ASSESEMENT OF RESERVOIR QUALITY ON THE BASIS OF PETROPHYSICAL AND GEOMECHANICAL PROPERTIES FOR KADANWARI-1, 10 AND 11, CENTRAL INDUS BASIN, PAKISTAN

By

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DEPARTMENT OF EARTH AND ENVIRONMENTAL SCIENCES

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ABSTRACT

The main objective of the study is reservoir characterization using Petrophysical and Geomechanical Facies of selected wells from Kadanwari field. Kadanwari Field was discovered in 1989 and was brought to stream in 1995. The field is located on the south-eastern flank of Jacobabad High. 40 wells have been drilled in this gas producing field. Sembar and Lower Goru Shales are presumed source of most of the gas fields in MIB. Digital data in LAS format of wireline open hole logs was used for the study. The evaluation was performed in Kadanwari-1, Kadanwari-10 and Kadanwari-11. Initial well correlation technique was used to identify four Zones of Interest. Petrophysical evaluation and Geomechanical properties computation was performed for these zones. The zones were further categorized in pay zones and non-pay zones. IPSOM was used to perform Facies Analysis, which used Petrophysical and Geomechanical outputs to classify them into four Facies. These facies are ranked from 1 to 4 depending on the quality of the reservoir with 4 being the best and 1 being the worst. Reservoir characterization and classifying it in facies helps getting better flow units and helps during development of the field and workovers. The presence of distinct units with certain Petrophysical and Geomechanical properties help geoscientists establish a strong reservoir characterization. On the basis of Petrophysical Analysis, Zone-2 is the best zone of interest with the cumulative Net thickness of 27.62m in studied wells. Facies-4 is showing maximum thickness in Zone-2 in Kadanwari-10 and Kadanwari-11 whereas in Kadanwari-1, Facie-4 is showing maximum thickness in Zone-4. The combination of Net Pays and Facies Analysis concludes Zone-2 being the best Zone in the wells.

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CHAPTER 1

INTRODUCTION

The area of study is in Central Indus basin which was discovered back in 1989. The main reservoir in Kadanwari Field is Lower Goru of Cretaceous that is encountered at the depth of 3250m, that came to be the first deep commercial gas discovery. With the development of field through drilling of several wells, more production data was gathered which resulted in the discovery of the reservoirs in different sections. Due to this, new model was generated that resulted in an increase in estimated reserves to be more. (Nasir and Siddique, 2002)

The Kadanwari Gas Field is located in the North-East of Jacobabad High, in Central Indus basin. There are multiple gas fields in the east of the locality occurring in the neighboring country. Due to numerous tectonic activities in the region, multiple structural configurations have been developed. During early Cretaceous period, uplift and erosion occurred in NNE-SSW direction. This lead to right lateral wrench faults in the Late Paleocene period with basement roots. They exhibit flower structure which are orientated in NNW-SSE direction. Finally, in Late Tertiary to recent, the uplifting of Jacobabad high occurred which had an important influence on the Kadanwari Field's petroleum play, creating structural and stratigraphic traps in the area. (Nasir et al., 2007)

1.1 Study Area

Kadanwari field is in Khairpur District of Sindh, in Central Indus Basin, Pakistan. The Geographic is between 27 ° 12' 30" to 27 °2' 30" N and 69 Deg 2' 30" E and 69 Deg 17' 30" (Fig. 1.1).

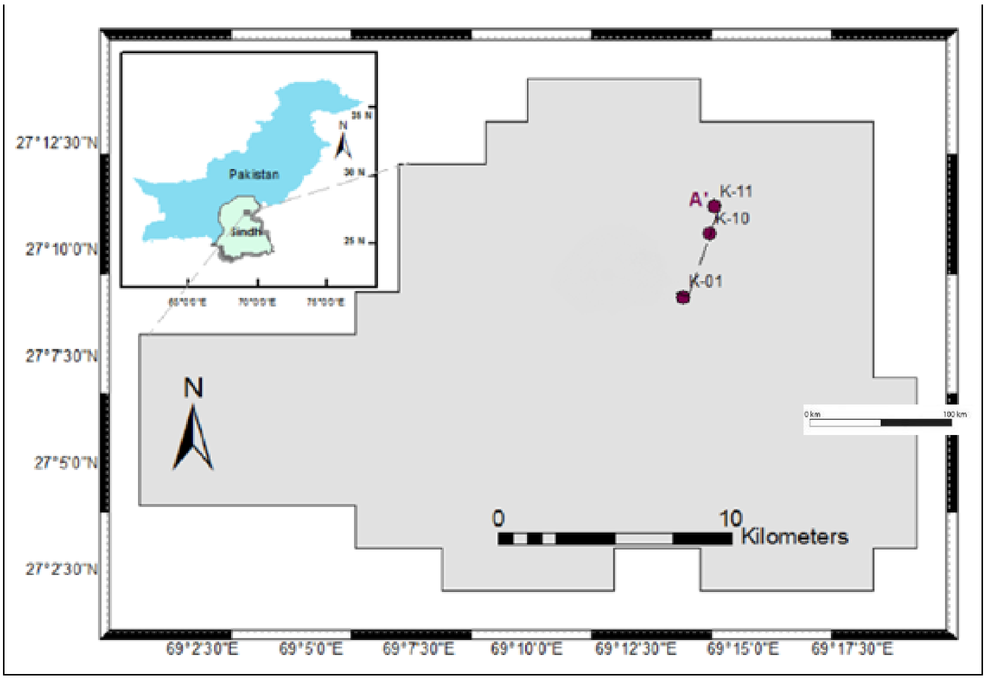

Figure 1.1 Site map of Kadanwari-1, Kadanwari-10 and Kadanwari-11 wells (Khan, 2018).

1.2 Objectives

The main objectives of the study are as follow

i. Petrophysical Analysis of the reservoir in Kadanwari-1, Kadanwari-10, Kadanwari-11
ii. Estimation of Geomechanical properties of the reservoir
iii. Facies analysis based on Petrophysical and Geomechanical Properties
iv. Reservoir Characterization

1.3 Data Obtained for Interpretation

The data provided by DGPC is Formation tops and wireline logs of Kadanwari-01, Kadanwari-10 and Kadanwari-11, which includes the basic Lithology, Porosity and fluid indicator logs. The log suits contain GR and SGR logs, Resistivity logs and Porosity logs that include Density, Neutron and Sonic log. Uranium, Thorium and Potassium concentrations are also available in data.

CHAPTER 2

REGIONAL GEOLOGY

2.1 Regional Geological Setting

Kadanwari gas field is situated on Jacobabad-Khairpur high. Early rifting of Gondwanaland (Paleozoic) that occurred due to rising basaltic magma, squeezed the over-lying Lithosphere, causing divergence and hence normal faults in it. The decrease in thickness of Lithosphere continued that resulted in the swelling of magma and progression of seafloor spreading. The Basement high are extended towards east where they are obscured by desert sands except Khairpur and Sukkur, where carbonates of Eocene age are present. Two major basins of Pakistan are Balochistan and Indus basins, formed by a series of geological events. There are three classifications of Indus basin, namely Upper, Central and Southern Indus Basins.

Kadanwari field is located in Central Indus basin. Sargodha Highs and Pezu uplifts marks the division of Upper and Central Indus basin. In the East, Indian Shield is present whereas marginal zone of Afghanistan is in the west. Central and Southern Indus basin are divided by Sukkur rift. Wulgai formation of Triassic age is the oldest rock in Jacobabad and Mari Kandhkot highs. Major gas fields situated in the area are Kadanwari, Miano and Sawan. Stratigraphic, structural and combination of structural- stratigraphic traps are present in this area. (Kazmi and Jan, 1997). The wrench faults in the field are dividing the field into multiple faulted blocks. The K-01 graben block is bounded by K-10 and K-11 horst blocks in east and west respectively (Fig 2.2). The trapping mechanism is complex and combination of structural dips and sealing faults (Ahmad and Chaudhry 2002).

2.2 Distribution and depositional environment

Sembar and Lower Goru are the assumed source of most of the gas fields in MIB. In Kadanwari, Lower Goru sands form the reservoir and marine shales of Lower Goru and Upper Goru are acting as seal. The sands of Kadanwari are represented by a shoreline estuarine system which is subjected to longshore currents and tidal influence. During the maor deposition, rate of sediments supply was low, due to this depositional trend like shoreline- parallel and shoreline- perpendicular are present. The deposition of D and E sand occurred during high supply of sediments and the shore- parallel depositional trend became dominant. The Paleocoastline was orientated in NE-SW fashion during the deposition of C, D and E sand. (Kazmi and Jan, 1997)

2.3 Aerial Structural Approach

Central Indus basin consists of three main as follow;

i. Punjab Platform
ii. Sulaiman Depression
iii. Sulaiman Fold Belt

2.3.1 Punjab Platform

Punjab Platform is located in the east of CIB. Sedimentary rocks are not exposed on the surface. Tectonically, the Punjab platform is a wide monocline which is dipping towards Sulaiman Depression. Pre-Cretaceous non-orogenic movements moved eastward in Paleozoic and westward, whereas Mesozoic was the result of Indian plate and Eurasian plate collisions. Tectonically, Punjab platform is least affected because it is located well away from the area of collision. (Kazmi and Jan, 1997)

2.3.2 Sulaiman Fold belt

Main tectonic feature in this area of collision zone contains many disturbed anticlinal features. The oldest rocks i-e Wulgai formation of Triassic age outcrops in the area. The major lithostratigraphic differences between Sulaiman Depression and Sulaiman Fold Belt are present in Paleocene/ Eocene. The age identifies facies change from North to South and East to West. (Kazmi and Jan, 1997)

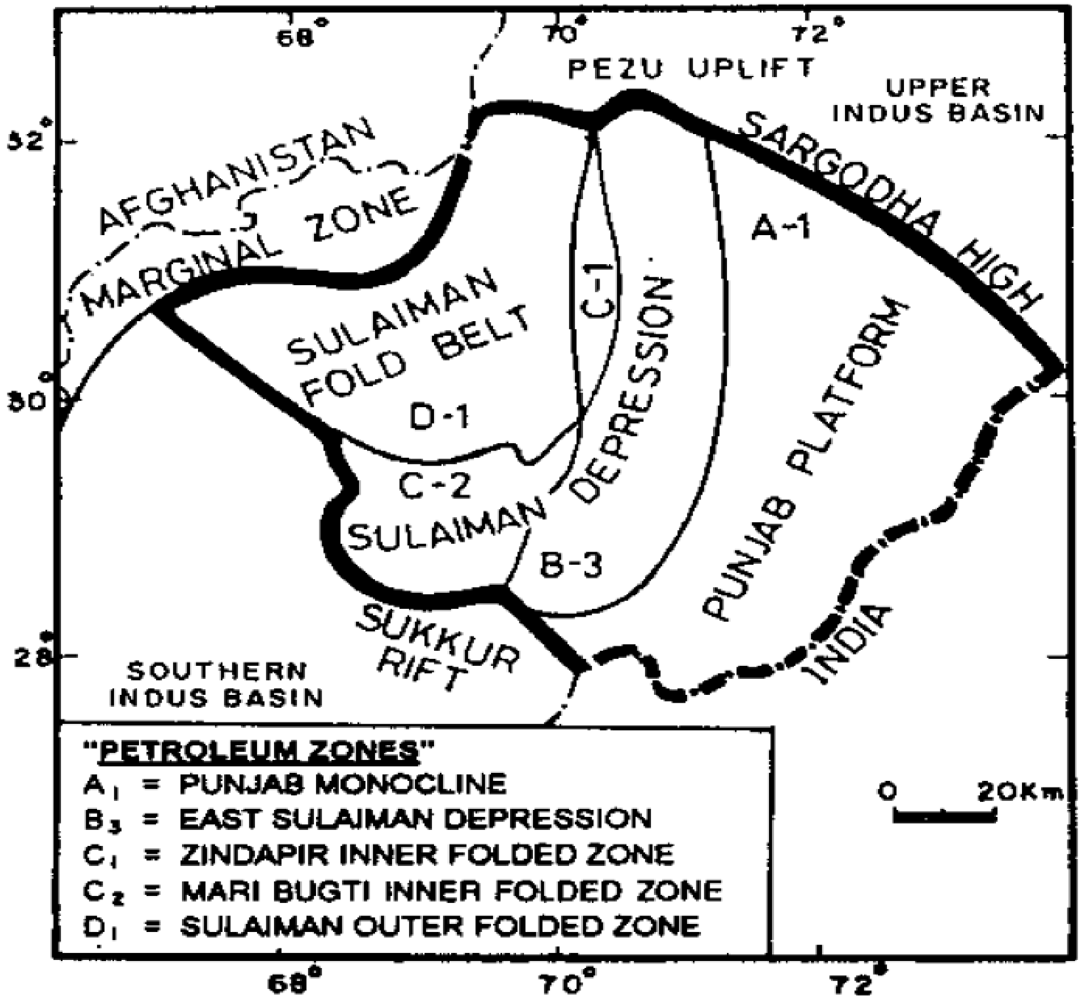

Figure 2.1 Tectonic Map of Central Indus basin (Raza et al, 1989)

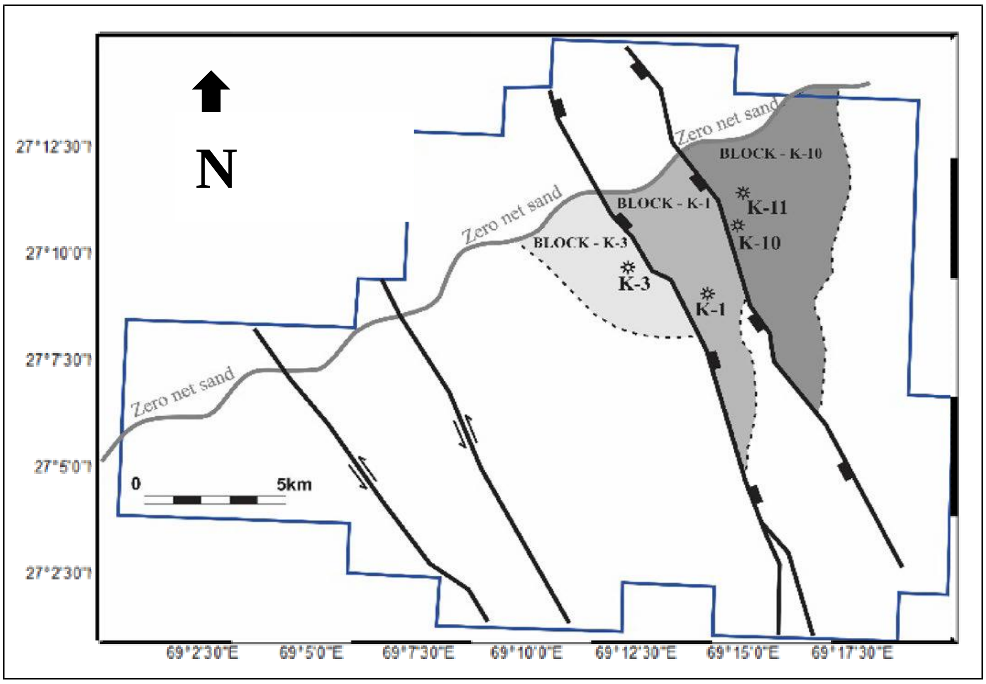

Figure 2.2 Structural Map of Kadanwari Concession (Ahmad and Chaudhry, 2002)

CHAPTER 3

STRATIGRAPHY & PETROLEUM PLAY OF THE STUDY AREA

The stratigraphy of study area contains the formations ranging from Cretaceous to recent, Sembar formation and Siwaliks. (Shah, 2009)

3.1 Sembar Formation

Sembar formation occurs virtually throughout the Indus Basin. Sembar is correlated with the Chichali formation of the Trans-Indus and Kohat-Potwar Provinces. The formation approaches thickness of more than 1000m in some areas. The Sembar formation is of Cretaceous age. The composition is black shales with interbedded siltstone, argillaceous limestone and sandy shale. Environment of deposition for Sembar formation is deep marine (Shah, 2009).

3.2 Goru Formation

The Goru sand is the most prosperous entity from the aspect of petroleum reservoir. Some of the wells drilled in Goru have encountered about 2360m of the thickness. Goru formation was deposited in Early Cretaceous age. It comprises of interbedded shale along with limestone and siltstone. Depositional environment of Goru formation varies from shelf to shallow marine. The upper contact with Parh formation and lower contact with Sembar formation are conformable respectively. The name of the lower sandy member of Goru is called Lower Goru. The Zone of facies laterally show variation between sand and shale, which has been a major area of interest for Oil Companies. The name of the upper shale unit of Goru is termed as Upper Goru (Shah, 2009).

3.3 Parh Limestone

Parh Limestone was deposited in Late Cretaceous age. This formation comprises of thin to medium bedded limestone which is hard in nature. Calcareous shale and marl intercalations are also observed in this formation. It has a conformable upper contact with the Mughal kot formation and Lower contact with the Goru Formation ((Shah, 2009)

3.4 Mughal Kot Formation

Mughalkot formation is of Late Cretaceous age. It contains calcareous mudstone and shale both showing dark grey color along with light grey argillaceous limestone and intercalated sandstone. Depositional environment for Mughal Kot formation is deep marine. (Shah, 2009)

3.5 Pab Sandstone

Pab formation was settled in Late Cretaceous age. It is composed of medium to coarse grained sandstone which is thickly bedded. In some areas, argillaceous limestone is also present along with quartzose and some marl. Depositional environment for Pab formation is transitional. The upper contact of Pab formation is unconformable with Khadro Formation whereas its Lower Contact is conformable with the Mughal Kot Formation (Shah, 2009)

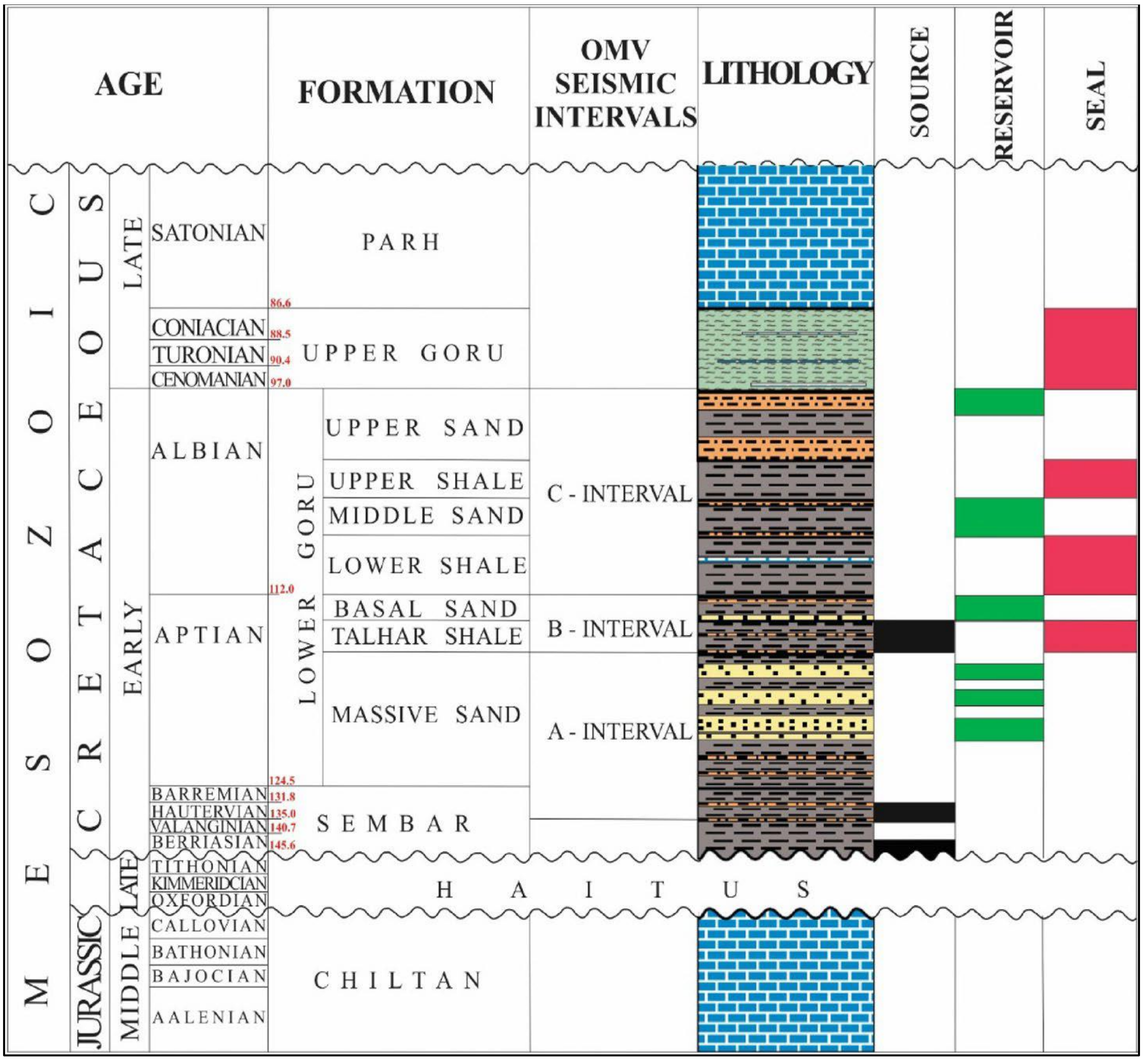

Figure 3.1 Generalized stratigraphic column of the Study area (Shah, 2009).

3.6 Source Rock

Sembar Formation of Createaceous age is the source rock for Kadawanri field, charging the reservoirs in the area. Most of the oil and gas discoveries in south prove Sembar to be the source rock. Sembar is organically rich, thermally mature and contains gas prone kerogen. (Kadri, 1995).

3.7 Reservoir Rock

Consecutive sand bed sequences of Lower Goru formation are the reservoir rocks in this Block. The Lower Goru in classified into five sand members, i-e B to G sands. More than 40 wells have been drilled in this field (Kadri, 1995).

3.8 Cap Rock

Cap and seal is provided by Upper Goru formation and the shale beds of Lower Goru formation. Upper Goru Formation encountered at 1997m depth measured by rotary table of Kadanwari-3 well. The thickness of the formation is approximately 500m in this well. Consecutive shale beds (Kadri, 1995).

3.9 Traps

The Kadanwari area was exposed to intense and episodic deformation since the beginning of the plate drifting northwards. This caused formation of very complex structures in the field. Due to the Early Cretaceous uplift, Early Eocene wrenching and late Tertiary compression. Small scale plunging folds are developed in the area along with, structural and structural com stratigraphic configuration of traps exhibiting negative flower structures, sand bed pinchouts and vertical to subvertical normal faults system (Kadri, 1995).

3.10 Maturation and Migration

The source rock matured in Tertiary, charging numerous reservoirs in this area. The hydrocarbons reached the reservoirs through fault planes and carrier beds (Kadri, 1995).

3.11 Borehole Stratigraphy

Three wells namely Kadanwari-1, Kadanwari-10 and Kadanwari-11 were selected for the research area to perform petrophysical analysis. All these wells are producing wells. The sands are encountered at 3545m depths. Total depth of Kadanwari-1 is 3994m. Kadanwari-10 was drilled to the total depth of 3545m whereas Kadanwari-11 was drilled to total depth of 3543m. The seal rock was identified at a depth of 1967m.

Table 3.1 Table Borehole Stratigraphy of KD-1, KD-10 and KD-11

Age	**Formation Top**	**Kadanwari-1 (m)**	**Kadanwari-10 (m)**	**Kadanwari-11 (m)**
Miocene - Pliocene	Siwalik	8	7.9	9
Eocene	Drazinda	306	310	325
	Pirkoh	400	410	413
	Sirki	474	465	474
	Habib Rahi	544.5	553	561
	Ghanzij	680.5	695	705
	Sui Main Limestone	1279.5	1320	1327
Paleocene	Rankiot	1380	1411	1415
Cretaceous	Upper Goru	1937	1967	1948
	Lower Goru	2415	3076	3084
	Sembar	3797		

CHAPTER 4

WELL LOG ANALYSIS

Shale volume and fluid saturation estimation are key factors in reservoir characterization. Computation of petrophysical parameters named porosity, permeability, fluid saturation and net to gross are significant to evaluate hydrocarbon bearing reservoir. Major reservoir potential of the Kadanwari field area lies in sands of Lower Goru Formation.

4.1 Data Analysis

All the wells are in the same field and have same geological formation. The wireline data available for the selected wells includes basic open hole logs. GR is the gamma ray, SP is spontaneous log, LLD is the deep resistivity log, LLS is the shallow resistivity log, MSFL is the Micro Spherically Focused resistivity log, DT is the Compensated Sonic log, RHOB is the bulk density whereas PEF is the Photoelectric factor of formation and NPHI is the compensated neutron log. Spectral Gamma ray was also recorded due to presence of radioactive sands. POTA, URAN and THOR are curves showing concentrations of Potassium, Uranium and Thorium respectively. Details about the description and logging methods can be found in the appendices.

Table 4.1 Table showing Logs data available in each well

LOG	Kadanwari-1	Kadanwari-10	Kadanwari-11
GR-SP	✓	✓	✓
SGR-URAN-THOR_POTA	✓	✓	✓
NEUTRON-DENSITY	✓	✓	✓
RESISTIVITY	✓	✓	✓
SONIC	✓	✓	✓

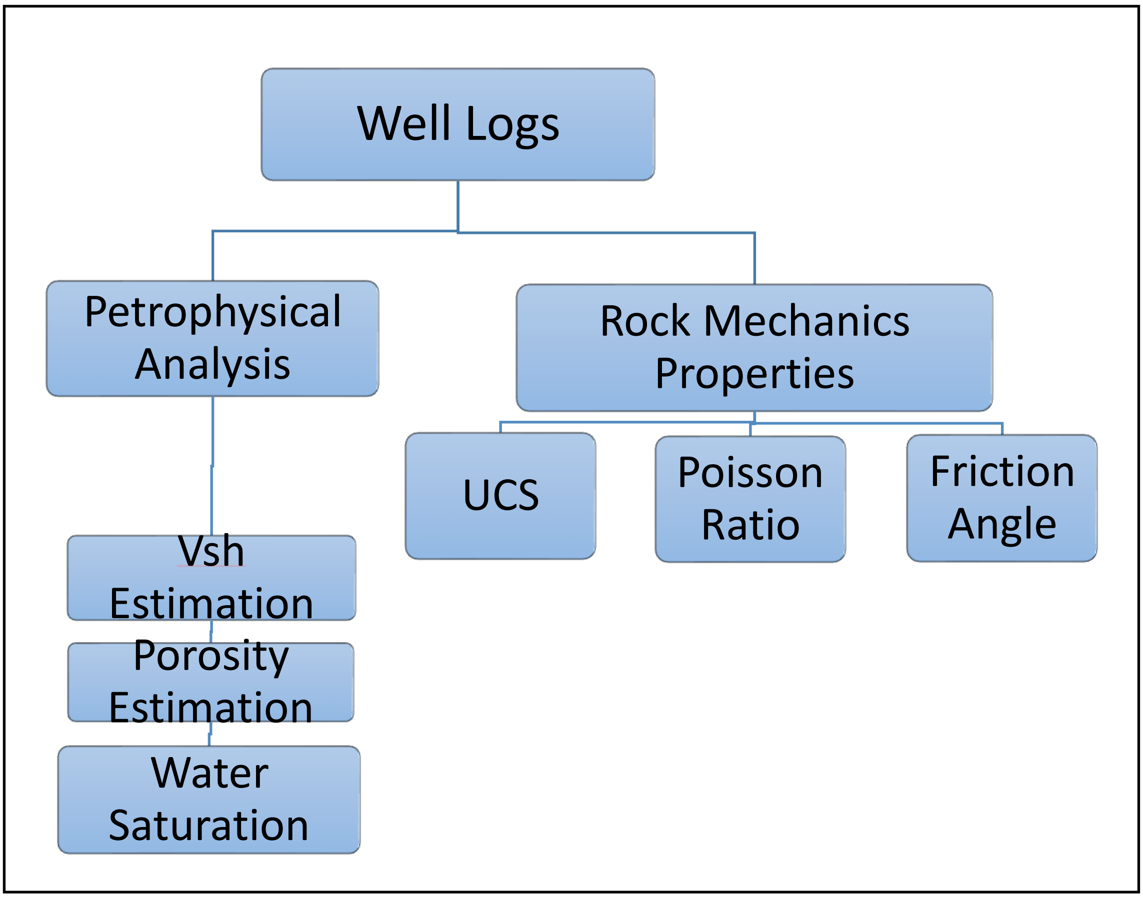

Figure 4.1 Workflow of methodology used for Reservoir assessment

4.2 Well Correlation Study

Marker bed correlation is the most used and one of the most reliable correlation techniques even if the lithology is unknown. In this study, four zones have been indicated using log responses. We used the gamma ray log response that indicates the marker beds in the wells and the thickness of those beds is correlated in the surrounding wells. The field map showing location of the wells is shown below (Fig.4.1).

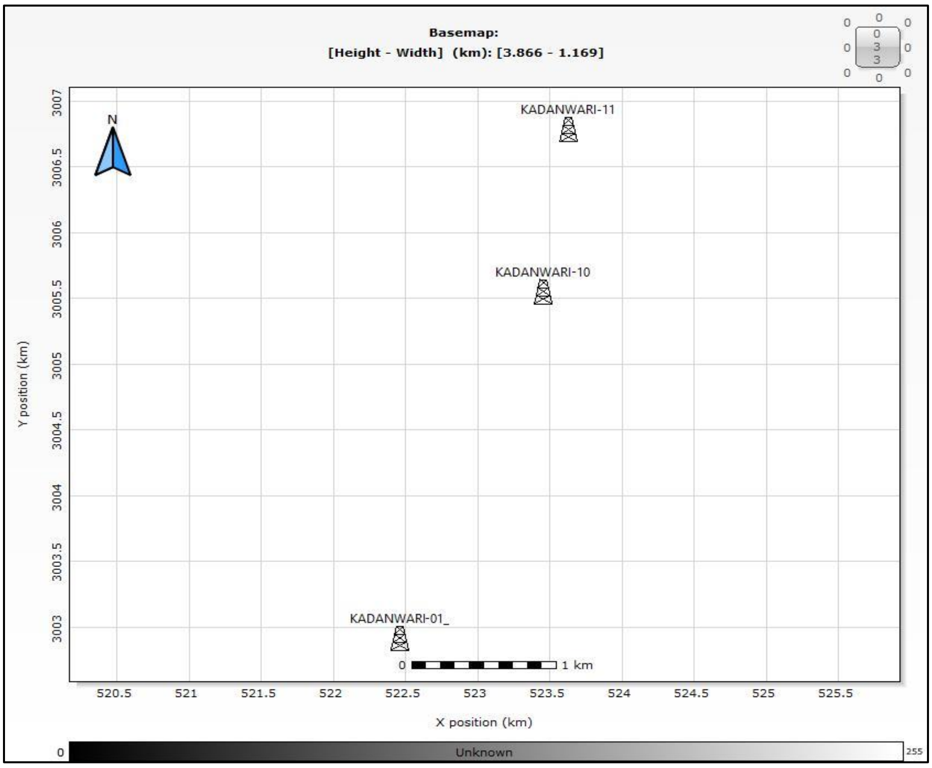

Figure 4.2 Location Map of the Wells Kadanwari-1, Kadanwari-10 and Kadanwari-11.

The Figure: 4.3 illustrates the borehole conditions in different zones, potential pay zones marked on basis of quick look method and thickness of zones is changing in NE direction. As in Track-1 of Kadanwari-1, it is evident from the calipers that there are major washouts in the entire interval. In Kadanwari-10 and Kadanwari-11, most of the borehole is gauged whereas there are some washouts in the middle and lower section. Density and MSFL data are very much affected by the washouts. Similar log trends were observed to demarcate prospect zones in the reservoir. Low GR, separation in Resistivities and Neutron-Density cross-overs were the main criteria for the demarcation.

Whereas all three criteria are not fulfilled in each zone. Borehole quality is better in Zone-2 among all the wells. Zone-4 is showing major washouts in KD-1, most of the density data is affected whereas Low GR, the separation is Resistivities and Neutron log are showing trend that is optimistic. Four prospect zones were marked based on similar GR, Resistivity and Neutron-Density trends (Fig.4.3).

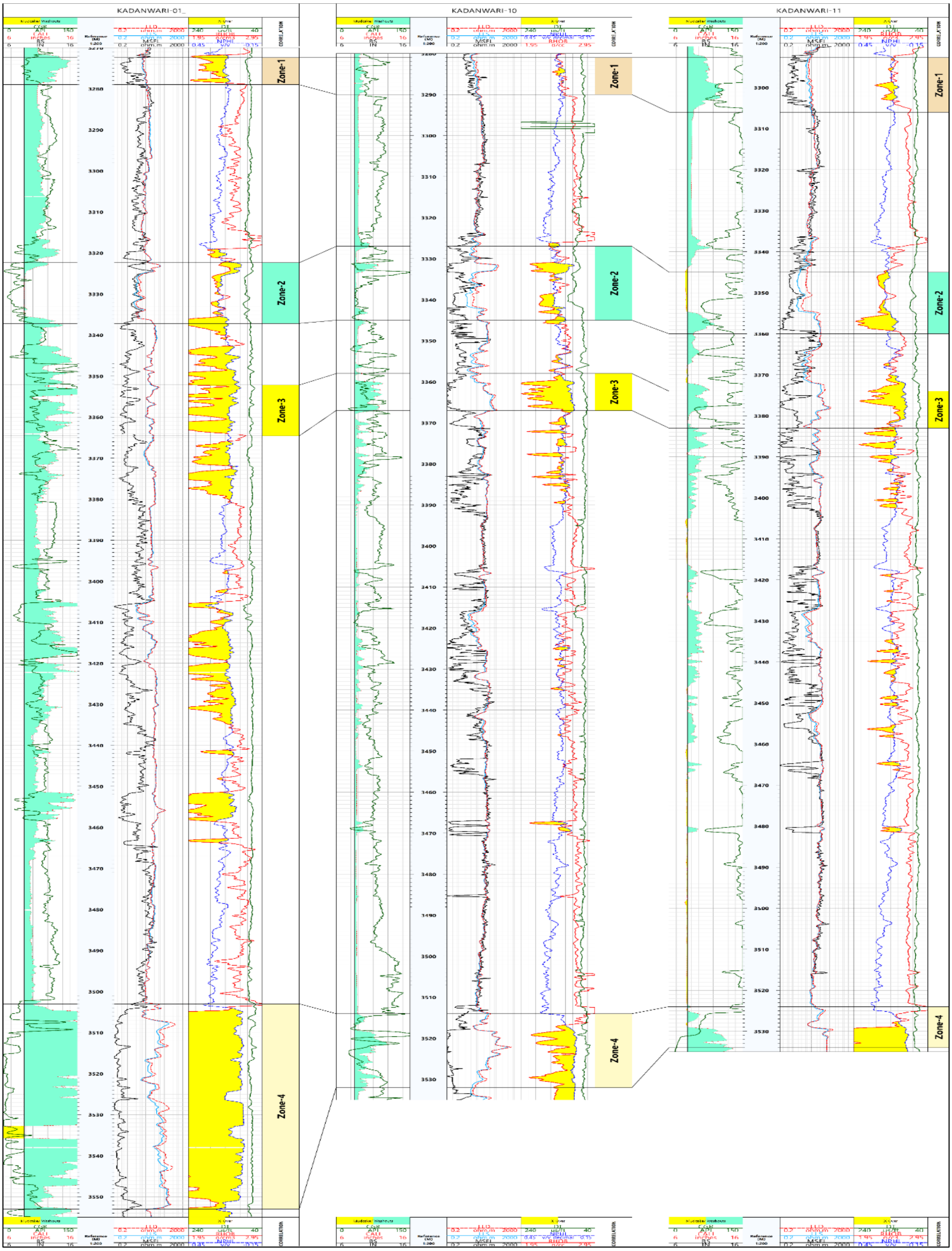

Figure 4.3 Demarcation of zones of interest within Lower Goru in Kadanwari-1, Kadanwari-10 and Kadanwari-11 comparing Log Trends.

The summary of the thickness of zones is given for each well (Table.4.2). From the table and figure of correlation, we can figure out the thickness of the zones is changing in the NE-SW direction. As moving from Kadanwari-1 well towards NE, Zone-1 is showing increase in thickness whereas Zone-2 have not shown any observable change. Zone-3 and Zone-4 are showing considerable decrease in thickness towards NE i-e Kadanwari-10 and Kadanwari-11 wells.

Table 4.2 Table showing Thickness of Prospect Zones marked on basis of Log Trends.

Zone Name	Thickness (m)		
	KD-1	KD-10	KD-11
Zone-1	6.60	9.00	13.29
Zone-2	15.02	18.00	15.00
Zone-3	12.40	9.00	9.00
Zone-4	50.00	18.00	10.00

4.3 Petrophysical Analysis

The petrophysical analysis of the wells were performed in several steps and with respect to zones. The analysis was done to compute porosity, fluid saturation and lithology of the formation. Four different zones were marked based on log response and each zone is evaluated separately using different parameters. Each of the steps is described in detail below.

4.3.1 Shale Volume Estimation

Shale volume calculation is key and important step in petrophysical interpretation. It will help in lithology estimation and differentiating reservoir from non-reservoir. More shale volume in the formation, can lead to higher water saturations as there is bound water in shales. Shale volume is an indicator of zone of interest, less shale volume cleaner the lithology. GR index is a function of shale content as GR tool is sensitive to radioactive emissions which are mostly higher in shales and lower in clean lithology. Generally, shale volume is computed from GR but in this case, CGR is used. The reason is that Lower Goru formation contains radioactive sands also known as Hot sands. The Radioactivity comes from the Uranium concentration present. Zone-2 and Zone-4 show comparatively low shale volume and cleaner lithology whereas Zone-1 and Zone-3 are relatively higher in clay content. SGR data is recorded due to presence of hot sands in reservoir. Neutron-Density cross plots as shown below confirms the main lithology to be sandstone. Volume of shale is computed using linear method i-e Gamma Ray Index (Fig.4.3).

Table 4.3: Average Shale Volume of different zones in each well

	KADANWARI-01	KADANWARI-10	KADANWARI-11
Zone-1	36.7	30.5	39.2
Zone-2	28.5	38.7	36.8
Zone-3	37.9	43.7	38.7
Zone-4	26.6	38.1	34.6

4..3.2 Neutron-Density Cross Plots

Neutron-Density data of Prospect zones was plotted on Neutron-Density cross plot for lithology identification. For every well, three clusters are shown. Green circle is showing the correct data that isn’t affected by badhole, the blue circle shows data effected by washouts and lastly the red circle shows presence of shales in the formation. Most of the points in gauged hole lie on sandstone line showing the matrix to be sandstone. The cluster of point encircled by blue ellipse are showing data effected by washouts whereas cluster encircled by red ring shows presence of shale in the formation. Presence of shale in the formation tends to shift the data downwards as some clay minerals have higher densities and commonly NPHI is higher in shales as well (Fig.4.4a-4.4c).

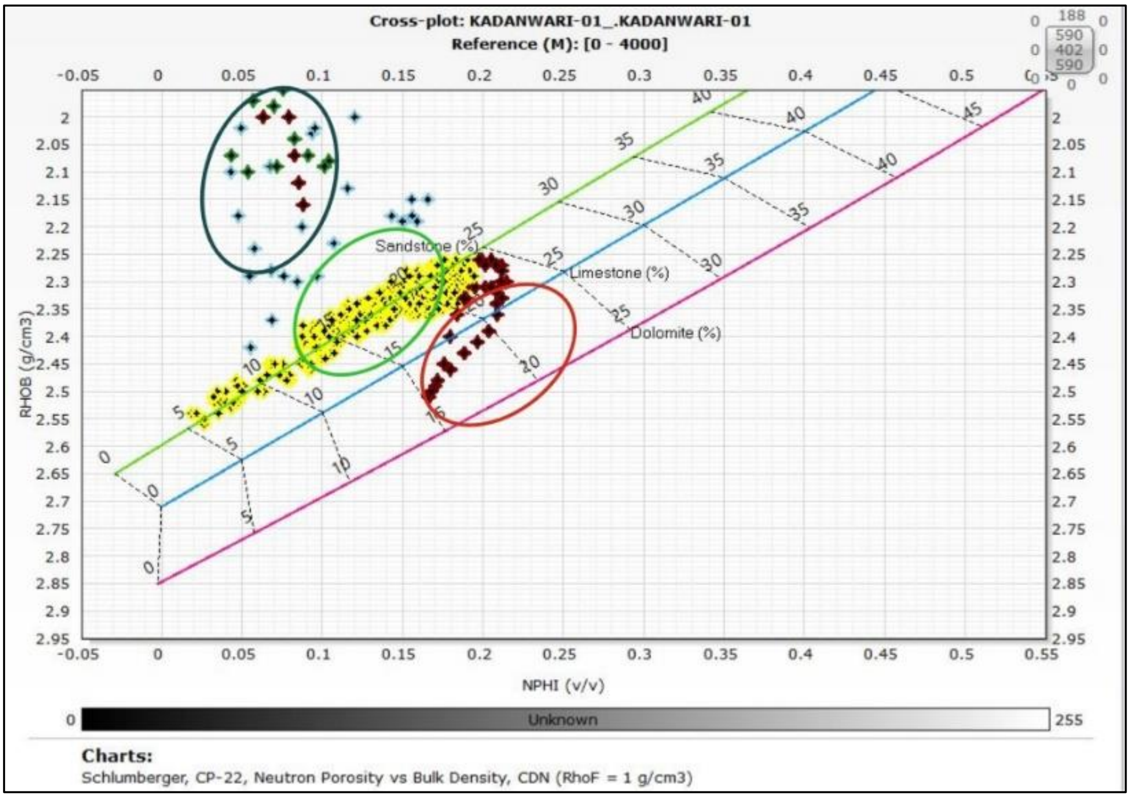

Figure 4.4a Neutron-Density Crossplot for Kadanwari-1 showing prospect zones data

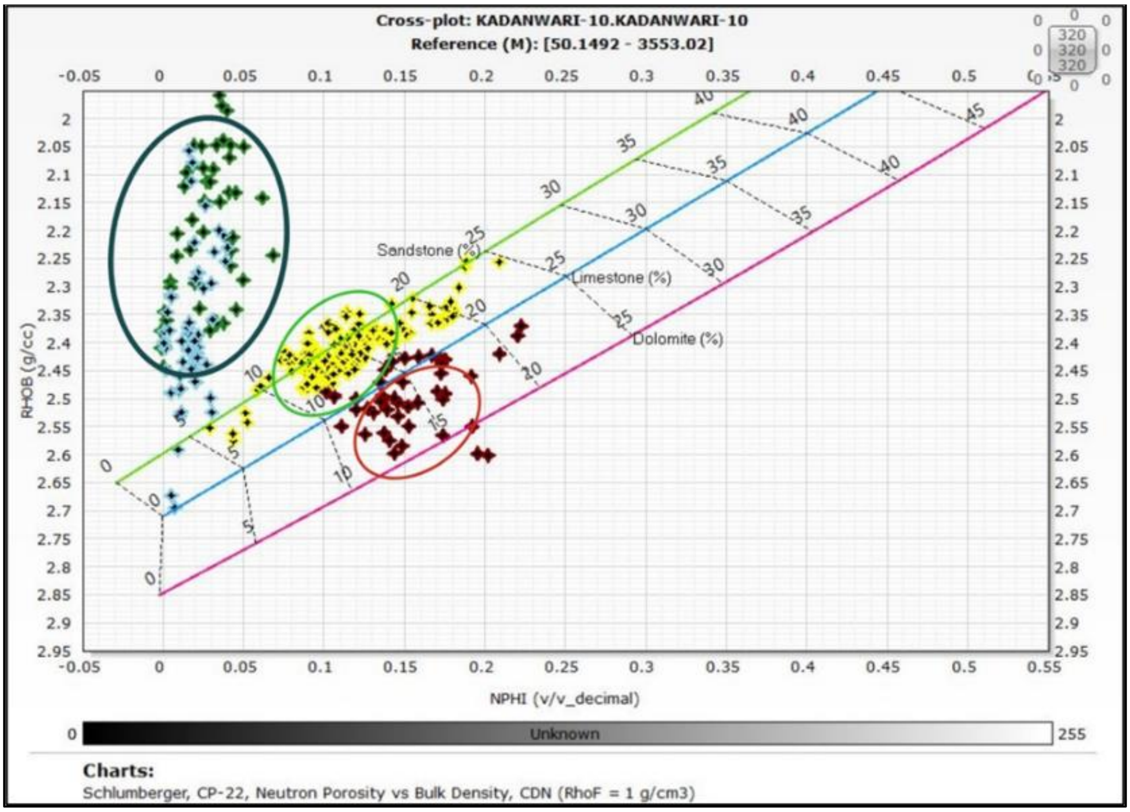

Figure 4.4b Neutron-Density Crossplots for Kadanwari-10 showing prospect zones data

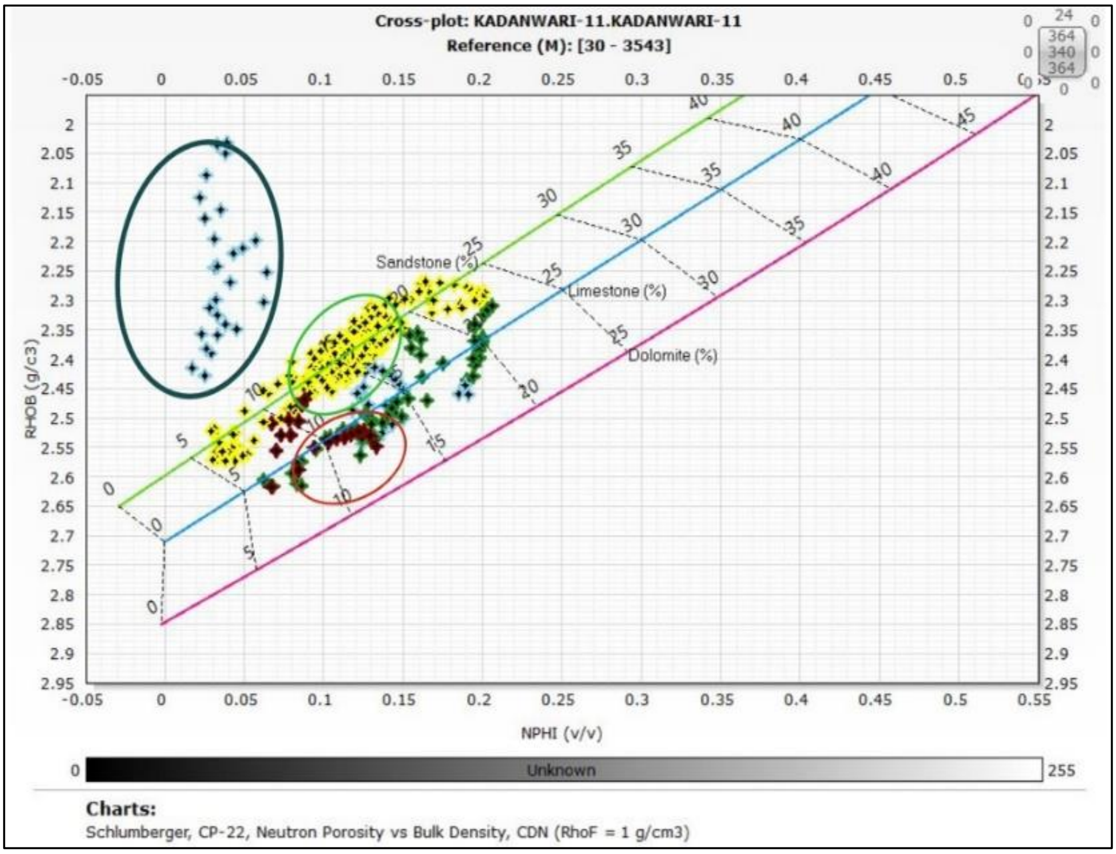

Figure 4.4c Neutron-Density Crossplot for Kadanwari-11 showing data for 4 Prospect zones.

4.3.3 Porosity Calculation

The void spaces inside rock is known as porosity. Porosity is the storage space inside the rock which can accumulate fluids in it. Reservoir quality is dependent on the effective porosity. Higher the effective porosity, better will be the reservoir quality and vice versa. There are multiple methods to compute porosity. In this study, we used Neutron-Density and Neutron-Sonic cross plots. For the prospect zones having major washouts, Neutron-Sonic porosity was used whereas in zones with gauged hole, average of both porosities was used. The method of porosity calculation is more reliable than the traditional method of using porosities from single methods. This combination of average porosities reduces the errors and minimizes the environmental effects of logs that cause overestimation of porosity. The result of the porosity calculation for all the wells is shown in Table:4.4. The fourth track is showing the Effective porosity with white shade. The limits for the scale are from 0 to 0.5 (Fig.4.3).

The analysis of porosity shows that overall porosity is good except Zone-3 which is a bit tighter. Maximum porosity is 14.8% in Zone-2in Kadanwari-10 and minimum porosity is 3.8% in Zone-4 in Kadanwari-10 (Table 4.4).

Table 4.4: Average effective porosities for different zones in each well

	KADANWARI-01	KADANWARI-10	KADANWARI-11
Zone-1	12.2	9.8	11.3
Zone-2	14.8	12.1	12
Zone-3	6.4	7.4	4.6
Zone-4	8.1	3.8	8.25

4..3.4 Fluid Saturation

To validate if the reservoir has potential, fluid saturations are computed. Water saturation is computed using Indonesian Equation (Poupon and Leveaux 1971). It is one of the equations that uses effective porosity to compute water saturation in shaly sands.

The saturation of water within the consolidated sandstone estimated with the following parameters:

tortuosity factor (a = 1), cementation exponent (m = 2) and saturation exponent (n = 2), Formation Water Resistivity= Rw= 0.024

Formation water resistivity was computed using SP method. In clean zone, value of SP was -57 which deflected to -78 in shale. SSP computed for this is -21. Values of Rmf, SP and temperatures are taken as input into the software and Rw is computed automatically. The parameters used for Rw computation are shown (Fig.4.5).

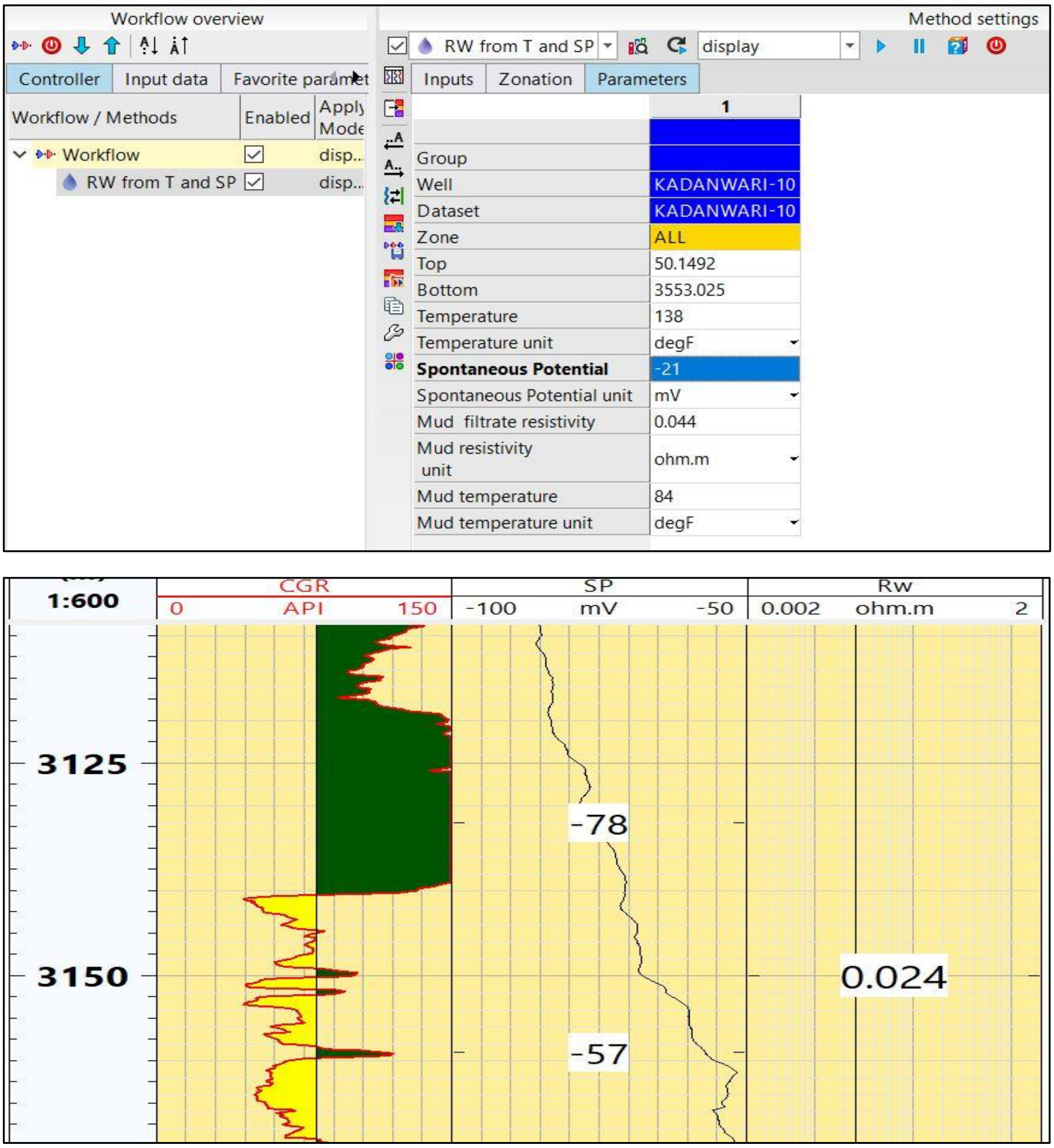

Figure 4.5 Rw computed using SP method, parameters used are shown.

Water saturation computed in three wells is displayed in the plot (Fig.4.3). The last track show Sw in blue color whereas red color depicts hydrocarbon saturation. The minimum average water saturation is 30.4% in Zone-4 in Kadanwari-01, whereas maximum water saturation observed is 57.5% in Zone-1 in Kadanwari-10, shown in Table 4.5.

Table 4.5: Average Water Saturation per zones in Kadanwari-1, Kadanwari-10 and Kadanwari-11.

	KADANWARI-01	KADANWARI-10	KADANWARI-11
Zone-1	44.9	57.5	43.8
Zone-2	47.6	40.9	45.1
Zone-3	53.2	29.9	54
Zone-4	30.4	44.2	39.9

4.5 Rock Mechanical Properties Analysis

The mechanical behavior of rock is termed as Rock Mechanical properties or Geomechanics. It is related to the forces, stresses and their effect on the rock. The method properties can be used along with petrophysical properties for rock classification. The basis of this method is that some of these properties are directly related to the rock properties such as porosity, permeability and elastic moduli.

The following mechanical properties were predicted from logs:

1 Unconfined Compressive Strength

2 Poisson’s Ratio

3 Frictional Angle

4.5.1 Unconfined Compressive Strength

The strength of the rock when it is crushed in one direction (uniaxial) without lateral restraint. It is important for drill bit selection, ROP Prediction, well bore stability determination and Enhanced Oil Recovery analysis. There are multiple methods to compute UCS using various logs. Sarda Method was used in this study. Sarda et. al. established three UCS porosity correlations for various porosities.

The following correlation was used for sand formation with porosity from 0% to 30%.

$$\sigma_{UCS} = 258e^{-9\emptyset}$$

The equation used the porosity computed in the zones. The equation was introduced in Techlog© with porosity value at each depth for different zones. For each value of porosity, UCS is computed against prospective zones.

Table 4.6: Average UCS per zones in Kadanwari-1, Kadanwari-10 and Kadanwari-11.

	KADANWARI-01	KADANWARI-10	KADANWARI-11
Zone-1	112.8	57.5	43.8
Zone-2	184.3	40.9	45.1
Zone-3	224.9	29.9	54
Zone-4	108.1	44.2	39.9

4.5.2 Poisson's Ratio

The ratio of expansion of rock in one direction when it is contracted at the right angles is known as Poisson's Ratio. The PR of common material usually lies between 0 to 0.5. the PR will be 0 when no Poisson contraction occurs due to extension and 0.5 when the material deforms elastically at small strains. PR can be calculated using set of logging data such as resistivity, fluid saturation or P and S wave slowness. PR can be used for modelling seismic response of selected formations. The method used to compute PR depends on shaliness index which is computed from Sonic and Density porosities (Craig, 2000). Here Poisson's Ratio is denoted by Greek letter "ν".

$$\vartheta = 0.125 * q + 0.27$$

Where: q= shaliness index

$$q = \frac{\emptyset_S - \emptyset_D}{\emptyset_S}$$

Where:

$\emptyset_S$= porosity from the sonic log

$\emptyset_D$= porosity from density log

Table 4.7: Average PR values per zones in Kadanwari-1, Kadanwari-10 and Kadanwari-11.

	KADANWARI-01	KADANWARI-10	KADANWARI-11
Zone-1	0.27	0.26	0.25
Zone-2	0.18	0.28	0.23
Zone-3	0.16	0.20	0.08
Zone-4	0.12	0.22	0.16

4.5.3 Frictional Angle

Frictional angle is the angle of shear stresses and normal stresses at which the shear failure occurs. This parameter defines the internal friction between the grains of rocks. Frictional angle of rocks is related to the size and shape of the grains exposed on the fracture surface. A fine-grained rock tends to have a low frictional angle whereas coarse-grained rock has high frictional angle. For frictional angle computation, we utilized GR log. A cutoff is applied to frictional angle. With default parameters, GR is 120 gAPI to FANG 20 DEG and GR 40 gAPI is mapped to 35 DEG

Table 4.8: Average Frictional Angle values per zones in Kadanwari-1, Kadanwari-10 and Kadanwari-11.

	KADANWARI-01	KADANWARI-10	KADANWARI-11
Zone-1	34.1	34.5	40.9
Zone-2	34	37	33.5
Zone-3	39.4	39	37.3
Zone-4	39.9	34.9	32.1

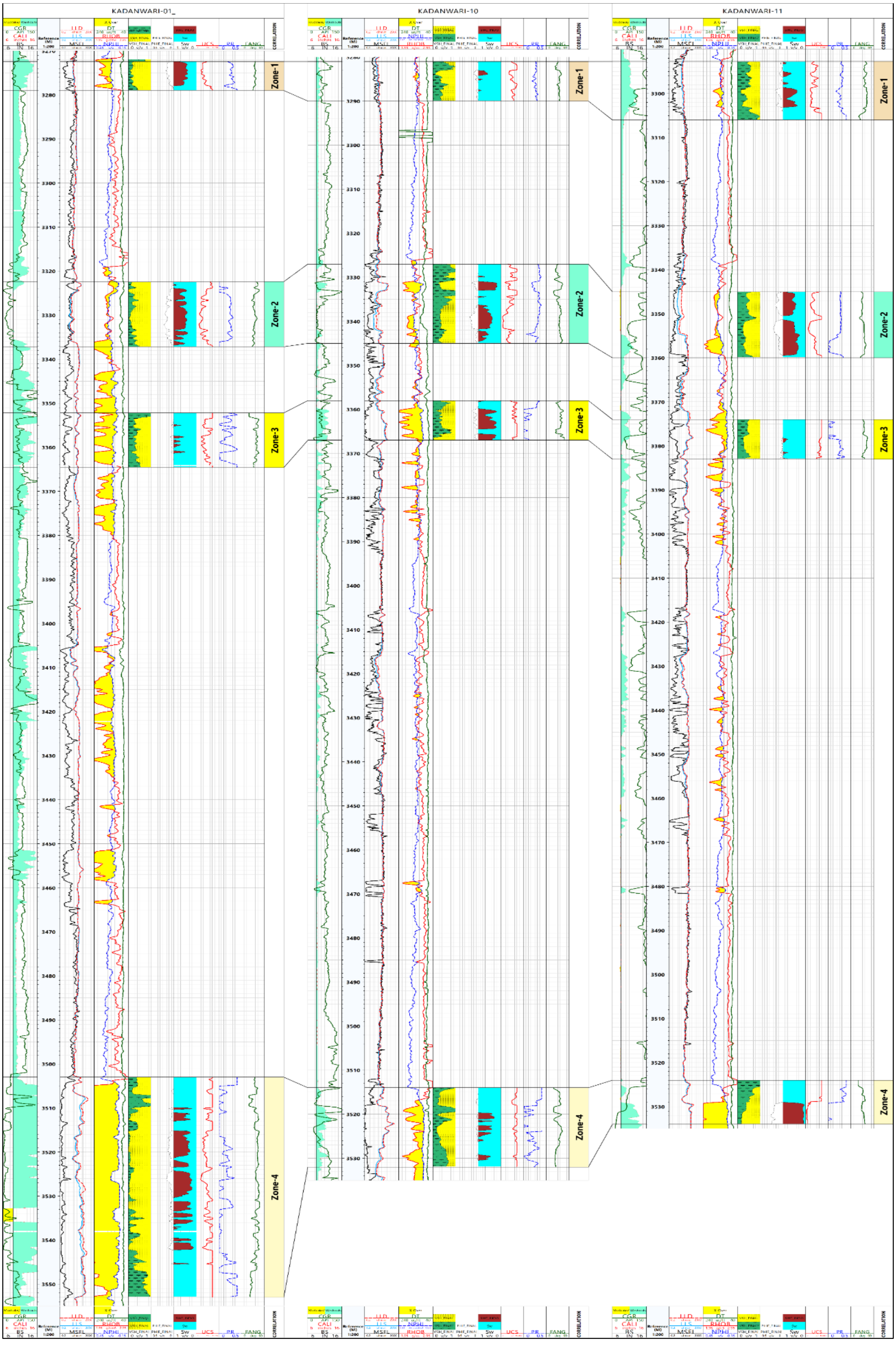

Figure 4.6 Composite log plot for Kadanwari-1, Kadanwari-10 and Kadanwari-11 showing Petrophysical and Geomechanical Properties.

4.6 Petrophysical and Rock Mechanical Properties Facies Analysis using IPSOM*

IPSOM is a self-organizing map which uses Index and probability. It provides automatic classification solutions with both supervised and unsupervised methods. These methods are based on the Neural Network Technology (The Kohonen algorithm 2013 Schlumberger). This approach is applied to all the wells where the units are encountered. Figure below shoes facies workflow using IPSOM.

The major steps involved in facies classification are:

a. Neural analysis clustering of the inputs to get a down sampled but a representative set of nodes.
b. Indexation, Model refinement and regroup nodes with similar properties or assign facies to each node based on the indexation inputs. Model refinement is optional but can be used to define optimal number of classification groups.
c. Model application on the wells to create classification groups.

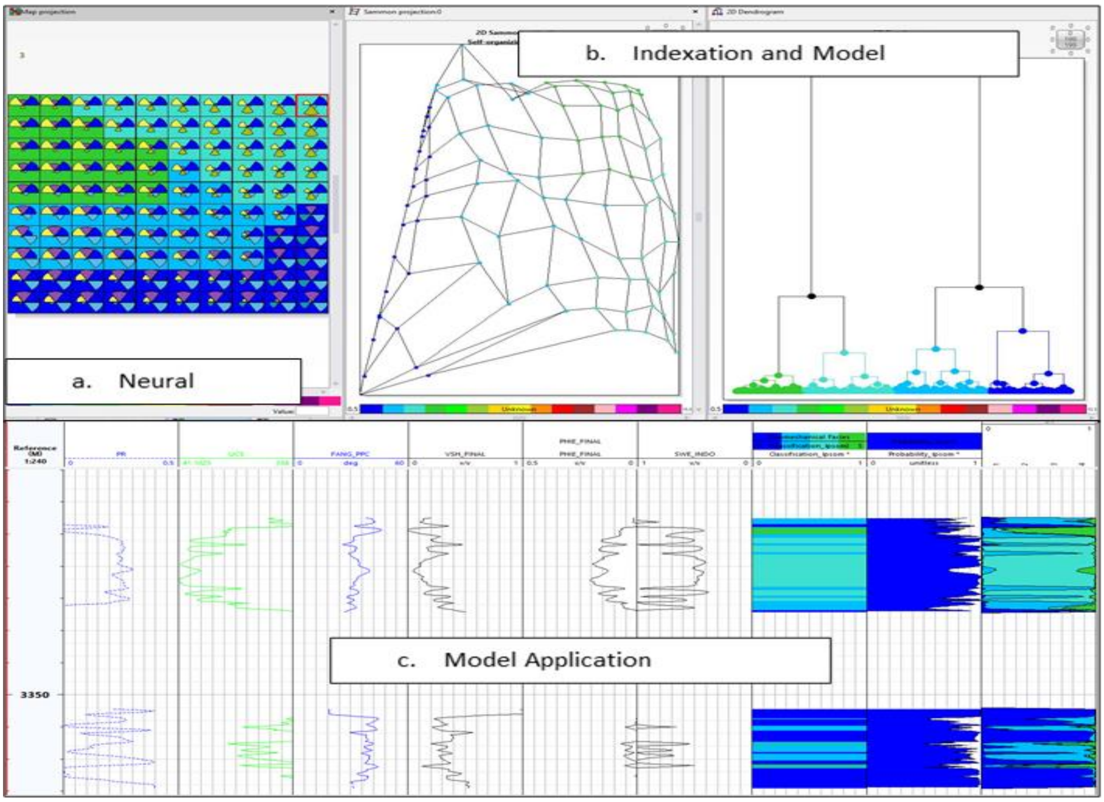

Figure 4.7 Example of Typical Workflow of IPSOM. a) Neural Analysis, b) Indexation and Model refinement and c) Model Application

Table 4.9: The Mean of each input variable within each modality.

		1	2	3	4
		Mean	Mean	Mean	Mean
1	Poisson Ratio (Dynamic)	0.12	0.23	0.19	0.03
2	Unconfined Compressive Strength	249.942	182.26	81.37	152.61
3	Friction Angle	30.78	38.45	36.41	42.90
4	Shale Volume	0.53	0.21	0.12	0.07
5	Effective Porosity	0.0046	0.04	0.13	0.06
6	Effective Water Saturation	0.99	0.81	0.40	0.38

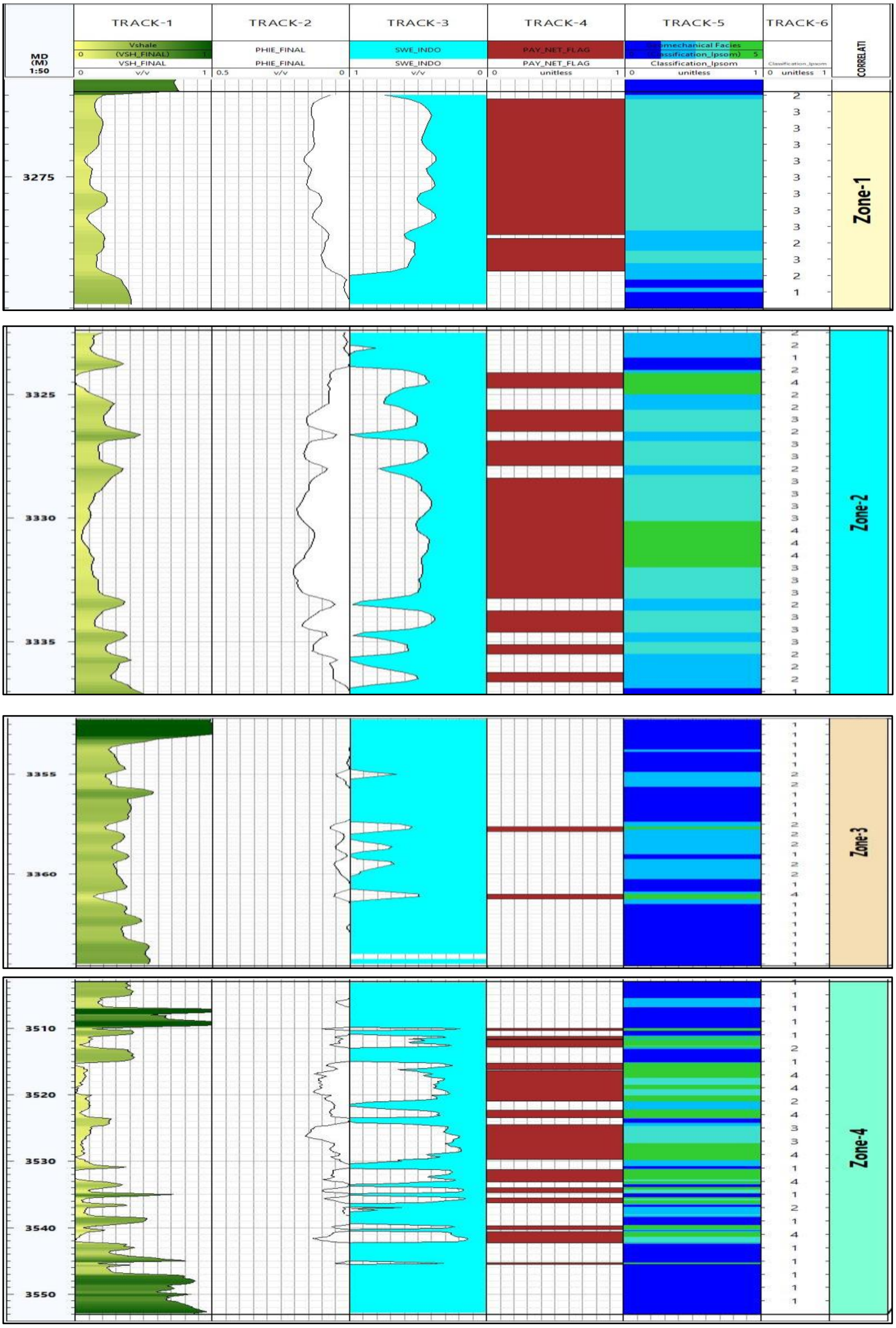

Figure 4.8 **Plots showing Facies interpreted using IPSOM for Kadanwari-1.**

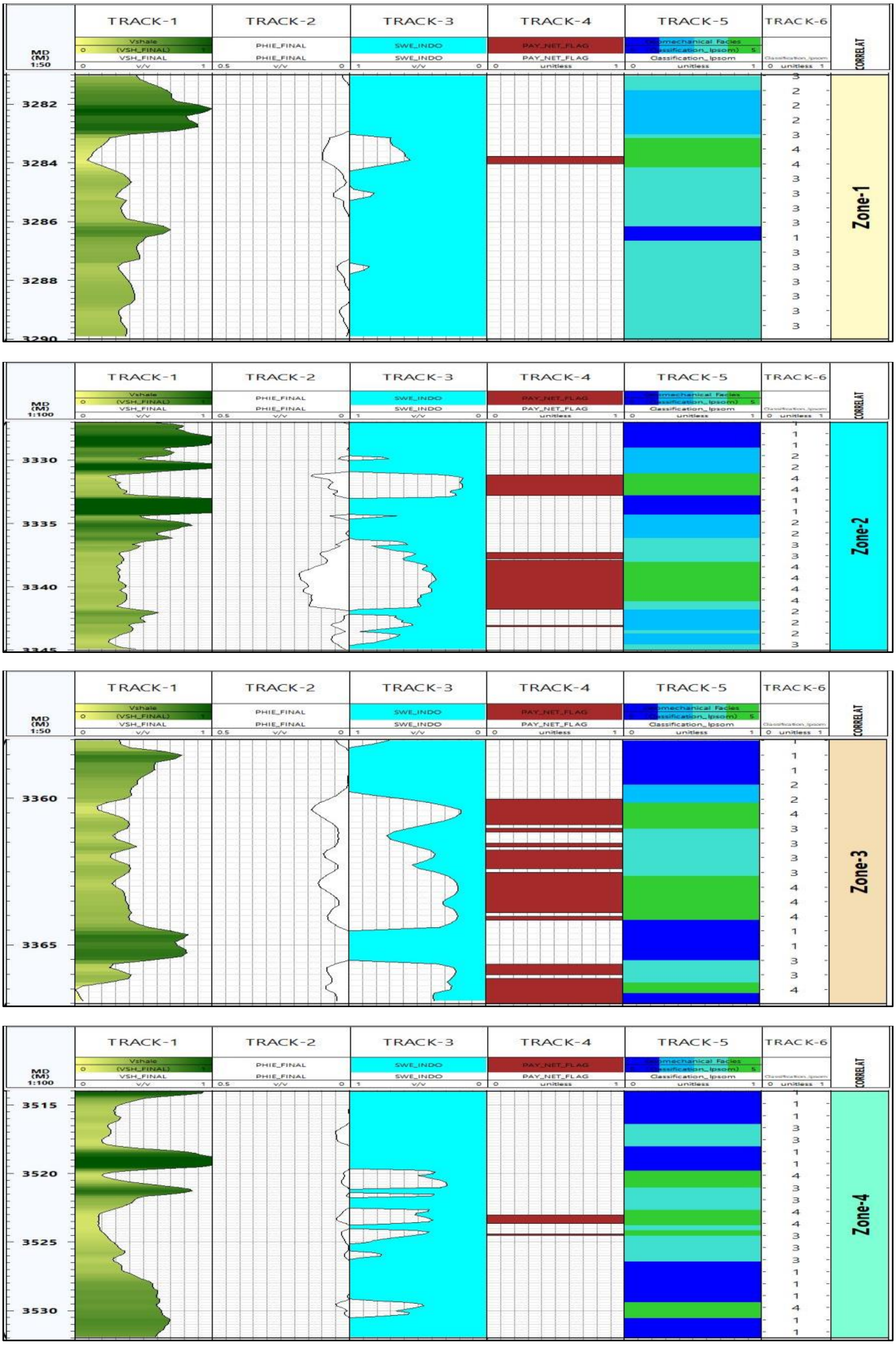

Figure 4.9 Plots showing Facies interpreted using IPSOM for Kadanwari-10.

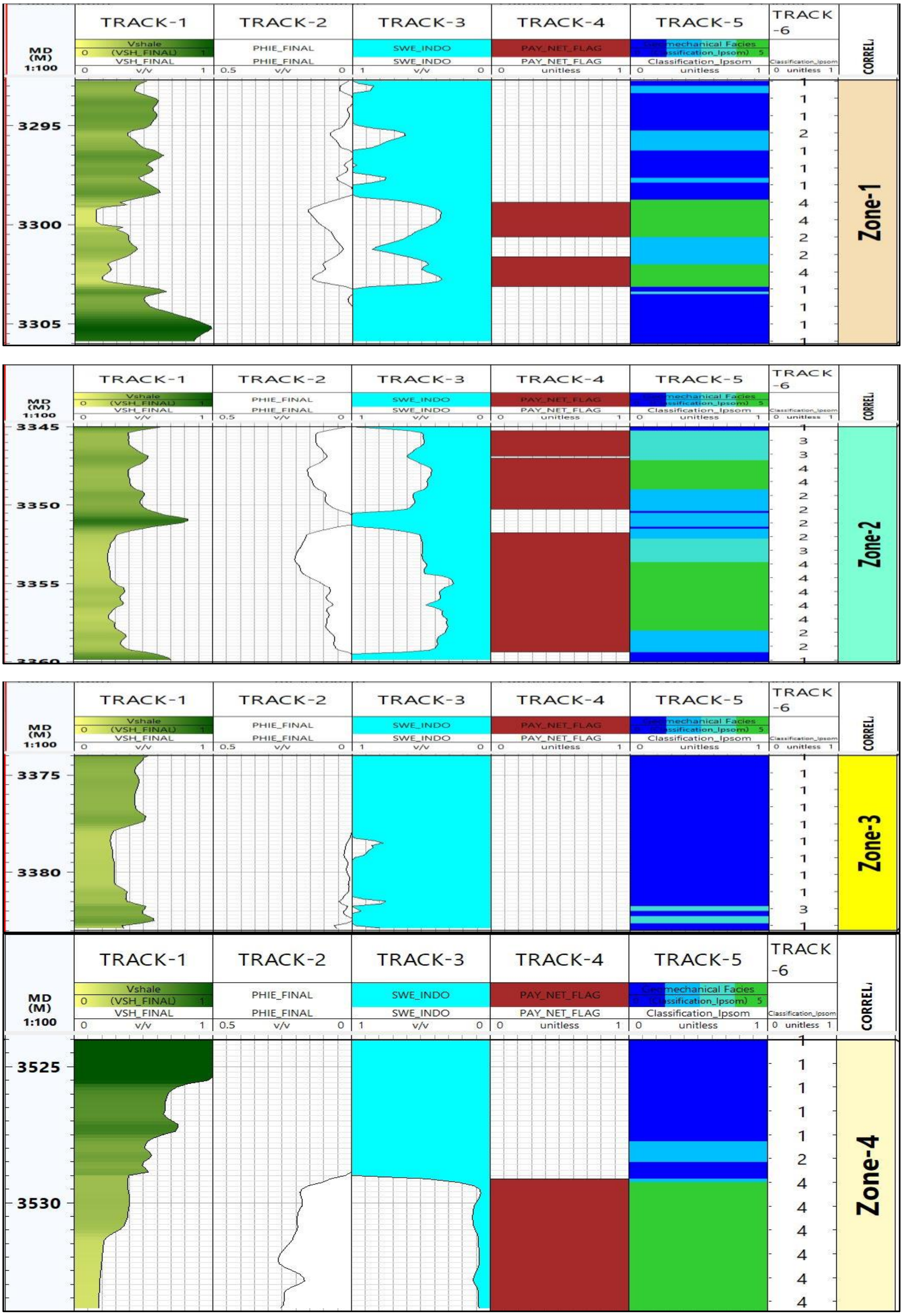

Figure 4.10 Plots showing Facies interpreted using IPSOM for Kadanwari-11.

The above plots show the Facies computed using Petrophysical and Geomechanical properties. Track-1 is showing the Shale Volume, in Track-2 Effective Porosity is shown along with Water Saturation in Track-3. Track-4 and Track-5 are showing Net Pay and Facies flags respectively. And the last Track-6 is showing the number of each facie ranked from 1 to 4, with 4 being the best type and 1 being the least (Fig 4.8-4.10).

Thickness of each Facie in every well is calculated (Table 4.10). As Facie-4 is the best, its maximum thickness is observed to be 14.5 m in Kadanwari-11.

Table 4.10: Table showing Thickness of Facies in Each Well.

	KD-1(m)	**KD-10(m)**	**KD-11(m)**	**Total**
Facie-1	33	14.62	19.12	66.74
Facie-2	12.75	7.75	7.37	27.87
Facie-3	16.25	15.25	3.5	35
Facie-4	14.5	11.25	8.75	34.5
Total Thickness	76.5	48.87	38.74	

CHAPTER 5

FINDINGS AND DISCUSSION

Kadanwari Field is located to South East of the regional Jacobabad High (Kazmi and Jan). The thickness of reservoir formation is changing between the wells. Kadanwari-1 is drilled in graben whereas Kadanwari-10 and Kadanwari-11 are drilled in horsts. From the well correlation, the thickness of the four zones can be observed as it is changing from well to well. The average thickness of Zone-1 in all three wells is 9.6 m which is showing an increase towards NE. For Zone-2, the average thickness is 16 m and the thickness is almost similar in all wells. In Zone-3, the average thickness is 10 m with the thickness decreasing towards NE. Zone-4 shows average thickness of 26 m with a sudden reduction in the thickness towards NE. Thickness changed abruptly from 50m to 23m in Kadanwari-10 and to 16m in Kadanwari-11. Concluding except Zone-1, thickness of all the zones is decreasing moving North.

The clay content is relatively increasing in the reservoir moving towards NE. Major lithology was Sandstone with intercalations of shale. The presence of interbedded shales provides seals against vertical migration of hydrocarbon within the formation. GR is showing relatively higher values in Kadanwari-11 as compared to Kadanwari-10 and Kadanwari-1.

Shale volume was computed using liner method. Use of GR will cause an overestimation in the Shale volume. Average GR values for Zone-1 is 102 gAPI, for Zone-2 it is 75.4 gAPI, in Zone-3 its 100.2 gAPI and for Zone-4 it is 85.6 gAPI. Average shale volume observed for Zone-1 is 24% with a max of 30 and min of 18.9%. In Zone-2, average shale volume is 24.56%, with a maximum of 33 % and a minimum of 18.9%. For Zone-3, average shale volume is 28%, with a maximum value of 31% and a minimum value of 24%. For Zone-4, average shale volume is 20%, with a max of 27 and min of 14.2%.

Effective Porosity was computed using a combination of Neuron-Density and Neutron-Sonic log. Zones with washouts have bad density data, that's why Neutron-Sonic was used in those intervals and in intervals with gauged borehole, mean of both were used. There was no availability of core data for correlation. In Zone-1, average porosity is 8.6% with the maximum of 11% in Kadanwari-11and minimum of 3.9% in Kadanwari-10. For Zone-2, average porosity is 11.3 %, with maximum of 11.7% and minimum of 10.8%. Zone-2 is showing good porosity in all the three wells. In Zone-3, average porosity is 3.36%, which is the least among all the four zones. For Zone-3, maximum porosity tends to be 7% in Kadanwari-10 and minimum value is 1.2% in Kadanwari-11.

In this study, water saturation was computed using Indonesian's Equation. Rw used for Sw computation was Rw=0.035 ohmm, that was computed using SP log method. This value was used for all the three wells. Average Sw for Zone-1 is 33%, for Zone-2 it is 29.3%, for Zone-3 it is 42.6% and for Zone-4 it is 28.16%. Zone-2 is showing the minimum Sw and hence the best Prospect Zone among the four zones marked.

Net Pay Thickness was computed using cutoffs for Shale Volume, Effective Porosity and Water Saturation. Following cutoffs were applied on the results (Table.6.1).

Table 5.1: Table showing Cutoffs for Net pays.

Shale Volume	**<**	**40 %**
Porosity	**>**	**3 %**
Water Saturation	**<**	**60 %**

Table 5.2: Table showing Thickness of Net Pays in Prospect Zones.

Well	Zones	Net Thickness	Sum Net Thickness
KADANWARI-01	Zone-1	5.125	34
KADANWARI-01	Zone-2	9	
KADANWARI-01	Zone-3	0.5	
KADANWARI-01	Zone-4	19.625	
KADANWARI-10	Zone-1	0.25	11
KADANWARI-10	Zone-2	6.125	
KADANWARI-10	Zone-3	4.476	
KADANWARI-10	Zone-4	0.75	
KADANWARI-11	Zone-1	3.25	20
KADANWARI-11	Zone-2	12.5	
KADANWARI-11	Zone-3	0	
KADANWARI-11	Zone-4	4.875	

Geomechanical properties i-e UCS, FANG and PR and Petrophysical parameters i-e Shale Volume, Effective Porosity and Water Saturation were used as inputs to classify them into Four facies with Facie-1 being the poor and Facie-4 being the best. Facie-4 is the best ranked facie, with a cumulative thickness of 34.5m in all three wells whereas Facie-1 has the maximum thickness of 66.74m (Table.5.3). The summary of the Net pay Zones and Reservoir Facies is shown in the Appendices.

Table 5.3: Table showing Thickness of Facies.

	KD-1(m)	%	KD-10(m)	%	KD-11(m)	%	Total
Facie-1	33	43.14	14.62	29.92	19.12	49.35	66.74
Facie-2	12.75	16.67	7.75	15.86	7.37	19.02	27.87
Facie-3	16.25	21.24	15.25	31.21	3.5	9.03	35
Facie-4	14.5	18.95	11.25	23.02	8.75	22.59	34.5

CONCLUSIONS

The following conclusions are drawn from this research study.

1. Study of Kadanwari-1, Kadanwari-10 and Kadanwari-11 was carried out for reservoir characterization. Facies analysis was performed using Petrophysical and Geomechanical properties. All three wells show Hydrocarbon potential based on Petrophysical Analysis. Four zones of interest were marked on basis of log trends and multiple pay zones were interpreted. Among the four zones delineated, Zone-2 turns out to be the best with cumulative net thickness of 27.62m in three wells. Zone-4 is the second best with cumulative thickness of 25m. Zone-2 has average net thickness of 9.2m whereas Zone-4 shows average net thickness of 8.4m.

2. UCS, PR and FANG were computed from logs using several equations. UCS and PR were computed using porosity whereas FANG was computed using GR as it is related to the grain size. Zones showing less porosity and are compact show high value of UCS and PR whereas more porosity leads to decrease in the values of these parameters. Low UCS values means the zone is more frackable.

3. Facies analysis was based on Petrophysical and Geomechanical Properties. Facie-4 is the best ranked facie, with a cumulative thickness of 34.5m in all three wells. Facie-4 has maximum thickness of 14.5m in Kadanwari-1 well whereas 11.25m and 8.75 m in Kadanwari-10 and Kadanwari-11 respectively.

4. Combination of Net Pay and Facie Analysis concludes that Zone-2 is the best Zone of interest with average Net thickness of 9.2m and mean thickness of Facie-4 is 5m.

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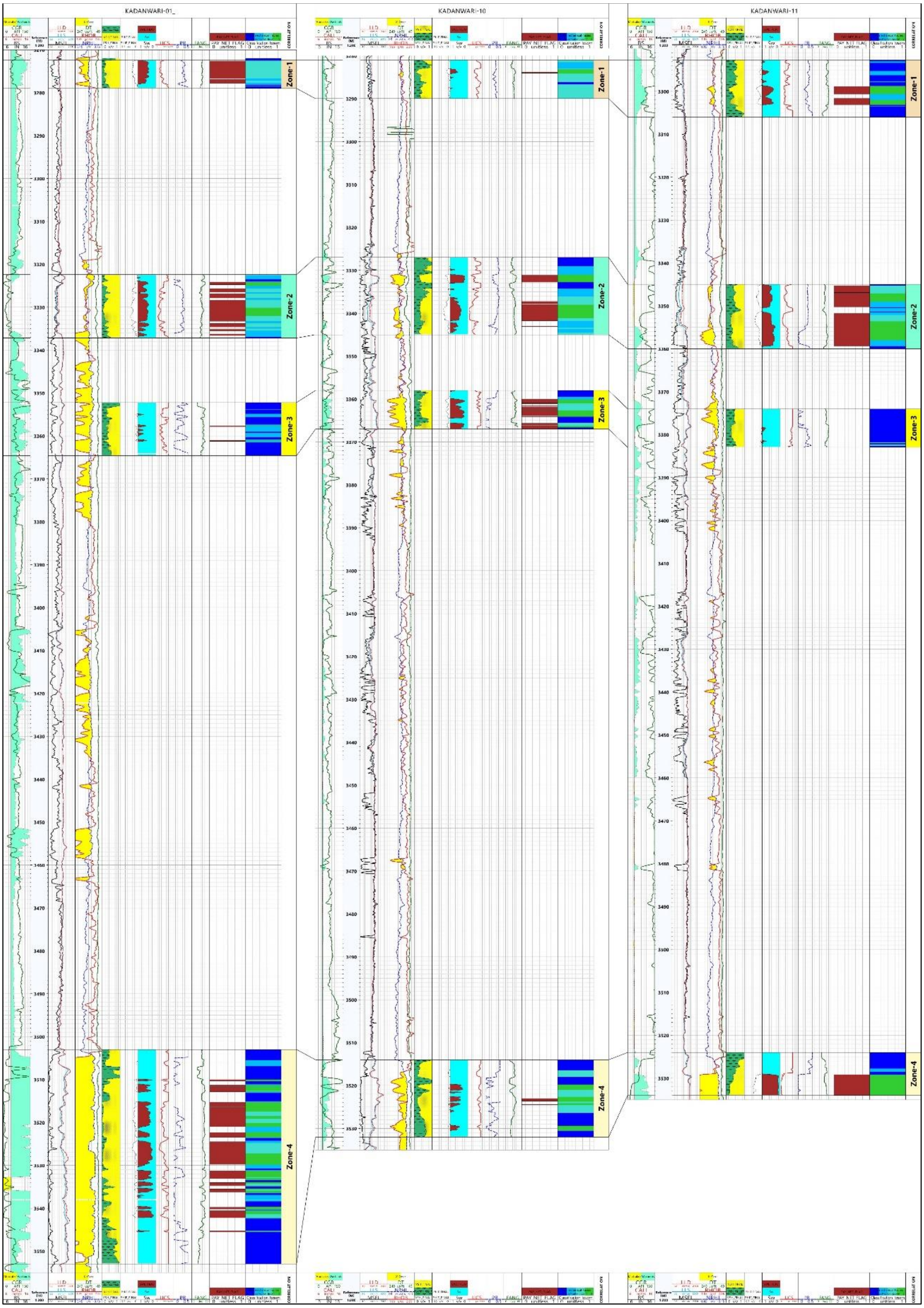
Appendix A


KADANWARI-01_
KADANWARI-10
KADANWARI-11
Zone-1
Zone-2
Zone-3
Zone-4

Appendix B

Zone	Wells	Top MD	Bottom MD	Thickness	Vsh Avg	PHIE Avg	Sw Avg	Shc Avg	Net Pay
		m	m	m	%	%	%	%	m
PZ-1	Kadanwari-1	3272.4	3279	6.6	36.7	12.2	44.9	55.1	5.12
	Kadanwari-10	3281	3290	9	30.5	9.8	57.5	42.5	0.25
	Kadanwari-11	3292	3306	14	39.2	11.3	43.8	56.2	3.25
PZ-2	Kadanwari-1	3322	3337	15	28.5	14.8	47.6	52.4	9
	Kadanwari-10	3327	3345	18	38.7	12.1	40.9	59.1	6.12
	Kadanwari-11	3345	3360	15	36.8	12	45.1	54.9	12.5
PZ-3	Kadanwari-1	3352	3364	12	37.9	6.4	53.2	46.8	0.5
	Kadanwari-10	3358	3367	9	43.7	7.4	29.9	70.1	4.47
	Kadanwari-11	3374	3383	9	38.7	4.6	54	46	0.4
PZ-4	Kadanwari-1	3503	3553	50	26.6	8.1	30.4	69.6	19.62
	Kadanwari-10	3514	3532	18	38.1	3.8	44.2	55.8	0.75
	Kadanwari-11	3524	3534	10	34.6	8.205	39.9	60.1	4.87

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ASSESEMENT OF RESERVOIR QUALITY ON THE BASIS OF PETROPHYSICAL AND GEOMECHANICAL PROPERTIES FOR KADANWARI-1, 10 AND 11, CENTRAL INDUS BASIN, PAKISTAN

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