



## Identifying the Potential in a Heterogeneous Reservoir Using Decline Curve Analysis Concept Augmented by Geostatistical Inversion: A Case Study from Cambay Basin, India

Satyajit Mondal<sup>1</sup>, Sanjai Kumar Singh<sup>2</sup>, Kishori Lal<sup>2</sup>, Anand Kumar<sup>3</sup>, Uma Goyal<sup>4</sup>, T.K.Mathuria<sup>4</sup>

**Key Words:** Geostatistical Inversion, Exponential Decline, Drainage Radius, Well Performance

### Summary

Reservoir Characterization of a heterogeneous reservoir like Kalol pays in Wadu-Paliyad field has been a big challenge due to presence of coal layers which has large impact on seismic amplitudes. It was observed that high amplitude contrast due to coal layers was masking the signature of reservoir unit. In addition to that discrimination of reservoir and non-reservoir at log scale and seismic scale based on p-impedance and Vp/Vs was also difficult due to overlap of these properties. To overcome this problem and address uncertainty involved in deciphering pay sand distribution of Kalol formation, Pre stack Geostatistical Inversion (GI) was carried out. The present paper deals with K-IX sand in the eastern part of Wadu-Paliyad field. The main challenge in this part was to find suitable areas for further development as nearby wells were already water flooded due to Water Injection (WI). A synergistic approach combining GI, exponential decline method and well performance analysis was adopted to reduce the uncertainty. In this work, we have applied constant-pressure solution of the diffusivity equation for a closed, circular reservoir in the form of an exponential decline equation to estimate drainage radius of the wells and permeability of pays in the prospective areas to identify unexploited areas. Few development locations already drilled based on this study have shown encouraging results both in well log and production performance.

### Introduction

Nowadays seismic inversion is a bridge between geology, seismology, well-logs and rock-physics. In modern days where easy oil is the word of the past, development of thin reservoirs, beyond seismic resolution require combining well data and Pre stack inverted seismic for proper understanding and reservoir facies distribution.

The common techniques for seismic inversion are deterministic inversion and geostatistical inversion. Deterministic inversion can broadly be divided into post and pre stack inversion. Post stack inversion provide estimation of only one elastic property (P-

impedance). On the other hand, Pre stack inversion can be used to solve for multiple elastic properties such as P-impedance, S-impedance, Vp/Vs and density if seismic gather data has sufficient offset/angle range (more than 350). Geostatistical inversion is defined as a mathematical approach that solve inversion problem combining geostatistical simulation with deterministic inversion. However, the deterministic approach can only provide a solution within seismic bandwidth, while the geostatistical algorithm may provide fine scale details below the resolution of seismic bandwidth (Filippova, Kozhenkov and Alabushin, 2011). In brief, Geostatistical Inversion integrates high resolution well data with low resolution 3D seismic and provide a reservoir description with high vertical detail both near and away from the well bore (Chen.J. et. al. 2017).

Present study pertains to the K-IX pay of Wadu-Paliyad field. Majority of the Kalol pay zones in Wadu-Paliyad field are below 10m of thickness and are of sub-seismic resolution because dominant frequency in seismic data is around 19-25 Hz. Rock physics analysis reveals that no facies other than coal can be discriminated on the basis of P-impedance even at log scale implying that deciphering reservoir facies through post stack inversion is not feasible. In order to overcome this challenges, Pre-stack geo-statistical inversion (GI) was carried out to delineate and map the pay sands in coal dominated sequence of Kalol formation (Mishra, P.K et. al. 2017).

The overall objective of this study was to identify unexploited part in the study area applying classical reservoir engineering methods like exponential decline method and well performance analysis.

### Geological Setting and Stratigraphy

The Cambay Basin is an elongated and narrow intracratonic rift graben oriented in NNW-SSE direction (Figure-1). This basin was formed during Early Cretaceous due to rifting along Dharwarian orogenic trends during northward migration of Indian plate after its breakup from Gondwanaland in Late Triassic-Early Jurassic time. The rift-drift transition

\* GEOPIC, ONGC, Dehradun-248195, UK, India, Email: mondal\_satyajit@ongc.co.in

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phase of Indian plate witnessed volcanic event in western India during K/T time which is attributed to the movement of Indian plate over the reunion hot spot. During initial phase of rifting, faulting had created numerous topographic lows and adjacent scarps. The first sedimentary system led to deposition of Olpad formation in Alluvial fan complex followed by transgressive facies Cambay Shale. The overlying Kalol formation is the result of the major longitudinal delta system in the Ahmedabad-Mehsana Block and is characterized by a thick arenaceous unit with alternating Shale and Coal. It consists of two sand dominated members known as Wavel and Sertha, separated by Kansari Shale. The dominant lithologies, which make up this formation, are sandstone, silty shale, siltstone, sideritic claystone, carbonaceous/coaly shale and coal. The Kalol Formation is overlain by the transgressive Tarapur Shale which provides effective cap in the basin. The generalized stratigraphy of the Cambay basin is given in Figure-2.

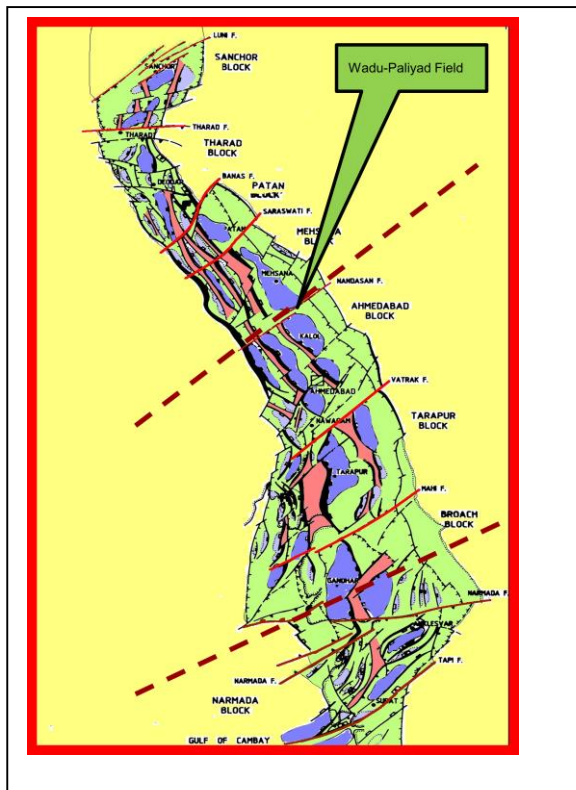


Figure 1: Tectonic Map of Cambay Basin showing Wadu-Paliyad Field

Figure 2: Generalized Stratigraphy of Cambay Basin

Reservoir Characterization

An exhaustive study incorporating old Geological & Geophysical (G&G) data and advanced interpretative techniques have been carried out in the present study. In study area, K-IX unit is developed between two prominent coal markers at the top and bottom. The lithofacies vary from silty shale to siltstone to fine / medium grained sandstone. The workflow adopted for this work is given in Figure-3. A detailed Well log correlation in study area shows deepening of stratigraphic unit towards south. In an attempt to decipher reservoir facies distribution, Sand / Silt Isolith maps have been prepared incorporating all the drilled well data. In order to decipher reservoir facies distribution, various seismic attributes like Seisfacies, Impedance, RMS & Mean Amplitude, Spectral decomposition and Sweetness attribute have been generated. The integration of Sand/Silt isolith maps with spectral decomposition attribute suggest a N-S trending channel feature corresponding to K-IX pay sand (Figure-4). The focus area for this study was in the southern and eastern part which is marked as red circles in Figure 4.

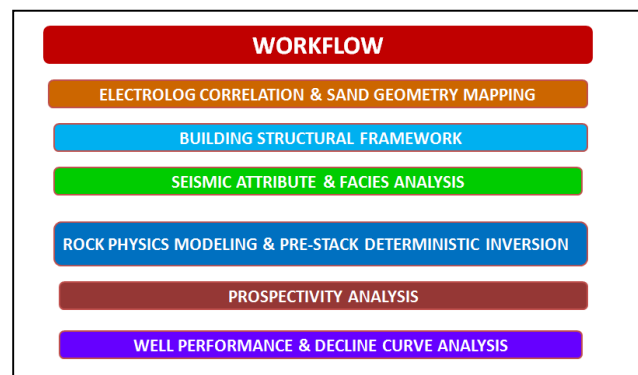
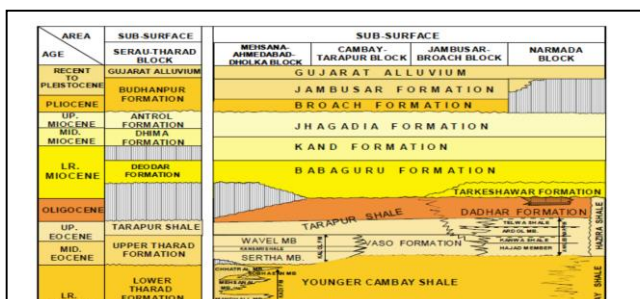


Figure 3: Reservoir Characterization & Field Development Workflow



Rock Physics Modeling (RPM) carried out in Wadu area indicate that coal and non-coal can only be discriminated on the basis of P-impedance even at log

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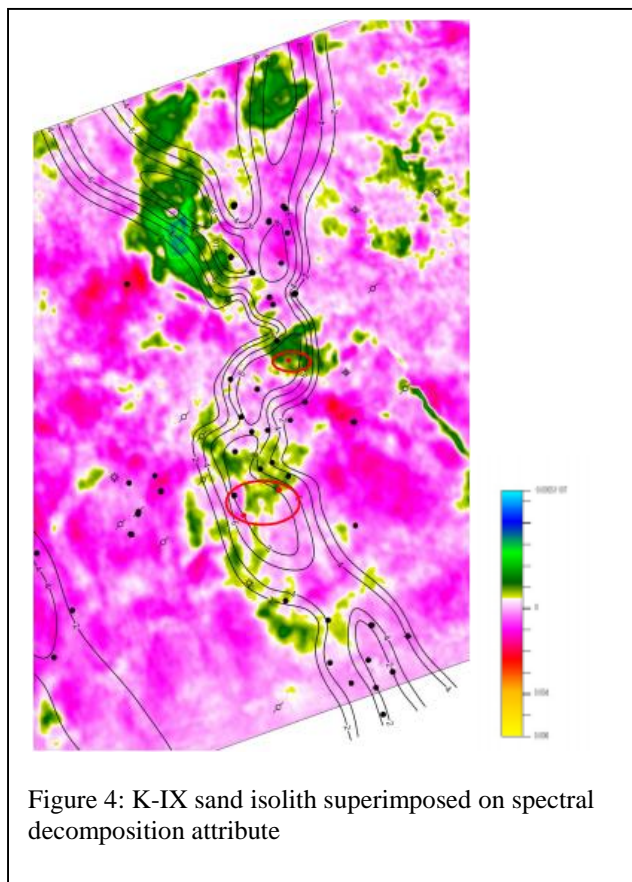


Figure 4: K-IX sand isolith superimposed on spectral decomposition attribute

scale. In seismic bandwidth, there is a large overlap of pay and non-pay facies as shown in the cross plot and histogram (Fig. 5a). Some pay facies points are falling in low  $V_p/V_s$  and are mainly contributed by thick pay zone (>21 m) of a particular well. This shows only thick pay zones (>20 m) can be deciphered from deterministic inversion results. But these plots generated using up scaled logs to 1 ms show hydrocarbon facies with lower  $V_p/V_s$  with little overlap (Fig. 5b). This acted as motivation for pre-stack geostatistical inversion.

Pre-stack geo-statistical inversion (GI) was carried out to delineate and map the pay sands in coal dominated sequence of Kalol formation. GI was preceded by pre-stack deterministic inversion which could not fulfill the objective of discriminating reservoir from non-reservoir facies. Pre-stack geo-statistical inversion was carried out to investigate the possibility of mapping thin pay sands within known limitations of input data (Fig.6a to Fig.6b). This study, could bring out most probable pay sands distribution which was supported by other G&G studies and reasonable blind wells validation. Final outcome of GI study was generation of Hydrocarbon Probability (HCP) map for the pay sand and same is depicted in Figure 7. From Figure-7 it is evident that HCP in the southern

prospective area is 40-50% and in central east area is around 60%.

Though HC probability map generated based on GI identified area with high probability of reservoir facies, however to identify suitable locales for further exploitation, it is necessary to calculate the drainage area of the existing wells and analyze performance of nearby wells. The following section describes the classical reservoir engineering approach adopted in this work.

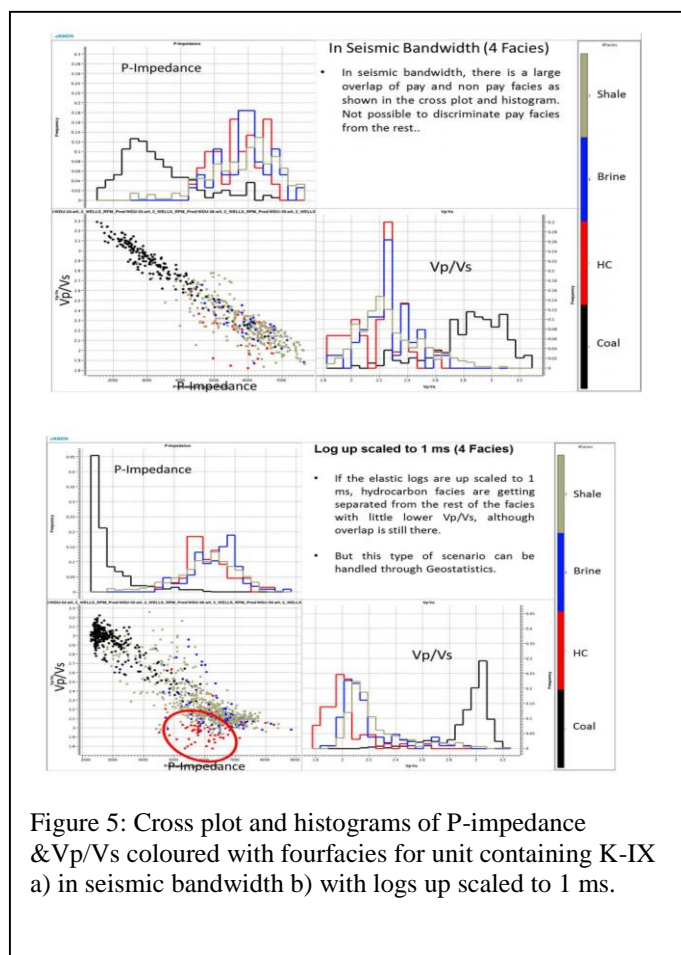
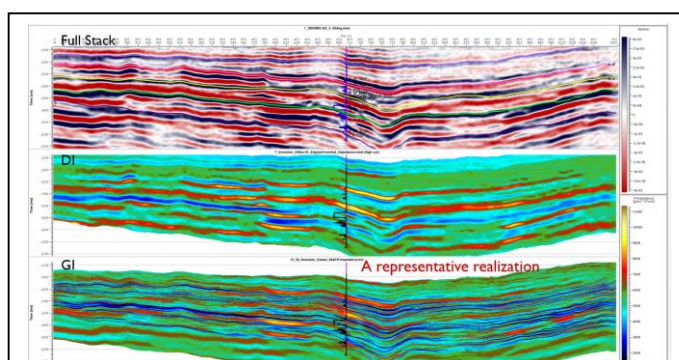


Figure 5: Cross plot and histograms of P-impedance &  $V_p/V_s$  coloured with four facies for unit containing K-IX a) in seismic bandwidth b) with logs up scaled to 1 ms.



radius of the wells and permeability of the zones in the study area.

**Estimation of Drainage Radius and Reservoir Permeability:**

The concept of Drainage Radius (DR) is important to understand the reservoir volume contributing to the well. In field development work, well drainage radius and reservoir permeability are key parameters for reservoir performance optimization and identify new locales. The primary method of estimating drainage radius and permeability is pressure transient analysis (PTA). However in absence of PTA, these parameters could be estimated from production data that satisfies criteria of exponential decline.

An exponential decline curve represents production response from a reservoir of limited extent which is producing from an essentially constant compressibility system where total hydrocarbon in drainage area influences the performance history (Poston et.al. 2008). This observation was initially observed by Arps (1956) and Brons (1963) and theoretically verified by Fetkovich (1980), who showed that the solution of diffusivity equation for constant pressure, boundary dominated depletion condition is of the same form as the Arps equation for an exponential decline curve (Poston et.al. 2008). The following section describes constant pressure solution of diffusivity equation and its relation to exponential decline and steps to estimate reservoir drainage area and permeability (Poston et.al.2008).

**The Constant Pressure Solution of Diffusivity Equation and Exponential Decline:**

Fetkovich expressed the van Everdingen-Hurst constant-pressure solution to the diffusivity equation for a closed, circular reservoir in the form of an exponential equation (Fetkovich et. al. 1987; Fetkovich et. al. 1980). The solution was developed from Fetkovich (1971) which deals with a method to calculate water influx in closed aquifer.

The rate transient solution for a closed, circular reservoir for the constant, bottom hole flowing pressure in exponential form is as follows:

$$q = \frac{kh(P_i - P_{wf})}{141.2B\mu[\ln(\frac{r_e}{r_w}) - \frac{3}{4} + s]} \exp\left\{\left(\frac{0.00633 kt}{\phi\mu C_t r_w^2}\right) \frac{-2}{(\frac{r_e}{r_w})^2 [\ln(\frac{r_e}{r_w}) - \frac{3}{4} + s]}\right\} \dots\dots(1)$$

Taking the logarithm of both sides, we get the equation 2.

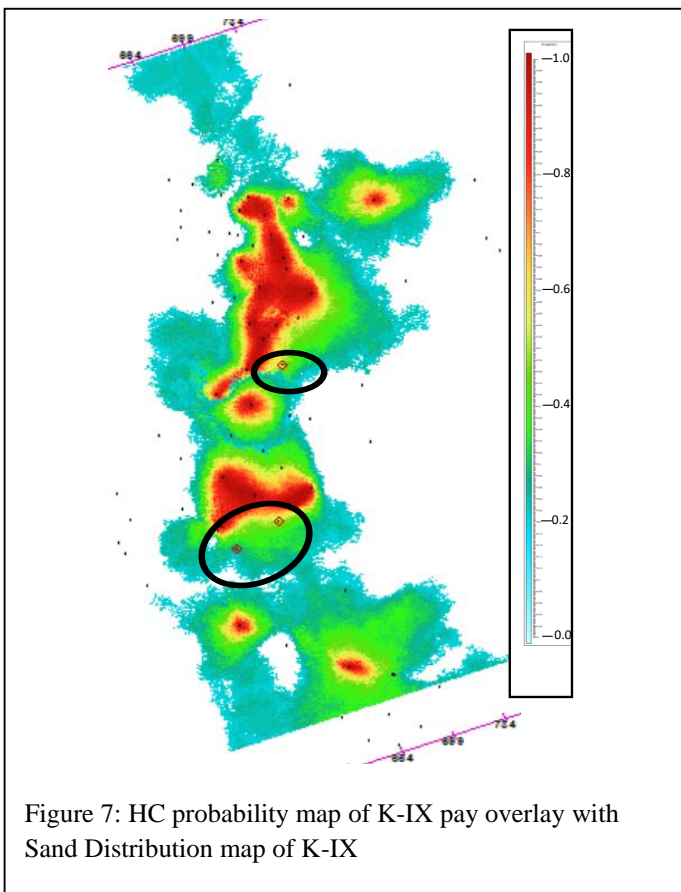


Figure 7: HC probability map of K-IX pay overlay with Sand Distribution map of K-IX

For the present area, one big constrain was lack of pressure history. To overcome this constrain, rate-time data was used extensively to find out the drainage

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$$\ln q = \ln \left\{ \frac{kh(p_i - p_{wf})}{141.2B\mu \left[ \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right]} \right\} - \left\{ \frac{(0.00633 kt)}{\phi \mu c_t r_w^2} \right\} \frac{2}{\left[ \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right]} \dots\dots\dots (2)$$

Now plotting of ln q (STB/D) vs. Time (days) gives a straight line in case of reservoir performing under exponential decline. Comparing Equation 2 with an equation of a straight line, we get

$$\text{Slope } D = \frac{0.0127k}{\phi \mu c_t r_w^2 \left[ \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right]} \text{ fraction/year} \dots\dots\dots (3)$$

$$\text{Intercept} = \frac{kh(p_i - p_{wf})}{141.2B\mu \left[ \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right]}, \text{ STB/D} \dots\dots\dots (4)$$

Substituting Equation 3 and 4 in Equation 1 yield

$$\ln q = -Dt + \ln q_i \dots\dots\dots (5)$$

Where initial rate  $q_i$  is a theoretical value which may not be the same as initial field rate. Equating the expression  $\ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S$  from both side of the equation 3 and 4 gives pore volume of reservoir in units of rcf, as

$$V_p = \phi hA = \frac{5.615q_i B}{D C t (p_i - p_{wf})} \dots\dots\dots (6)$$

Equation 6 indicate that reservoir pore volume or drainage area can be estimated when a continuous decline rate is interpreted from the semilog rate-time plot. Extrapolation of the semilog rate time plot back to initial time when  $t=0$  gives initial producing rate. Equation 6 can be used to calculate drainage radius assuming a circular drainage area. Now rewriting the equation 4 gives reservoir permeability in millidarcies which is as follows

$$k = \frac{141.2qB\mu \left[ \ln \left( \frac{r_e}{r_w} \right) - \frac{3}{4} + S \right]}{h(p_i - p_{wf})} \dots\dots\dots (7)$$

In brief, both drainage area/radius and the reservoir permeability can be calculated if the production decline curve exhibits exponential decline characteristics. However one limitation of this method is that formation damage effect can mask the true formation permeability.

The aforementioned technique was used to calculate the drainage radius of the producing wells in the area of interest and same was used to decide the distance of new locations from existing wells in unexploited area.

Figure 8 shows the exponential decline curve of a well W-B in study area. Table 1 enumerates the reservoir parameters estimated based on aforementioned technique for one well from southern area and two wells from central east area.

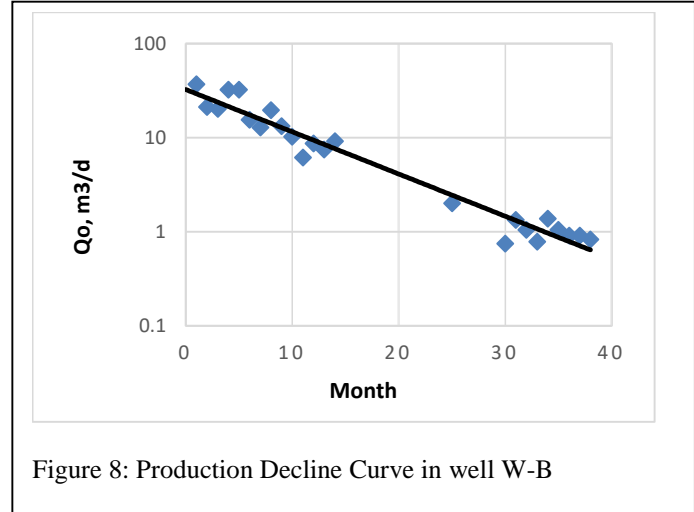


Figure 8: Production Decline Curve in well W-B

Table 1: Reservoir Parameters based on production decline

Well	Drainage Radius, m	K, md
W-B	100	14
P-B	250	43
P-A	307	20

**Well Performance Analysis:**

K-IX sand in Wadu-Paliyad area is overlain by a regional and consistently developed coal of 5 m thickness. In the study area, porosity ranges from 20 - 26% and water saturation ranges from 40-50%. The permeability data reported for K-IX based on pressure transient analysis is in the range of 23-35 md. This reservoir operates under depletion drive. To supplement the reservoir energy, WI was initiated in 1997, when the reservoir pressure depleted to 158 Ksc from initial 167 Ksc (Ahmedabad Asset, Nov 2016). WI was stopped in 2016 due to water breakthrough in most of the producing wells and pressure measured was almost near initial pressure. The WI effect was evident in nearby wells within 3 to 4 years as there was sharp increase in WC preceded by improvement in oil production and same is depicted in Figure-9 and Figure-10. It was also evident that there was reversal in declining oil production trend after onset of water injection at this pay level in the field. The current study

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has been largely supported by this good connectivity depicted by the water injection response suggesting possible extensions of the pay even away from the main producing area where in unexploited area has been identified with encouraging results. As already mentioned the main challenge in this part of reservoir was to find suitable development locations. However, based on the performance analysis, it was evident that pressure was already jacked up in this area. The performance of wells as shown in Figure-11 and Figure-12 also depicts that well performance in the south western part is relatively better than south eastern part.

**Results & Discussions:**

Reservoir characterization of Kalol pays in Wadu-paliyad field is always challenging due to coal effect that dampens seismic signature of the reservoir units. In addition to that, reservoir units below seismic resolution impose more uncertainty in identification of reservoir geobodies. A synergistic approach combining Geostatistical Inversion, Exponential Decline method and well performance analysis was adopted for reservoir characterization of K-IX pay followed by identification of unexploited area for Wadu-Paliyad field (Mondal S. et. al. 2017, Mondal S. et. al. 2018). Few wells already have been drilled. In these wells, well log recorded is very encouraging and production performance also shows good potential. Figure-13 shows correlation of one new well with nearby well. This will not only lead to enhancement of production from the reservoir but also open new area for future development.

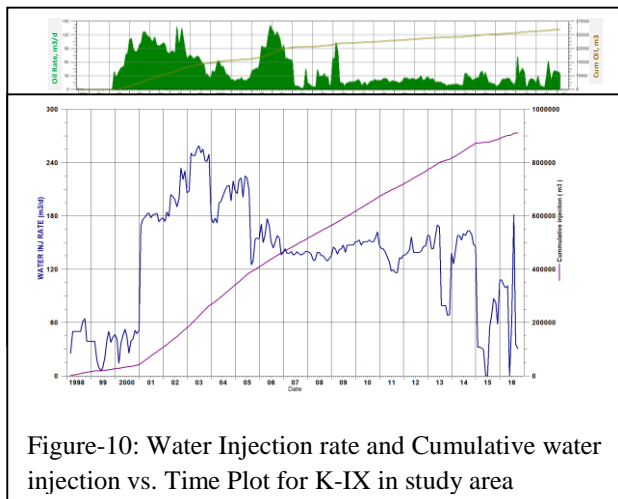


Figure-10: Water Injection rate and Cumulative water injection vs. Time Plot for K-IX in study area

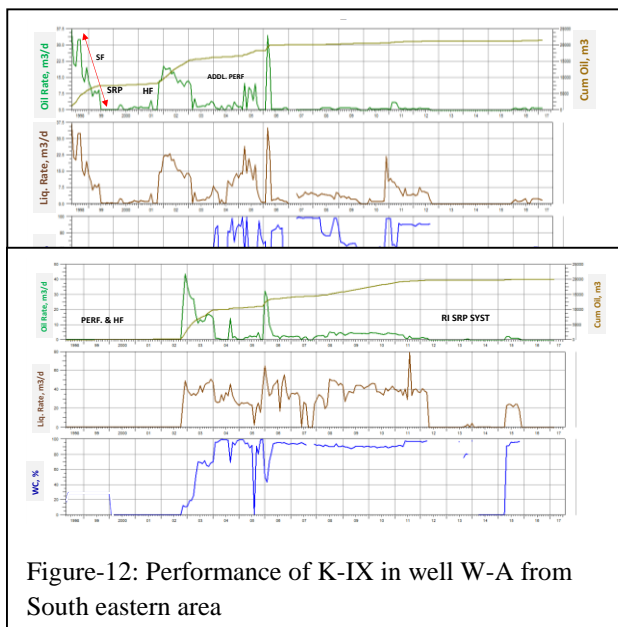


Figure-12: Performance of K-IX in well W-A from South eastern area

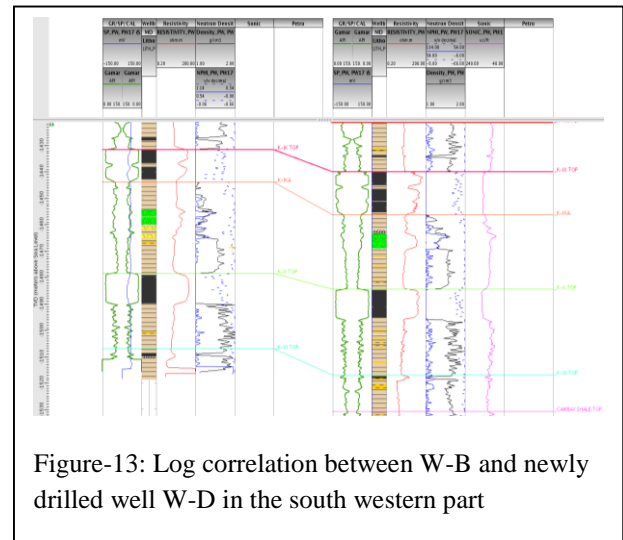


Figure-13: Log correlation between W-B and newly drilled well W-D in the south western part

**Conclusions**

The following conclusions could be made based on the result obtained from this study

1. Applying Geostatistical Inversion in the K-IX sand of Wadu-Paliyad Field demonstrates that improvement in reservoir characterization along with

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addressing uncertainty when reservoir is below the seismic resolution is possible.

2. Applying Constant-pressure solution of the diffusivity equation for a closed, circular reservoir in the form of an exponential decline equation to rate-time data helped immensely to estimate drainage radius of wells and reservoir permeability in prospective areas.

3. The current study has been largely motivated by the good connectivity depicted by the water injection response suggesting possible extensions of the pay even away from the main producing area where in these locations have been proposed and some of them actually drilled

4. The workflow adopted in this study integrating Geostatistical Inversion and Reservoir Analysis has led to identify unexploited area for further development with encouraging results. This will also lead to open new area for development in the southern part of the field.

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**Nomenclature**

q = production rate, STB/day

k=average effective permeability, md

h=reservoir net pay thickness, ft

$P_i$  =initial reservoir pore pressure, psia

$P_{wf}$  =sandface flowing pressure, psia

B= liquid formation volume factor, STB/RB

$\mu$  = reservoir fluid viscosity, cp

$r_e$  =effective reservoir drainage radius, ft

$r_w$  =wellbore radius, ft

s= skin factor

t= time, days

$\phi$  = reservoir average effective porosity, %

$C_t$  =total system compressibility, 1/psia

D= continuous decline rate, 1/unit of time

$q_i$  =initial flow rate, STB/day

$V_p$  =reservoir pore volume, acre-ft

A= drainage area of a well, ft<sup>2</sup>

**References**

- Ahmedabad Asset, Nov 2016. Proposal for Release 3(OP) Development locations 1 each for K-VIII, K-IX and K-V Pay in Wadu-Paliyad Field, Ahmedabad Asset. ONGC Unpublished Report, File No. AMD/SST/Area-I/16th ADB/Prop.2016
- Arps, J.J. 1956. Estimation of Primary Oil Reserves. Trans., AIME 207: 182-191.
- Brons, F. 1963. On the Use and Misuse of Production Decline Curves. The Production Monthly (September) 22-25
- Chen, J., Lin, J., Li, J. Lin, Yu, Li, Y., Bie, J., Wang, Y. 2017. Integrated Reservoir Characterization of Thin Bed Reservoir in Desert Area. Search and Discovery Article#20391
- Fetkovich, M. J. (1980, June 1). Decline Curve Analysis Using Type Curves. Society of Petroleum Engineers. doi:10.2118/4629-PA
- Fetkovich, M.J., Vienot, M.E., Bradley, M.D. and Kiesow, U.G. 1987. Decline Curve Analysis using Type Curves: Case Histories. SPEFE 2(4):636–657.
- Fetkovich, M.J. 1971. A Simplified Approach to Water Influx Calculation- Finite Aquifer Systems. JPT



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23(7): 814-828. SPE-2603-PA.DOI: 10.2118/2603-PA

Filippova, K., Kozhenjov, A. and Alabushin, A. 2011, Seismic inversion techniques: choice and benefits: First Break, v 29/5, p.103-114

Kumar, Anand, Singh, S.K., Soni, A., Lal, K., Chetia, B. 2017. Reservoir Characterisation of Kalol Pays in WADU-PALIYAD Area, North Cambay Basin. ONGC Unpublished Report

Mishra, P.K & Singh, S.K, Soni, A., Kumar, P. Bhagat, S. Chaudhuri, P.K 2017. Geostatistics for Sub-surface Uncertainty Estimation in Wadu-Paliyad area, Western Onshore Basin. ONGC Unpublished Report

Mondal, S., Negi, J.K, Singh S.K., Kumar, A., Lal, K., Singh, D. 2017, Proposal for Release of 5 (OP) Development Locations for K-VI+VII and K-IX Pay in Wadu - Paliyad Field, Ahmedabad Asset. August 2017. ONGC Unpublished Report, File No. ONGC/GEOPIC/INTEG/ADB/1/2017

Mondal, S., Singh S.K., Shukla A.C, Soni, A., Goyal Uma, Kumari Reha. 2018, Proposal for Release of 6 (5OP and 1 WI) Development Locations for K-VI+VII and K-IX Pay in Wadu - Paliyad Area, Ahmedabad Block. North Cambay Basin, September 2018. ONGC Unpublished Report, File No. ONGC/GEOPIC/INTEG/ADB/1/2018

Poston, Steven W. and Poe, Bobby D. 2008. Analysis of Production Decline Curves, first edition. Richardson, Texas: Society of Petroleum Engineers