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Effective Delineation of Formation Tops Using Wavelet Transform on Well log Data of Kutch Offshore Basin, India

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Summary

Continuous wavelet transformation (CWT) was applied to gamma-ray, resistivity and neutron porosity log data sets from two wells of Kutch offshore basin, in western India, to determine the depth to the top of Oil and/or Gas formation zones. A variety of wavelets were employed to analyse the above log data sets to not only identify the depths to tops of the formations but also to determine the optimum wavelet that best suits for well-log data analysis. Among the number of wavelets used for analysis, the Gaus1 wavelet is found to be the most suitable one, which gave the best resolution in identifying the depths of formation tops in all the logs. A histogram analysis of CWT coefficients was also made to further quantify this observation. Histogram analysis showed that, of all the wavelets considered for the present study, the number of occurrences of high CWT coefficients is more for Gaus1 wavelet, implying that Gaus1 wavelet to be the most appropriate and optimum one for determining the depths of the formation tops in data sets of both wells. The depths of formation boundaries estimated from scalogram plots of logs agree well with the known depth estimates, obtained from petrophysical analysis of well data.

Key words: *Continuous Wavelet Transform, Kutch offshore basin, Well log analysis*

Introduction

Geophysical well-log data manifest physical properties of the subsurface formations as a function of depth. They contain numerous transitory characteristics, including cyclicities, trends, and abrupt changes. Each of these signifies particular frequency characteristics representative of the subsurface formations. Since the depth-locations of these formations are irregular and without any order, conventional signal processing tools, such as Periodogram analysis, Fourier transformation, etc. fail to identify their spatial location in well data. They can only provide the frequency information of the signal and fail to provide any further information about where in space (depth) these frequencies occur (see Chandrasekhar and Rao, 2012 and references therein).Therefore an effective signal processing tool, which can provide information about the presence of characteristic frequencies as a function of depth, is required. Wavelet analysis (WA) just does this. WA of well logs can identify cyclicities, trends, depth to the top of formations, etc, and thus provides space-frequency localizations of differentformations (Vega, 2003; Chandrasekhar and Rao, 2012).

In the present study we have applied continuous wavelet transformation (CWT) on gamma-ray, resistivity and neutron porosity logs of two wells (A and B), situated in Kutch offshore basin in Western India. The main objectives of this study are: (1) To identify the depths to the formation tops using WA and (2) To identify the optimum wavelet that shows the best resolution in identifying the formation tops. For this purpose, various wavelets were applied and their scalograms of each log of wells A & B were examined. A further quantitative study to determine the optimum wavelet for well-log data analysis has been done by histogram analysis of CWT coefficients.

Data Base

For the present study, gamma-ray, resistivity and neutron porosity logs from two vertical wells (Well A and Well B) from the Kutch offshore basin, located in the northern part of the Arabian Sea, of the west coast of India (Fig. 1) was

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provided by the Oil and Natural Gas Corporation Limited (ONGC Ltd.).The data were sampled at 0.1524 m. Data length for Well A and Well B are 550m-1200m and 600 to 1400 m respectively.

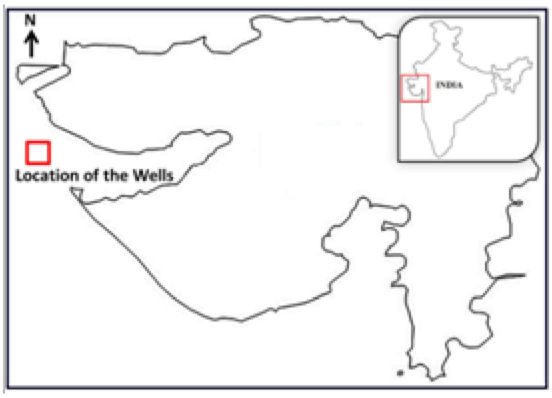

Fig.1. Geographical location of the Kutch offshore basin. Location of Wells, whose data are used for the present study, is indicated by square.

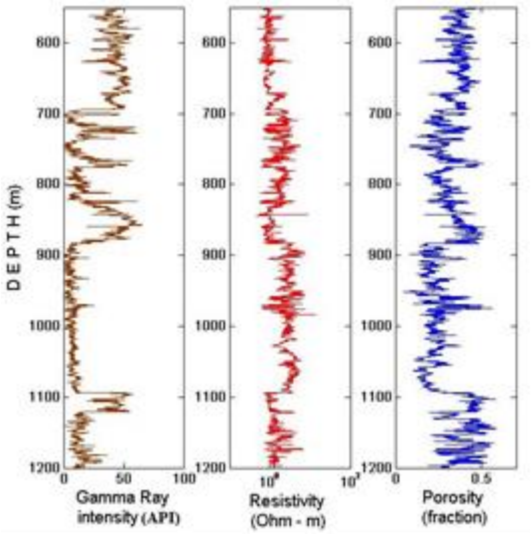

Fig.2. Gamma-ray, Resistivity and Neutron porosity logs of Well-A.

Wavelet Analysis

Theory

The continuous wavelet transform of a signal f(x), as a function of space is given by

$$CWT(\delta x, s) = \frac{1}{\sqrt{s}} \int f(x)\, \psi\left(\frac{x-\delta x}{s}\right) dt$$

As seen in the above equation, the transformed signal is a function of two variables, δx and s, the translation and scale parameters, respectively. ψ(x) is the transforming function, and it is called the mother wavelet. The term wavelet means a wave of finite duration whose average amplitude is zero (see Mallat, 1999).The spatial translation δx is related to the space location of the wavelet, as it is slide continually along the signal. This term, obviously, corresponds to depth information in the transform domain. The scale parameter, s, in the wavelet analysis is similar to the scale used in maps. As in the case of maps, high scales correspond to a non-detailed global view (of the signal), and low scales correspond to a detailed (local) view. Similarly, in terms of frequency, low frequencies (high scales) correspond to a global information of a signal (that usually spans the entire signal), whereas high frequencies (low scales) correspond to a detailed information of the signal (Chandrasekhar and Rao, 2012).

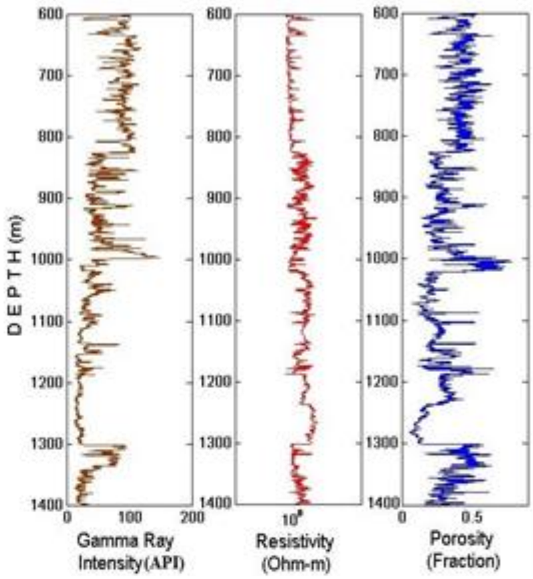

Fig.3.Same as Fig. 2, but for Well B.

Continuous Wavelet Transform

As shown in the above equation, in CWT the signal to be transformed is convolved with the mother wavelet and the transformation is computed for different segments of the data by continuously varying δx and *s* (see Chandrasekhar et al., 2013). Because the wavelet window can be scaled (shrinked or expanded) at different levels of analysis, identification of depth location of thin formations in particular, becomes much easier. Fig. 4 shows the flow diagram of CWT operation. Selection of the mother wavelet forms an important aspect of WA. Therefore, in the present study, we have used different wavelets and checked for their suitability in identifying depth location of formation zones in each log data of both wells.

Edge Effect

Generally, CWT of truncated signals yield high CWT coefficient values at the edges of the signal as shown in the scalogram plot of neutron porosity log of well A (see Fig. 5a). In the present study, the presence of such edge effects in the CWT scalograms has masked the features of subsurface formations of interest in the data. Therefore, prior to further analysis, edge effects in the data were removed using the symmetric half-point method (Strang and Nguyen, 1995).

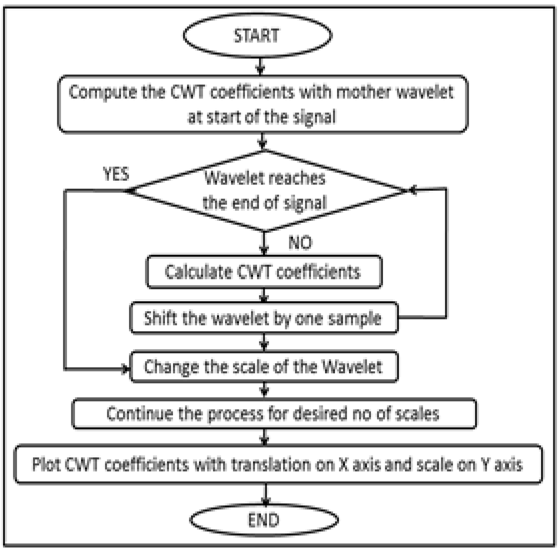

Fig.4.Flow chart for Continuous wavelet transformation.

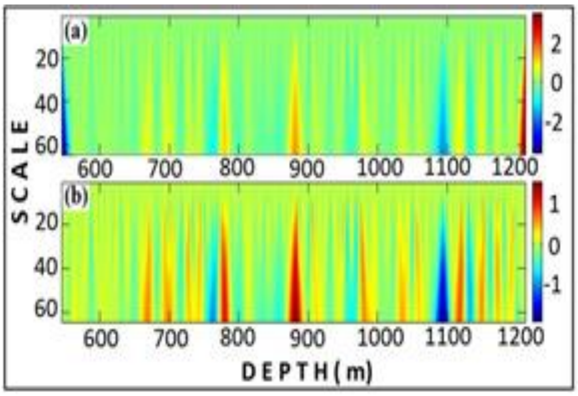

Fig.5.Example of scalogram plots of CWT analysis of neutron porosity log data of Well-A, when edge effects in the signal are not removed (**a**) and removed (**b**).

On visual examination of the edge-effect-removed scalograms of different wavelets corresponding to each log data of each well, we have found Gaus1 and Gaus3 wavelets to have shown acceptable resolution so as to enable correct interpretation of the data. Although Vega (2003) has shown that Morlet wavelet to be useful in well log data analysis, Chandrasekhar and Rao (2012) in their recent study have proved that Morlet wavelet to be unsuitable for analysing well log data of Bombay offshore basin. However, in the present study, Morlet wavelet is used again to test its suitability for well log data of Kutch region. Fig.6. shows the shapes of the above three wavelets.

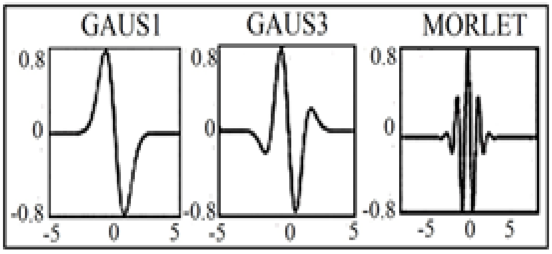

Fig.6. Shapes of the wavelets Gaus1, Gaus3 & Morlet

Fig.7, Fig.8 and Fig. 9 respectively show the scalogram plots of gamma-ray, neutron porosity and resistivity logs of Well A, corresponding to Gaus1, Gaus3 and Morlet wavelets.

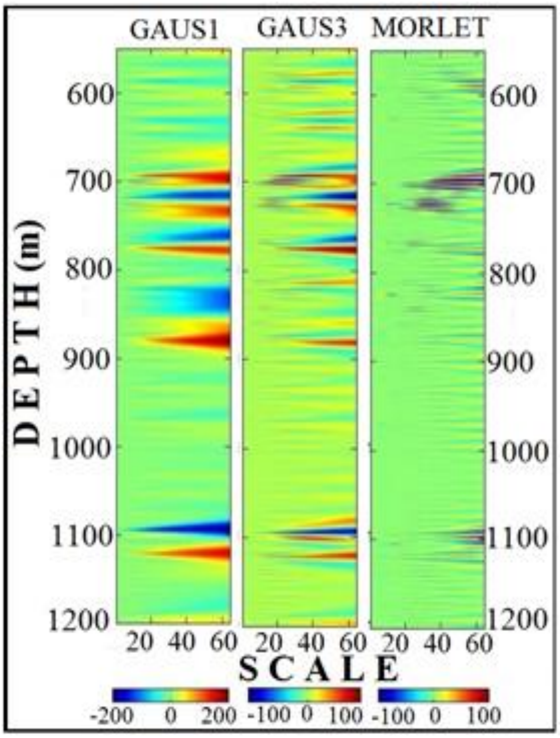

Fig.7. Scalograms of the Gamma-ray log of Well-A generated using Gaus1, Gaus3 and Morlet wavelets

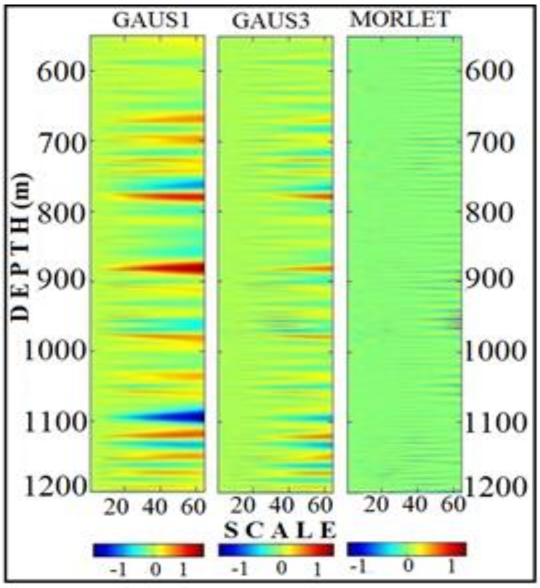

Fig.8. Scalograms of the Neutron log of Well-A generated using Gaus1, Gaus3 and Morlet wavelets.

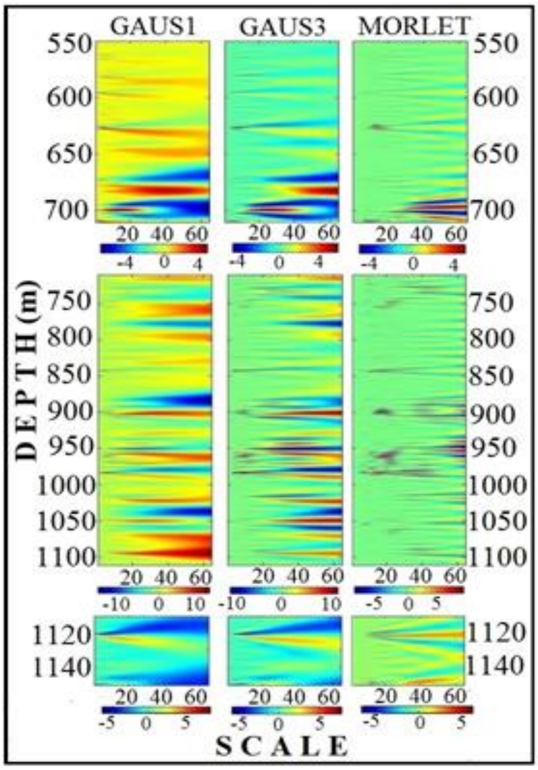

Fig.9. Scalograms of the Resistivity log of Well-A generated using Gaus1, Gaus3 and Morlet wavelets.

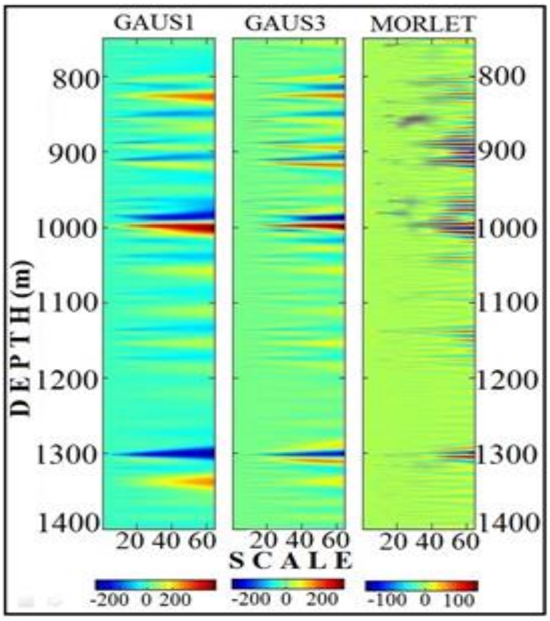

Fig.10. Scalograms of the Gamma-ray log of Well-B generated using Gaus1, Gaus3 and Morlet wavelets.

Similarly, Fig.10, Fig.11 and Fig. 12 respectively show scalogram plots of gamma-ray, neutron porosity and resistivity logs of Well B, corresponding to Gaus1, Gaus3 and Morlet wavelets. To facilitate better interpretation, resistivity data of well A were first divided into three parts with overlapping data levels with each part individually analyzed (Figs. 9). Similarly, resistivity data of Well B were divided into two parts before further analysis (Fig. 12).

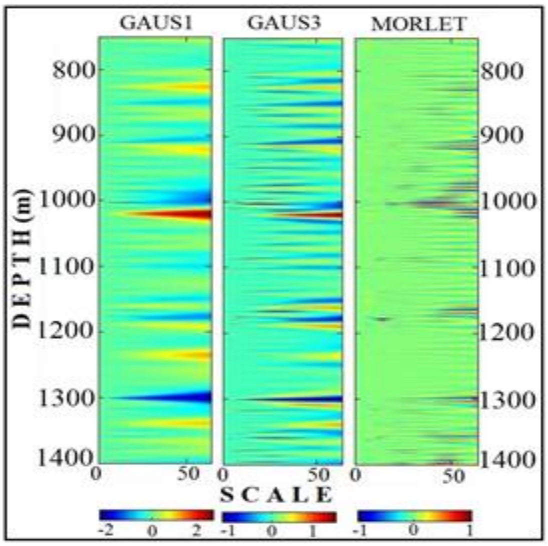

Fig.11. Scalograms of the Neutron log of Well-B generated using Gaus1, Gaus3 and Morlet wavelets.

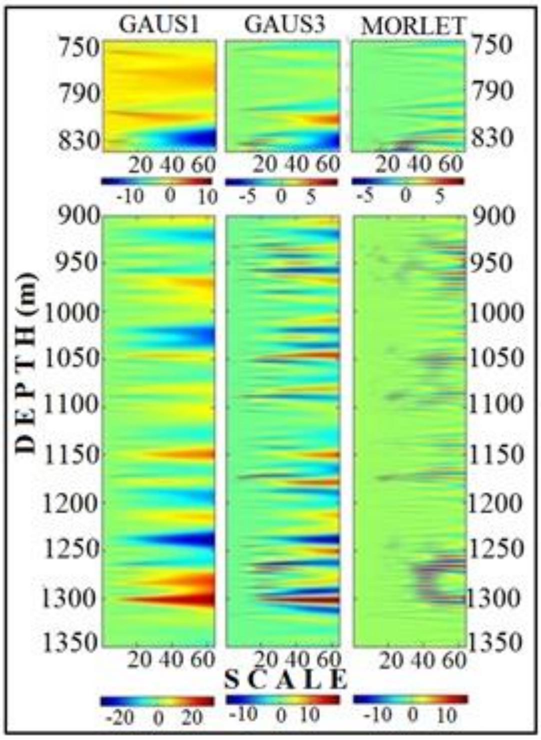

Fig.12. Scalograms of the Resistivity log of Well-B generated using Gaus1, Gaus3 and Morlet wavelets.

Identification of Optimum Wavelet

Visual inspection of results of both the wells clearly indicates that, among all the wavelets used, the Gaus1 wavelet has effectively resolved the depths to the tops of formations in all the logs of both wells. A histogram analysis of CWT coefficients was done to further quantify this observation.

Utilizing all the CWT coefficients corresponding to each log and each wavelet, histogram plots depicting the number of times the same coefficient values occurred, have been generated. Such plots corresponding to Well A and Well B are shown in Figs. 13 and 14.The number of occurrences mentioned on the vertical axes in Figs. 13 and 14 indicates the number of times a CWT coefficient occurs. That means, for example, the CWT coefficient values ranging from 15-25 occur about 600 times corresponding to scale 64 in the Gamma-ray log analysis using Gaus1 wavelet, for Well A (Fig. 13). Similarly, high CWT coefficient values in the range of 65-75 occur about 100 times (Fig.13).When compared to the number of occurrences of high CWT coefficients of Gaus1 wavelet with those of Gaus3 and Morlet wavelets in all data sets of both the wells (Figs. 13 and 14), it can be clearly seen that the number of times the high CWT coefficients occur is more in case of Gaus1 wavelet than in Gaus3 and Morlet wavelets. This confirms the suitability of Gaus1 wavelet in the present study. This also supports the observation made by Chandrasekhar and Rao (2012) that Gaus1 wavelet is more suitable for identification of depth to the tops of formations in different well log data sets. Different colours in the histogram bars represent different scales of the wavelets. Blue, green and red respectively indicate the scales 16, 32 and 64 (see legend of Figs.13 and 14). While the good resolution in scalogram plots at lower scales indicates the suitability of the wavelet to correctly identify the depth to the top of formations, the resolution at higher scales indicates its suitability to identify the large-scale variations of formations. The high number of occurrences of CWT coefficients in histograms at all scales indicates greater suitability of the wavelet for analysing the well log data.

Results & Discussion

Shale (sand) formations show high (low) gamma-ray intensity. Accordingly, the alternate sequences of shale and sand/limestone formations show high and low gamma-ray intensities. Since we are interested in identifying reservoir rocks (which are non-shaly), identification of these boundaries in well-log data is very essential. We have identified five formation tops, Sandstone top 1 (ST1), limestone top 1 (LT1), Limestone top 2 (LT2), shale top (ShT) and Sandstone Top 2 (ST2) whose depths are obtained from the petro-physical analysis of well data.

A careful examination of scalograms corresponding to gamma-ray logs of well A (Fig. 7) and Well B (Fig. 10) clearly shows that among the three wavelets, the results of Gaus1 wavelet show a well-marked high CWT coefficients (red colour) representing a reduction in gamma-ray intensity, indicating the presence of non-shaly formation. In well A, corresponding to Limestone2 top (LT2) located at 879 m, high positive CWT coefficients observed (see Fig.7). Similarly Shale Top (ShT) is observed with high negative CWT coefficients (blue colour) at depth 1093m. Although such features are less distinct in the results of Gaus3 wavelet compared to that of Gaus1, the resolution is further poor in the results of Morlet wavelet. Thus we believe that Gaus1 wavelet is best suited for analysis of gamma-ray log data.

Analysis of the scalograms of the Neutron logs of well A (Fig. 8) and Well B(Fig. 11) show high positive coefficients at different depths corresponding to the decrease in neutron porosity. Generally, shaly formations show high neutron porosity than the non shaly formations because of the clay bound water. Hence decrease in neutron porosity is an indication of change of non-reservoir rock to reservoir rock. Depths corresponding to positive CWT coefficients (red colour in Figs.8 and 11) observed in the scalograms of the Gaus1 wavelet match well with the depths of the formation tops ST1, LT1, LT2 and ST2. In neutron porosity log data also, Gaus1 wavelet shows higher resolution in identifying the depths to the top of formations than Gaus3 and Morlet wavelets.

Resistivity of the reservoir rock mainly depends on the resistivity of the fluid (water/hydrocarbon) present in it. Hydrocarbon-bearing formations generally possess high resistivity. Accordingly, scalograms of resistivity logs ofwell A (Fig.9)and Well B (Fig. 12) show high CWT coefficients (blue colour) at different depths corresponding to increase in the resistivity values. As mentioned earlier, the formation tops ST1, LT1,LT2, and ST2 are associated with increase inresistivity, which clearly identified with the high CWT coefficients (blue colour in Figs. 9 and 12) in the scalograms of the Gaus1 wavelet. Similarly shale top (ShT) is also identified with high coefficients (red colour in Figs. 9 and 12). As regards to resistivity data, Gaus3 wavelet also shows considerable resolution in delineating the formation tops, albeit, very poor resolution seen in the scalograms of Morlet wavelet.

Table 1 provides a comparison between the known estimates of the depths to the tops of formations obtained from petrophysical analysis of well data and those determined from wavelet analysis with Gaus1 wavelet, corresponding to both wells. Table 1 clearly explains the good agreement between the known depth estimates and those obtained from wavelet analysis using Gaus1 wavelet.

Conclusions

Continuous wavelet transformation is an efficient tool for the analysis of the non-stationary signals like well logs. Gaus1 wavelet shows good resolution in delineating the formation boundaries in well log data sets of both well A and Well B, belonging to Kutch offshore basin. The estimated depths of the formation boundaries using CWT analysis match well with the known depth estimates. The resolution of the Gaus3 wavelet is less when compared with the Gaus1 wavelet. Morlet wavelet has very poor resolution in identification of the formation, confirming the observations made by Chandrasekhar and Rao (2012) on these lines. Histogram analysis of the CWT coefficients further validates our observation. Accordingly, we conclude that the optimum wavelet identified for the present study is Gaus1 wavelet.

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

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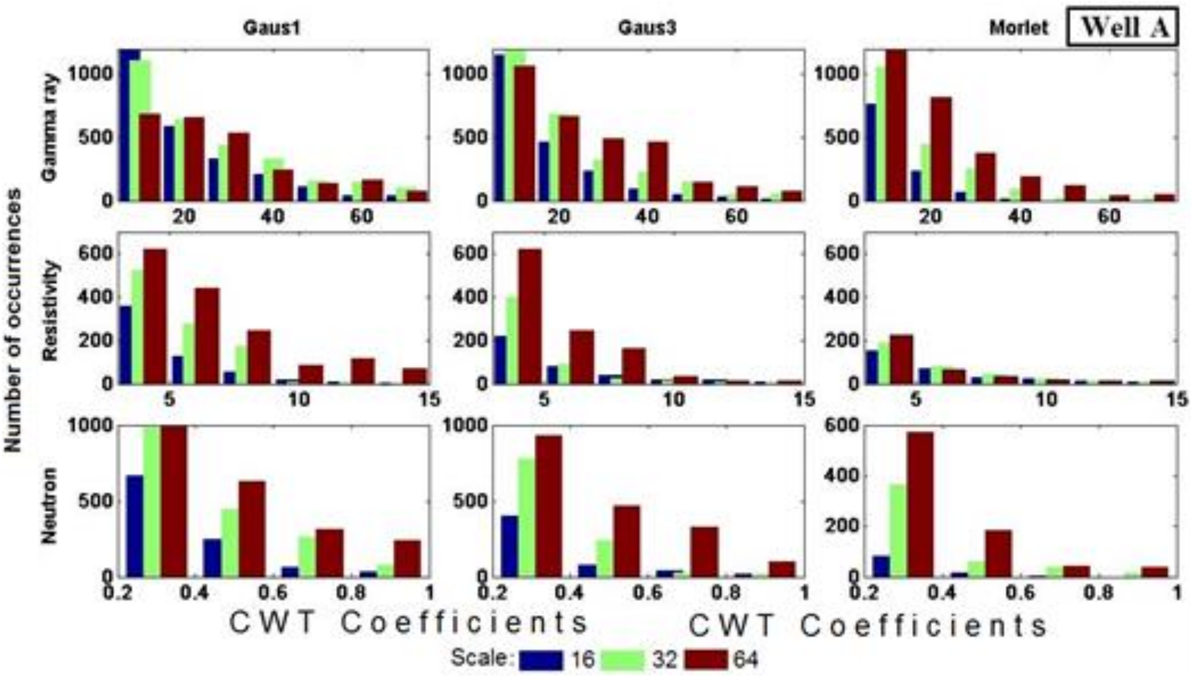

Fig.13. Histogram plots of Gamma-ray, Neutron and Resistivity logs of Well A.

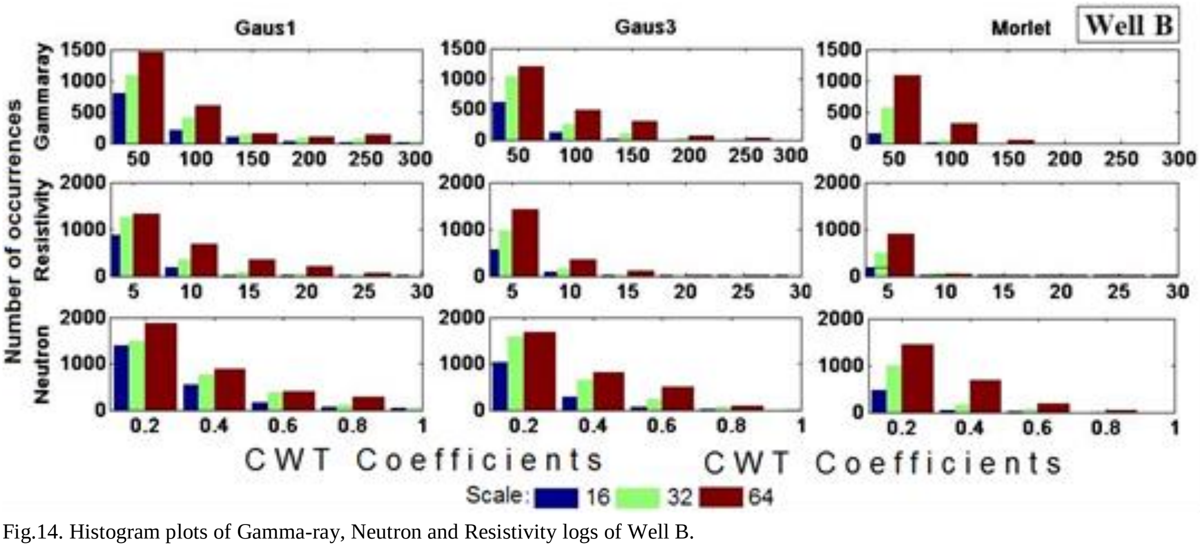

Fig.14. Histogram plots of Gamma-ray, Neutron and Resistivity logs of Well B.

Table.1. Comparison of the depths of formation tops estimated from Scalograms (gamma-ray, neutron porosity and resistivity logs) of Gaus1 wavelet with known depths of the formation tops corresponding to both the wells.

Gaus1	Formation tops	Known Depths	Gamma-ray	Neurtron Porosity	Resistivity
Well A	ST1	672	671	670	671
	LT1	697	697	697	699
	LT2	879	879	879	879
	ShT	1096	1093	1093	1095
	ST2	1122	1121	1119	1120
Well B	ST1	808	805	806	805
	LT1	827	827	827	829
	LT2	1020	1017	1020	1020
	ShT	1302	1301	1302	1302
	ST2	1338	1336	1339	Not clear