Validation of Shaly Sand Model using Electrical Core Measurements in Low Resistive Reservoirs of Upper Assam, India

Kamleshwar Rai[1]*, Lalaji Yadav[2], B.S. Haldiya[3]
[1]SST-Ahmedabad Asset, ONGC Ahmedabad
[2]Petrophysics Division, KDMIPE, ONGC, Dehradun

Summary

Clean and relatively clean water bearing sandstone reservoirs conducts electrical currents according to Archie's law. In such reservoirs, formation factor defined as ratio of conductivities of saturating water and water saturated rock, does not change for a particular range of salinity of saturating water with underlying condition that rock does not conduct through matrix. Change on either of the condition or both results in a change of formation factor with salinity.

It is a necessary condition that formation factor changes with shaliness owing to its higher tortuosity as compared to clean reservoirs but only a sufficiently high value of cation exchange capacity ensures the conduction of electrical currents through shaly sand model. Validation of shaly sand model for the conduction of electrical currents through a rock sample is to be performed for both necessary and sufficient conditions. First existence of shaliness has to be established through correlation of basic parameters viz. intrinsic formation factor, cementation factor with cation exchange capacity on rock samples and then conductivity value of clay component Cc has to be computed through negative C_w intercept on C_w–C_o plots derived from multiple salinity conductivity measurements.

Validation of shaly sand model on electrical core measurements of low resistive complex reservoirs of oil fields of Upper Assam, India, is presented in this paper. Electrical core measurements verify for increase of resistivity with shaliness in accordance with theoretical Waxman-Smits model. However, it does not verify for decrease of resistivity with shaliness. No relationship of cation exchange capacity with weight percentages of the finer fractions comprising the rock samples of Lakwa/ Lakhmani fields could be established. Co-Cw plots are generated from over hundreds of available electrical core measurements at multiple salinities. These plots clearly indicate that there is a general increase of formation resistivity factor with shaliness or cation exchange capacity. Average Qv values for TS-2 reservoirs of Lakhmani are around 0.1 which happens to be half of the corresponding value reported for Lakwa field. This is also reverse to the general perception that Lakhmani reservoirs are low resistive and exhibiting less cation exchange capacity as compared to Lakwa.

Introduction

Archie's law relates, conduction of electrical currents in clean water bearing sandstone reservoirs as function of conductivity of saturating water (Archie, 1942). Accordingly, resistivity of a water saturated rock (Ro) is directly proportional to resistivity of saturating water (R_w), Ro = F R_w where constant of proportionality, formation factor (F) is related to porosity as $F = 1/Phi^{m}$ and porosity (Phi) exponent "m" is a measure of degree of cementation. In terms of conductivity, F is also defined as ratio of conductivities of saturating water (C_w) and fully saturated rock (C_o) as

$$C_o = C_w/F.$$

The rocks for which F is independent of C_w over a range of C_w are termed as Archie's reservoirs. On a C_w–C_o plot, such reservoirs are clearly defined by a line passing through origin with slope 1/F. In case of shaly sand, the straight line relating C_o and C_w does not pass through origin as in case of Archie's reservoirs. Shaly sand reservoirs exhibit additional conductivity Cr at origin i.e. presence of conductivity due to presence of shale even if conductivity due to water, C_w is zero.

$$C_o = C_w/F^* + Cr$$

Where F* is intrinsic formation factor corrected for shale and defined as function of total porosity and intrinsic porosity exponent, m* as

$$F^* = 1/Phi^{m^*}$$

Intrinsic formation factor also honors the boundary condition that its value is unity at the limiting porosity value of 100%. The problem in dealing with electrical response of shaly sand is to quantify C_r or C_c= F* C_r, the shale's electrical conductivity. On a C_w–C_o plot, Cc represents a negative value of C_w when C_o is equal to zero (Figure-1). It defines the new origin as if rock is saturated with water having apparently more conductivity of (C_c + C_w) instead of C_w as predicted from salinity. In other words rock will conduct through Cc even if Cw = zero and exhibit conductivity Cr. Waxman and Smits, 1968 (W-S model), demonstrated that the cation exchange capacity per unit volume, Qv, is it self related to shale conductivity Cc =BQv.

$$C_o = (C_w + BQv) / F^* \quad (1)$$

Where B is empirical factor for the conductance of clay per exchangeable cation. B represents slope derived on Cc-Qv plot. Waxman and Smits established correlation of basic parameters like intrinsic formation resistivity factor, cementation factor and tortuosity with Qv which was thought to be directly related with shaliness responsible for parallel electrical conduction of rock samples.

All type of shale/clay may or may not conduct electrical currents. The sufficient value of cation exchange capacity ensures the conduction of electrical currents through shaly sand mechanism. Validation of shaly sand model for the conduction of electrical currents through a rock sample has to be performed in following steps. First existence of shaliness has to be established through correlation of basic parameters viz. intrinsic formation factor, cementation factor with cation exchange capacity on rock samples and then conductivity value of clay component Cc has to be computed through negative C_w intercept on C_w–C_o plots derived from multiple salinity conductivity measurements. Necessary and sufficient conditions for the conduction of electrical currents through shaly sand mechanism are illustrated in Figure-1 and 2. Positive value of Cr is an indication of deviations from Archie's conditions. Three lines (blue) are showing similar Cr. Lines with increasing formation factor exhibiting higher values of Cc or increasing shaliness. In case of line with lowest formation factor indicate nominal value of Cc and does not ensure the electrical conduction through shaly sand mechanism. Higher shaliness can only be achieved with higher formation factor and sufficiently high value of Cc ensures conduction through shaly sand mechanism with respect to clean sample (CS-2) of same formation factor. Once sufficient value of shaliness is achieved then rock sample SS-3, starts exhibiting excess conduction through cation exhange. It is a very rare situation to have clean formation with formation factor similar to shaly formation. In reality formation with similar porosity as in case of

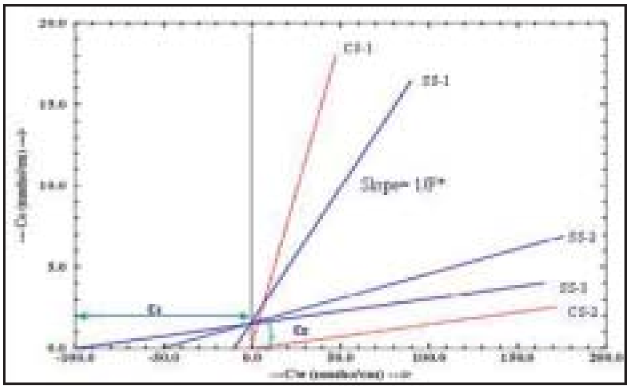

Fig.1: General shaliness concept-Necessary condition

reservoirs of Upper Assam, generally exist in nature. In such case conduction through shaly sand mechanism predominates only in lower salinity range marked with shaded region (effective shale, Figure-2).

This paper deals with validation of shaly sand model on electrical core measurements of low resistive complex reservoirs of Upper Assam, India. Co-Cw plots are generated from over hundreds of available electrical core measurements at multiple salinities. These plots clearly indicate that there is a general increase of formation resistivity factor with shaliness or cation exchange capacity. Electrical core measurements verify for increase of resistivity with shaliness in accordance with theoretical WS model. However, it does not verify for decrease of resistivity with shaliness even in lower salinity range.

Electrical core measurements

Conductivity curves and other plots presented in this paper cover almost all the electrical core measurements of rock samples from Lakwa, Lakhmani and Geleki fields reported by various authors in the past.

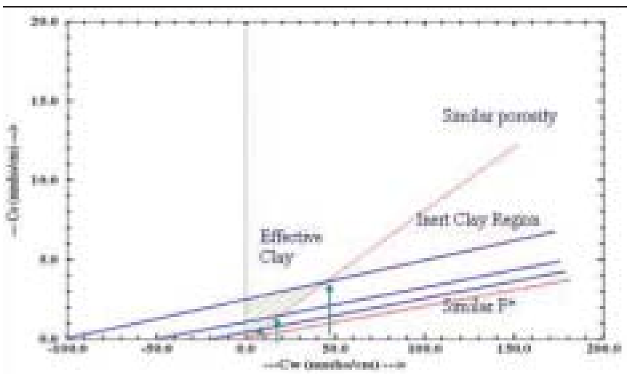

Fig.2: General shaliness concept-Sufficient condition

* Multiple salinity electrical core measurements of over hundred rock samples from twenty five conventional cores of Tipam Sand stones spread over seventeen wells of Lakwa Field have been carried out by Koithara et al 1969. Measurements on cation exchange capacity as well as shale percentages are also available for detailed study.
* About 92 dual salinity measurements on core plugs of over dozens of Lakhmani field are also available in the work carried out by Nowhar et al 1979.
* Gupta, et al., 1985, carried out a multiple salinity measurement for fifteen samples from a well from Lakhmani Field.
* Reports on dual salinity measurements for over hundred thirty rock samples from Geleki Fields are available for detailed analysis (Koithara et al 1971, Nowhar and Hasraj, 1980).
* Triple salinity measurements without cation exchange capacity and clay percentages have been carried out by Hari Kumar and Tiwari, 1999, for fifty five samples of Lakhmani field.

Variation of Qv with M*, F*, and Porosity

Plots of cation exchange capacity with intrinsic cementation factor and formation resistivity factor are presented in Figure- 3. There is a variance of intrinsic cementation factor from 1.55 to 1.95 for any value of Qv from 0.10 to 0.60 in case of Lakwa and Lakhmani Fields. These plots do not indicate any definite correlation of cation exchange capacity with these parameters. However, it is a necessary condition that cation exchange must show a definite correlation with these parameters for the existence of shaly sand mechanism and application of shaly sand model.

There is a negative correlation between Qv and porosity. Qv values are increasing with decrease of porosity. This is mainly due higher Qv values noticed against the rock samples from Tipam sand 4 and 5 reservoirs with reduced porosity.

Formation factor was found to be substantially reduced at higher formation resistivities. The results could not be extended for quantitative purposes for the lack of control (Koithara, et al. 1971).

Variation of Clay component Cc on Conductivity curves

Conductivity relationship for shaly sand is a linear curve that does not pass through the ordinate. Co-Cw plots

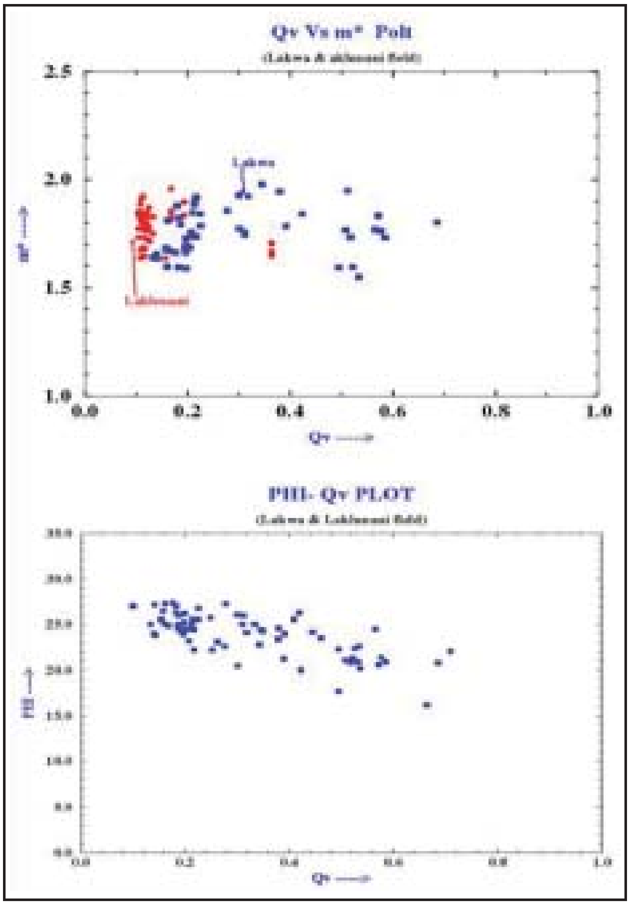

Fig.3: Variation of Qv with m* and porosity

are generated only for key rock samples with varying cation exchange capacity (Qv). Observations on these plots are capitulated in following points:

* In general, all the Co-Cw curves clearly indicate that formation factor is increasing with cation exchange capacity Qv as suggested in W-S model. There is an increase of resistivity with shaliness/ Qv at all salinity measurements of Lakwa Field (Figure-4, Koithara et al 1969).
* Rock samples from Geleki field also exhibit increase of resistivity with shaliness /Qv over entire range of salinity. All the rock samples are indicating Cc value of 2.0 mho/m independently with Qv (Figure-4, Nowhar and Hans Raj, 1980).
* Few samples from Tipam sand 4 and 5 with very high values of Qv in the range of 0.423-0.585, indicates conduction through shaly sand mechanism, where conductivity of the rock samples are increasing with increase of Qv. Cc values are varying in the range of 1.5 mho/m to 3.2 mho/m. In spite of its higher Cc

values resistivities are higher as compared to TS-2 samples with lower Qv values (Figure-4).

- In case of rock samples from Lakhmani, which is known to be classical low resistive reservoirs, value of Cc is decreasing with increasing of Qv. Cc values are in the narrow range of 2.5-3.5 mho/m respectively corresponding for Qv values in the range of 0.426 - 0.11. It is totally reverse to the conventional shaly sand model applied to compensate the decrease of resistivity with shaliness. Obviously shale/clay components are not contributing towards decrease of reistitivity of rock samples in these measurements (Figure-5, Gupta, et al., 1986).
- Cation exchange or Qv values are not available with core measurements reported by Hari Kumar and Tiwari, 1999. Conductivity curves presented in Figure-5, provides further authenticity to our inferences on variation if resistivity with formation factor for the rock samples from Lakhmani reservoirs.
- Electrical measurements on all rock samples exhibit increase of intrinsic formation factor with shaliness/

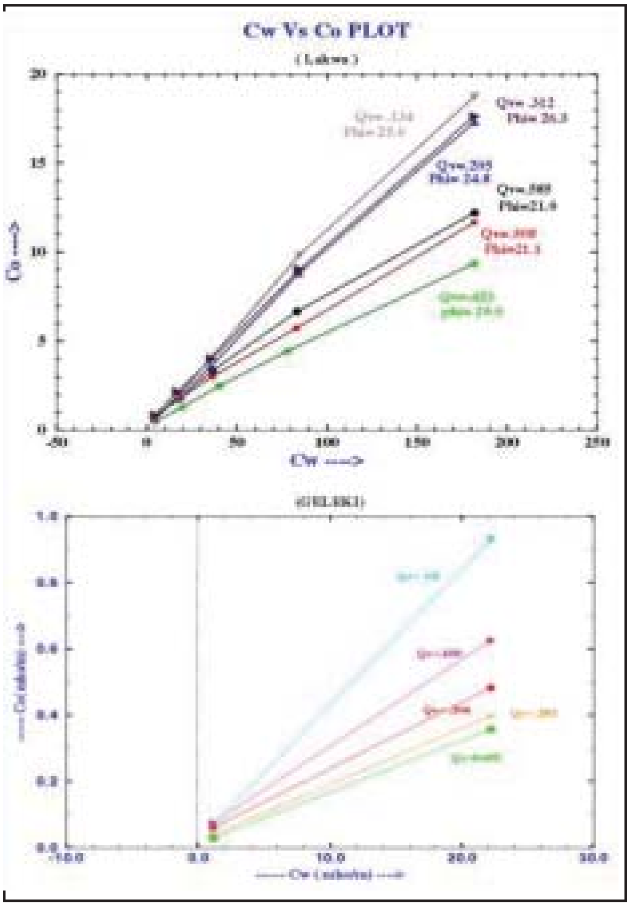

Fig.4. Conductivity curves for Lakwa and Geleki Fields

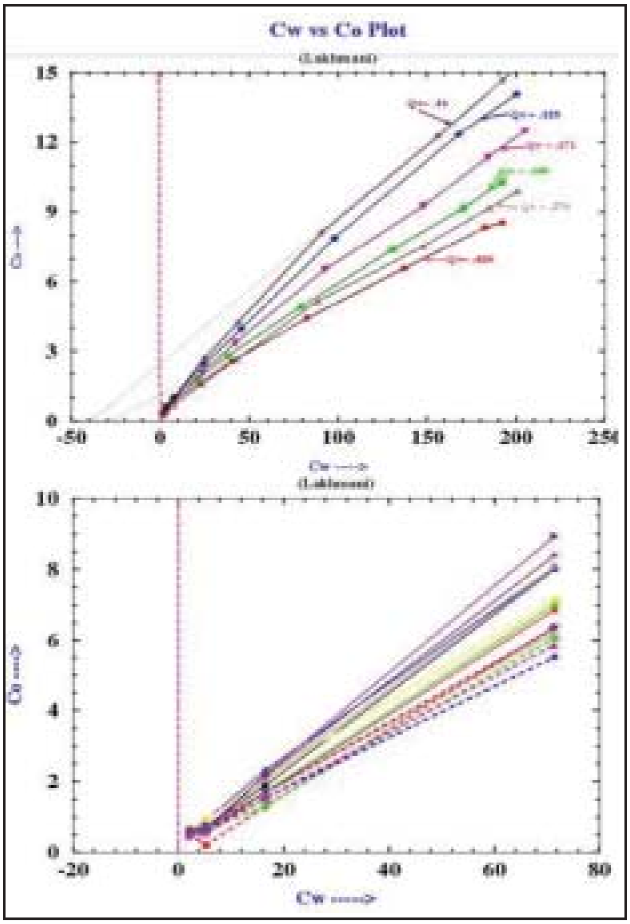

Fig.5. Conductivity curves for Lakhmani Field

Qv i.e. decrease of conductivity, Co with increasing shaliness at lower as well as higher salinities. Conductivity curves validates only for basic necessary conditions for existence of shaliness. However, rock samples do not validate for the sufficient value of Cc for conduction of electrical currents to reduce the resisistivity of the rock samples. Excess conductivity through shaly sand mechanism is not noticed even in lower salinity range.

Variation of cation exchange capacity with clay percentage

The next step towards validation of shaly sand model is correlation of Qv and clay percentages derived through independent core measurements. Qv values were measured by methylene blue method and clay percentages are reported by separating particles with diameters less than 2 microns after crushing the rock samples. Koithara etal 1969, attempted to correlate the cation exchange capacity with weight percentages of the finer fractions comprising the rock samples of Lakwa Field but no relationship could be established between the two.

For TS-2 average value of Qv = 0.22 meq/cc was recommended for interpretation purpose (Figure-6). Average Qv values for TS-2 reservoirs of Lakhmani are around 0.12 which happens to be half of the corresponding value reported for Lakwa field. This is also reverse to the general perception that Lakhmani reservoirs are low resistive and exhibiting less cation exchange capacity as compared to Lakwa (Figure- 6).

For Geleki # 1, a fairly good relation has been noticed between the cation exchange capacity per unit pore volume and the shale percentage of particles less than 5 microns in diameter. The weight percentage of particles with diameter less than 10 microns can be taken to represent only the upper limit of the shaliness for interpretation (Koithara etal 1971). This observation was mainly based on few rock samples covering all the reservoirs Tipam sand-1 through 6 and could not be generalized for entire field.

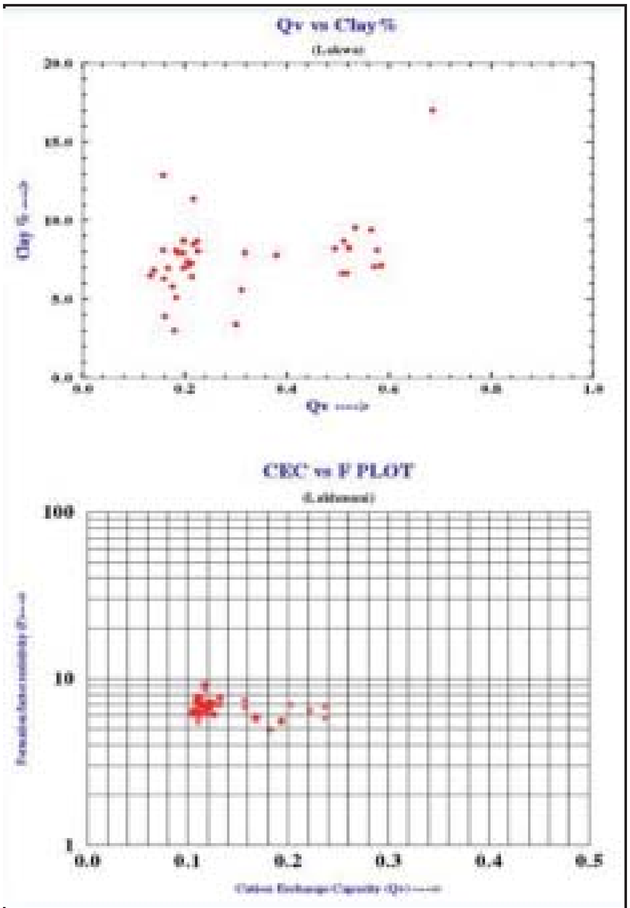

Fig.6. Variation of Qv with Clay percentages and formation factor

Variation of Excess Conductivity with Cation Exchange capacity

Theoretical conductivity curves derived from Archie's (Black Colour) and Waxman-Smits model (Red curves are also presented along with actual core measurements (Dotted blue curve joining blue filled circles) in Figures-7-9 for Lakhmani and Lakwa Fields. Rock samples selected with different Qv values. Archie's conductivity curve is drawn as line with slope 1/F* passing through origin. Theoretical Co values at different Cw are computed using equation-1 for known values of F* and Qv values. B factor has been computed with following equation (Waxman-Smits, 1968).

B= {1 – a exp(-Cw/γ)}0.001 λ_{Na} where a= 0.6, Υ= 0.02 and λ_{Na} = 38.3 $cm^2 equiv^{-1} ohm^{-1}$

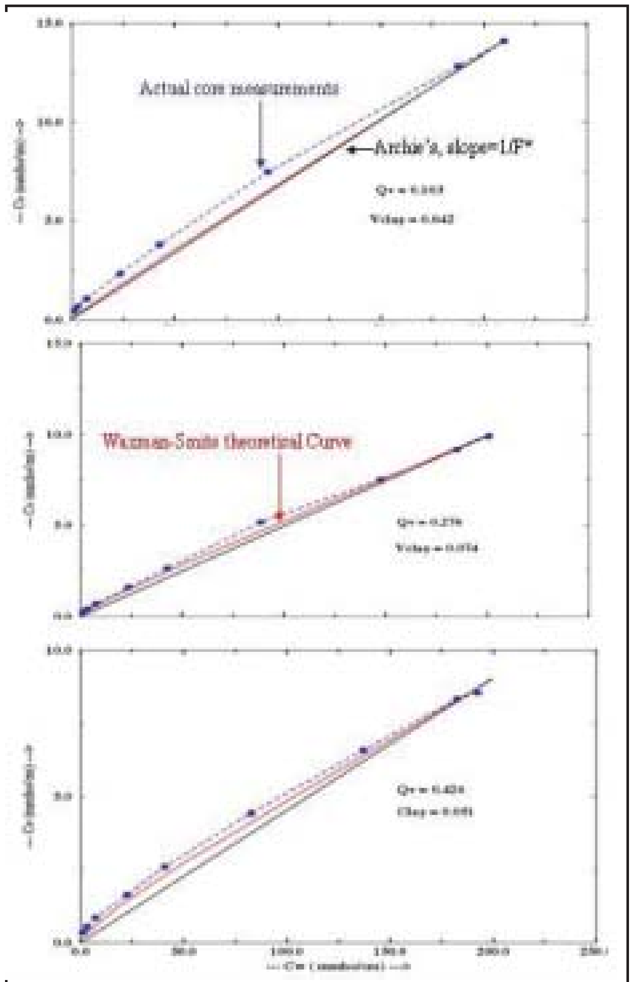

Fig.7. Variation of Excess Conductivity with Qv for Lakhmani Field

A comparison of conductivity curves derived from available electrical core measurements with theoretically derived curves for Waxman and Smits model, clearly indicates that relatively cleaner reservoir rock does not conduct through shaly sand mechanism. Cation exchange mechanism explains only nominal portion of the conduction of the rock sample. Excess conductivity through shaly sand mechanism increases with the increase of formation factor or Qv. Nearly half of the electrical conduction is through W-S model for an increase of Qv value from 0.11 to 0.426 .i.e. nearly four times(Figure-7).

Conductivity curves (Figures- 8 and 9) are presented for six samples of Lakwa Field with varying Qv values from 0.13 to 0.508. All the rock samples with Qv values more than 0.3, from Tipam sands-4 and 5, are conducting through shaly sand mechanism. Departure of W-S curves from actual one is noticed below this value is indicative of some other mechanism for conduction of electrical conduction as in case of samples from Lakhmani field.

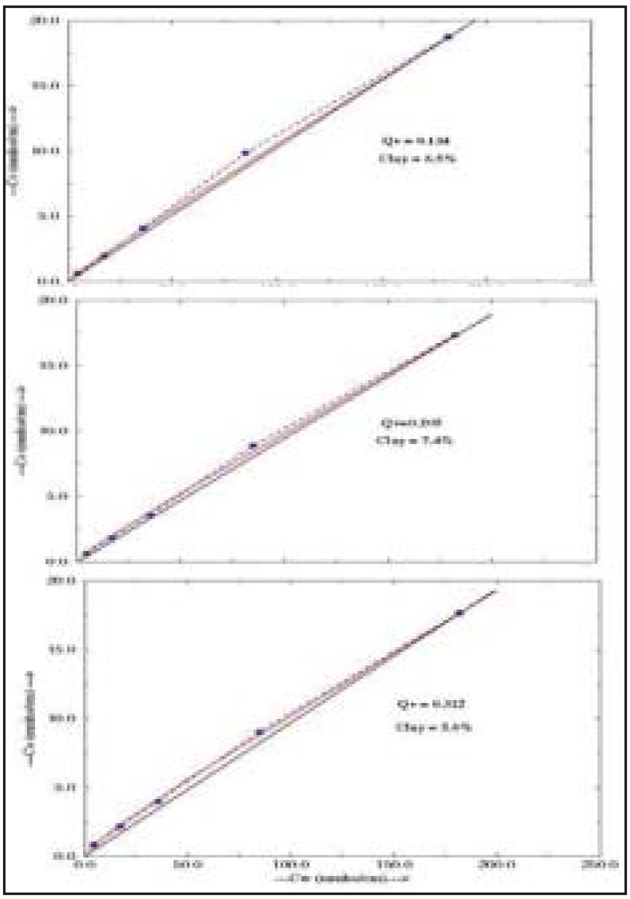

Fig.8. Variation of Excess conductivity with QV for Lakwa Field

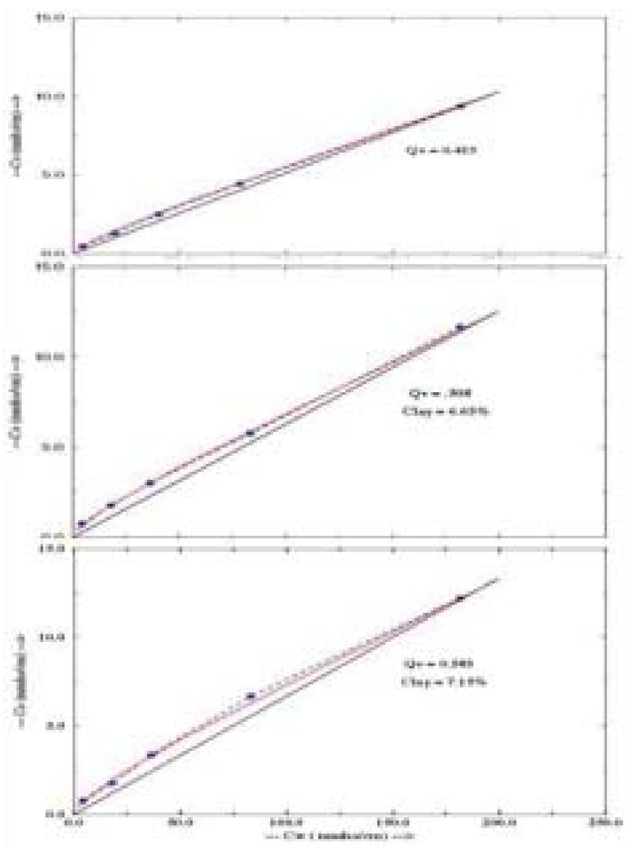

Fig.9. Variation of Excess conductivity with QV for Lakhmani Field

Discussion and conclusions

Using the experimental data of Waxman and Smits (1968), Clavier et al (1977), found a strong correlation between the exponent m* and clay content. The exponent m* increases with shaliness, reaching values as high as 2.9 in shale. This would suggest that the tortuosity of shaly sand is much greater than that of clean sands. It means F* will be higher in case of shaly sand as compared to clean sand. Apparent decrease of F with salinity may not always be associated with shaliness. It only represents some positive value of Cr. So, ratio F/F* is an electrical measure of departures from Archie's conditions and it is not an electrical measure of shaliness (Worthington, 1995). Attributing the decrease of apparent formation factor F as compared to F* at lower salinity, to the shaliness without verification on the sufficient value of Cc on Co-Cw plot, may be misleading and far from realistic situation.

In general, higher clay content in shaly reservoir leads to greater resistivity factor which should result in higher resistivity. But at the same time higher clay content results in greater Qv which tends to reduce the resistivity of the reservoir. Which of these two competing forces will prevail depends on such factors as clay type and mode of distribution, and total and effective porosities. All of these to a certain extent determine values of F* and Qv. In shaly reservoirs filled with water of same mineralization, higher formation factor, as defined by Waxman-Smits model, could corresponds to either higher, lower or same resistivity depending on formation water salinity and cation exchange capacity associated with shale fraction of the reservoir as indicated in Figure-2. At lower water salinity or water conductivities Qv prevails over F* in shaly sample.

Co-Cw plots are generated from over hundreds of available electrical core measurements at multiple salinities. These plots clearly indicate that there is a general increase of formation resistivity factor with shaliness or cation exchange capacity. Electrical core measurements verify for increase of resistivity with shaliness in accordance with theoretical W-S model. However, it does not verify for decrease of resistivity with shaliness.

No relationship of cation exchange capacity with weight percentages of the finer fractions comprising the rock samples of Lakwa/ Lakhmani fields could be established. Average Qv values for TS-2 reservoirs of Lakhmani are around 0.1 which happens to be half of the corresponding value reported for Lakwa field. This is also reverse to the general perception that Lakhmani reservoirs are low resistive and exhibiting less cation exchange capacity as compared to Lakwa.

A comparison of conductivity curves derived from available electrical core measurements with theoretically derived curves for Waxman and Smits model, clearly indicates that relatively cleaner reservoir rock does not conduct through shaly sand mechanism. Cation exchange mechanism explains only half of the conduction of the rock sample even with highest value of cation exchange capacity/ shaliness. Relatively cleaner rock samples exhibit large values of negative cutoff computed through extrapolation of linear trend and seems to have the apparent electrical conduction some what similar or even more as compared to shaly sand mechanism. Excess conductivity can only be modeled with decrease of formation factor or decrease of resistivity due to surface conductance phenomenon (Evers and Iyer, 1975) associated with smaller grain sizes and micro porous network (Swanson, 1985).

Acknowledgements

Authors are thankful to ONGC authorities for permission to publish this article. Authors are grateful to Dr. D.M. Kale, E.D.- Head, KDMIPE for his kind permission to undertake this study and for providing necessary facilities. Critical review of the work and encouragement by Shri Debyendu Sar, G.M. (Geophysics) and Shri R. P. Verma, Dy. G.M. (Logging), KDMIPE, Dehradun are gratefully acknowledged.

Views expressed in this paper are those of the authors only and may not necessarily be of ONGC.

References

Archie, G.E, 1942, The electrical resistivity log as an aid in determining some reservoir characteristics, SPE-AIME, transactions Vol. 146.

Clavier, C., Coats, G., and Dumanoir, J., 1984, Theoretical and experimental bases for the Dual-Water model for interpretation of shaly sand, SPEJ, April,153.

Evers, F. E. and Iyer, B.G., 1975, Quantification of surface conductivity in clean sandstones, SPWLA, 16th Annual Logging Symposium Transaction of Society of Professional Well Log Analyst.

Given, W.W, 1987, A conductive rock matrix model (CRMM) for the analysis low-contrast Resistivity formations, The Log Analyst.

Gupta, N.C., Chandra, Y., De, D. and Sinha, G.S., 1985, Study of surface conductance on the core samples of LT-47, under in-situ condition of pressure, KDMIPE, ONGC, Dehradun, India, Unpublished Report.

Juhasz, I. 1979, The central role of Qv and Formation water salinity in the evaluation of shaly formation, SPWLA 20th Annual Logging Symposium, June 3-6.

Koithara, J., Bisht, J.S. and Nohwar, U.V.S., and Hansraj, 1971, Laboratory measurement of logging parameters on cores from Tipams of Geleki field., IPE, ONGC, Dehradun, India, Unpublished Report.

Koithara, J., Hashmy, K. H., and Mehra, Y.M., 1969, Laboratory measurement of logging parameters on the Tipam sandstone cores on Lakwa field, IPE, ONGC, Dehradun, India, Unpublished Report.

Nohwar, U.V.S., Verma, R.P., and Hansraj, 1979, Laboratory determination of Petrophysical parameters and their Inter-relationships for TS-1 & TS-2 sands of Lakhmani field. IPE, ONGC, Dehradun, India, Unpublished Report.

Nohwar, U.V.S., Hansraj, 1980, Laboratory determination of Petrophysical parameters and their Inter-relationships for TS-5 of Geleki field, IPE, ONGC, Dehradun, India, Unpublished Report.

Wilson, M.D., Pittman, E.D., 1977, Authigenic clays in sandstones: Recognition and influence on reservoir properties and paleoenvironmental analysis, vol. 47, no.1, 3-31.

Shivsharan, V. P. and Ramanan, S., 1989, Petrography of low resistivity reservoirs in Lakhmani Field, Probe Centre, IRS, ONGC, Ahemdabad, India, Unpublished report.

Swanson, B. F., 1985, Microporosity in reservoir rocks, its measurement and influence on electrical resistivity, SPWLA, 33 rd Annual Logging Symposium Transaction of Society of Professional Well Log Analyst, June, 17-20.

Triplehorn, 1967, Occurances of pure well crystallized 1M illite in Cambro-Ordovician sand stone from RhowideE1 Baguel Field, Algeria, Journal of sedimentary petrology, 37, 879-884.

Waxman, M.H, Smits, L.J.M. 1968, Electrical conductivities in oil bearing shaly sand, SPE journal, June 1968.

Worthington, P.F., 1995, A continuum approach to the petrophysical classification and evaluation of reservoir rock. Petroleum Geoscience.