismic correlation. The top of the C-Interval is recognized by a bright reflection due to the occurrence of sandstone in the upper part, where it generates a significant impedance contrast with the shales of the Upper Goru Formation. As a whole, the Lower Goru Formation was deposited in a deltaic setting over a ramp resulting in the deposition of interlayered sandstone and shales (Ahmed et al., 2004; Munir et al., 2011). An example of diagonal seismic cross section from 3D seismic is presented in Fig. 9. The early C-Interval deposition was dominated by regressions resulting in the deposition of offshore bars (Ahmed

et al., 2004) (here referred as ‘regressive sand bodies’). These sand bodies are positively identified on the seismic section by the thickening (broadening of seismic reflection patterns) within the C-Sand Interval as seen in Fig. 9. The regression possibly generated incision in the underlying sediments, which were later transported and deposited as regressive sand bodies. The regressive sand bodies have preferably flattened and bright bases due to the impedance contrast with the underlying sediments.

In order to obtain the depositional style and prolific sands in the C-Interval, seismic sweetness attribute has been applied. The results are presented in Fig. 10 in correlation with the diagonal seismic section extracted from 3D seismic cube. The sweetness slice highlights some significant features (yellow-red color) within the C-Interval. One of the most significant features on the map is the coastline identified by the green-purple border (Fig. 10). This represent the coastal onlaps for the prograding sand wedge of the C-Interval. The further drop in sea level is believed to generate incision in the older sediments. The incision reworked the sediments and transported them basinward in the form of “sand bodies” which are regressive by nature and deposited under forced regression (Fig. 10). The isolated bright colored attribute near the interpreted coastline represents the presence of sand and are interpreted as channel bars as seen in Fig. 10. This suggests the presence of feeder channels for the regressive sand bodies as highlighted in Fig. 10. The C-Interval horizon also show variable thickness on the seismic section (Fig. 11). The thickness of the horizon decreases towards the northeast due to the presence of coastline and increases southwest towards the shelf margin forming a regressive body. The increase in thickness is indicated by the broad amplitudes on the seismic section as seen in Fig. 11.

Figure 9. Example of an interpreted section with key seismic horizons obtained as a diagonal slice from 3D seismic cube.

Figure 10. Interpreted seismic sweetness attribute for the C-Interval of Lower Goru Formation. The figure highlights the location of sand bodies and possible coastline in addition to key seismic horizons.

Figure 11. Seismic characteristics of C-Interval of Lower Goru Formation. The sand bodies within the formation show flat bases due to the significant acoustic impedance contrast with B-Interval.

3D Facies Model

In order to build 3D facies and property models, the layering of the initial grid is required to make a grid skeleton. These layers are inserted in the initial grid at regular depth intervals as shown in Fig. 12. The GR log is calibrated with known lithologies to define specific lithofacies at well locations. Three facies are defined namely sand, shaly sand and shale (as discussed in Section 4.1). These facies logs were scaled up and distributed through SIS. Figure 13 shows a 3D view of the resultant facies model. Modeling results indicate that V_{sh} increases towards the southwest direction which is consistent with the more basinward setting of the reservoir (Ahmed et al., 2004; Munir et al., 2011). The dominant sand facies are distributed in the northeast direction along the interpreted coastline and marginal setting. The northeastern portion is characterized as a prolific sand facies as depicted in Figs. 6, 9, 10 and 13.

3D Effective porosity (ϕ_e) Model

A three-dimensional view of ϕ_e model of Sawan field is shown in Fig. 14. The SGS method was used to estimate reservoir porosity beyond wells locations. The map shows good

Figure 12. Defined structural layers for reservoir static model.

Figure 13. Resulting facies model after sequential indicator simulation.

Figure 14. Resulting ϕ_e model after sequential Gaussian simulation.

ϕ_e values at some region which ranges from 8 to 16% and indicate that the wells are located within good ϕ_e zones. For a detailed visualization of the ϕ_e distribution in subsurface, a cross section has been drawn as shown in Fig. 14 oriented from northeast to southwest direction. The 3D view depicts that C-Interval is characterized by higher ϕ_e range (16%) towards the northeastern side, indicating that the reservoir holds economical quantities of hydrocarbons. This zone is correlated with clean shelfal and coastal sand deposits. However, the ϕ_e decreases towards southwest with range 0 to 5% which suggests that the chances of economical production to be pessimistic, as this zone is correlated with shelf and basinal settings where shale has accumulated.

3D Water Saturation (S_w) Model

A three-dimensional S_w model gives a direct indication about the percentage of hydrocarbons contained by the formation. For a prolific zone of interest, interpreter search out those locations where low S_w and high ϕ_e are present. Figure 15 shows a computed spatial distribution of S_w in the study area with low S_w around well locations. A cross section of S_w from northeast to southwest direction clearly reveals a subsurface distribution of S_w ranging from 40 to 50% in the study area.

Model Based Inversion

Seismic impedance inversion is applied to the 3D seismic cube with an example of extracted impedance section provided in Fig. 16. In general, shale horizons exhibit low seismic impedance with sand horizons having high seismic impedance with the exception of the C-Interval. The low impedance of C-Interval is attributed to the accumulation of clean sands with the presence of hydrocarbons (gas). Furthermore, probable gas sand facies were identified within the C-Interval (identified by green color patches within the C-Interval, Fig. 16). The model based inversion resolved anomalous zones with low impedance values ranging from 7,000 to 9,000 (m/s)(g/cc) in the southern compartment as shown in Fig. 16. It is important to mention that seismic impedance inversion is used here in order to improve the confidence level of our results from static modelling (SIS and SGS) to confirm the presence of gas sand facies for prospect generation. Similarly, the results extracted through sweetness seismic attribute have highlighted the presence of possible anomalous sand bodies, where our static modelling (SIS and SGS) results have shown good ϕ_e and low S_w values. The seismic post stack impedance inversion can be utilized to extract spatial distribution of reservoir properties e.g., ϕ via

Figure 15. Resulting S_w model after sequential Gaussian simulation.

geostatistical relationships (Ali et al., 2018), but the focus of this study is on static modelling to obtain the spatial distribution of different complex reservoir properties i.e., ϕ and S_w . Furthermore, except porosity the spatial distribution of reservoir properties like S_w via seismic post stack impedance inversion can be highly questionable (Ali et al., 2019), however, that is not the case for static modelling.

Overall Significance of the Study

This study helps to improve the understanding of heterogeneities in spatial distribution of important reservoir properties ultimately leading towards better 3D subsurface reservoir characterization. The techniques presented in this study have been applied to various oilfields in western Africa (Niger delta), Egypt, Iran and China to overcome the reservoir complexities and for the optimization and development of producing fields.

According to Adeoti et al. (2014) and Adelu et al. (2019), the appli-

cation of SIS and SGS techniques provided realistic results in the Niger delta basin - one of the most productive hydrocarbon belts of the world with the Agbada formation having commercial accumulations of hydrocarbons. The presence of intercalations of sand shale and structurally deformed subsurface strata induced extreme heterogeneities in the Agbada formation. In order to realistically image these heterogeneities, 3D static modelling has been applied for estimation of discrete and continuous complex reservoir properties. Similarly, the application of static modelling successfully captured the reservoir (sandstone with thin streaks of shale) complexities in the South Umbarka area, Western Desert, Egypt and enhanced the recovery rate of the field (Abdel-Fattah et al., 2018).

Furthermore, a study in Hendijan oilfield in southern Iran showed a high confidence level for the results of SGS and SIS studies on subsurface development in complex reservoir scenario (Amanipoor, 2019). With the help of these techniques, the Ghar and Sarvak formations have been identified as promising reservoirs in the field. Furthermore,

Figure 16. Seismic impedance inversion model and well logs example.

mapping of reservoir heterogeneities using the above-mentioned techniques for the Shenvsi oilfield (Dagan oilfield) in the south of Cangzhou City China (Al Rassas et al., 2020) showed promising results. Property modelling via SGS techniques for ρ_e , S_w , δ and net to gross ratio confirmed, that the Es1 formation in block Nv32 is a prolific hydrocarbon reservoir. In addition, the use of sequence stratigraphic principles (in siliciclastic sediments) combined with static modelling have highlighted the potential linkage between reservoir properties and their depositional settings within the context of hydrocarbon exploitation. Overall, the techniques applied in this study appear to be useful for the analysis complex oil and gas basins with similar geological settings.

Conclusions

The study highlighted the reservoir potential of C-Interval within the Sawan area utilizing static modelling procedures in a 3D domain. Well logs and 3D seismic data coupled with SIS and SGS predicted the facies models and their reservoir potential in areas away from well locations. The seismic sweetness attribute successfully highlighted the paleo-coast line along which thick clean sand deposits. These sand deposits are ideally part of the prograding sands of the C-Interval horizon. The sweetness attribute also highlighted the regressive sand bodies forced basinward having apparent feeder channels indicated by isolated sand bars beyond the interpreted coastline. Modeling results indicate that the northeastern half of the investigated area appears to be sand prone with higher ρ_e and lower S_w , whereas, the southwestern half is dominated by shaly sands and shales with lower ρ_e and higher S_w . The forced regressive sand bodies resulting from transgressive-

regressive cycles are interpreted as key locations for the accumulation of hydrocarbons. Seismic impedance inversion highlighted the C-Interval as a low impedance horizon due to the clean sands saturated with hydrocarbons. As such, low impedance locations within the C-Interval provide prospects for future hydrocarbon exploration and development.

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