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ISSN 0974-5904, Volume 10, No. 02

DOI:10.21276/ijee.2017.10.0202

International Journal of Earth Sciences and Engineering

April 2017, P.P. 155-160

Analytical Velocity Modeling In High Pore-Pressure Environment, Offshore East Coast of India

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Abstract: *A reliable time-to-depth conversion becomes quite challenging in a complex high pore-pressure depositional environment. This study examines various relations between depth and interval velocity to ascertain plausible models to be used for conversion from time to depth when processing surface seismic data. Sonic data from two wells each from the Mahanadi basin, the Krishna-Godavari basin and the Cauvery-Palar basin in the offshore east coast of India have been used for analysis. Four time-depth models have been tested on selected data set. The first is a linear interval velocity model in depth; the second, the linear interval velocity in time; the third, the average velocity in time and the fourth, the exponential interval velocity in time. The results from time-depth modeling suggest that the average velocity model in time is the most plausible model among all the models analyzed here. This model can be used for time to depth conversion of surface seismic data in the high pore-pressure zones of Mahanadi Basin. This study suggests that the testing of various analytical velocity models is extremely important before utilization of well velocities for the prediction of pore-pressure at any new drilling location.*

***Keywords:** High porepressure, Modeling, Interval velocity, Average velocity*

1. Introduction

Abnormal pore pressures occur in almost all types of reservoirs. Fluid pressures in the pore spaces of rocks affect various aspects of petroleum exploration and production (Bruce and Bowers, 2002). Elevated pore pressures which are common in shallow, unconsolidated section of a sedimentary basin present a significant hazard such as kicks, blowouts, borehole instability, stuck pipe and lost circulation during the drilling and completion of offshore wells (Sayers, 2006). One of the ways to predict potential hazards such as high-pressured subsurface zones is through the use of seismic surveys. Such an analysis was developed by Hottman and Johnson (1965) and Pennebaker (1968). A range of disciplines are involved and needed in a comprehensive pore pressure analysis. Seismic interval velocities and velocity-to-effective stress transforms can be utilized for a given area combined with an estimated overburden stress to obtain pore pressure. Thus, the accuracy of seismic derived velocity models used for pore pressure determination is of paramount importance.

Bruce and Bowers (2002) showed that compaction is primarily a function of effective stress, and therefore, a reduction in stress will impede compaction. Thus, any measurement that measures porosity (seismic or sonic velocities, density and resistivity logs) may provide a means of estimating overpressures. Increasing pore pressure softens the elastic mineral by opening grain contacts and microcracks and thus tending to lower velocities (Bowers 1994, Osborne et al. 1997). As compaction is largely an inelastic process, only early under-compaction can reliably be predicted from porosity or one of its so called proxies (velocity or resistivity). Late overpressures (overpressures which reduce the stress below the maximum historical values) impact rock properties differently and the methods commonly used for the prediction of early overpressures often do not provide reliable pressure estimates in these environments. Therefore in case of early compaction, pore pressure is mostly dependent on the velocity of the formations. In general, subsurface-sediments follow a gradual increase in velocity with depth because of the effect of compaction but the presence of erosional channels breaks this trend and show as a sudden decrease in velocity, which are recognized as high pore-pressure zones (Fuloria 1993). These high pore-pressure zones can be predicted from well log and seismic data. However, this requires an appropriate time-depth model that should be used in seismic data processing for integration of well velocities with seismic data.

The present study performs time-depth modeling for high-pressure depositional environment along the offshore eastern coast of India. The signature of high pressure boundaries, depositional breaks and lithological boundaries are analyzed from sonic log data of 6 wells of different basins. The zone of interest lies between 2 and 3 km below the water column.

2. Methodology

2.1 Interval velocity trend from six wells

Received: November 11, 2016; Accepted: February 14, 2017; Published: April 26, 2017
International Journal of Earth Sciences and Engineering, 10(02), 155-160, 2017, DOI:10.21276/ijee.2017.10.0202

The interval velocity trends from sonic log data of six wells (1A, 1B, 2A, 2B, 3A and 3B) from offshore east coast of India is taken up for this study. Two wells each are from the Mahanadi Basin (Basin-1), the Krishna-Godavari Basin (Basin-2) and the Cauvery-Palar Basin (Basin-3). Water column has been removed from all logs to bring the data to the level of reference which is the mean sea level (MSL). For all six wells, sonic log data has been calibrated with available mud logs for identification of lithological boundaries. This data is further calibrated with gamma-ray logs for confirmation of depositional breaks which match well with seismic data. The interval velocity profile for all six wells is shown in figure 1.

Well 1A demonstrates a typical velocity-depth profile in a young clastic basin (figure 1, 1A). The velocity increases uniformly with depth following a smooth empirical compaction trend. Close to a depth of around 3.2 km, there is a noticeable decrease in velocity away from the trend line where the wellbore intersects an unconformity. The region of low velocity below the unconformity corresponds to a region of high pressure of approximately 17.2 ppg.

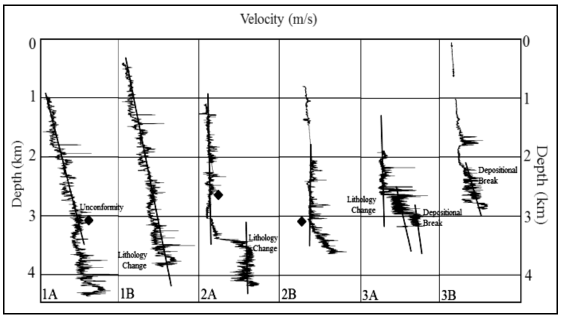

Figure1: *Sonic-velocity versus depth for six wells - 1A, 1B, 2A, 2B, 3A and 3B. Approximated normal compaction trend has been shown as smooth lines on each of the curves. Overpressure zones are indicated by grey-filled diamond symbols. Calibration of unconformity boundaries, lithological boundaries and depositional breaks was done using available wireline logs (including gamma-ray and mud logs).*

This has been calibrated using gamma-ray log which is further confirmed by mud log. Well 1B (figure 1) shows a similar velocity decrease around 3.5 km depth which correlates with lithology change in the same classic sequence. Also, there is a positive break in the trend line at around 2.65 km depth which shows a drop down in velocity but it is not at all related to any change in the pressure. The possibility of multiple compaction curves in the wells of same basin suggests that accurate pore-pressure prediction requires an understanding of the depositional and tectonic history of that area.

The velocity profile in well 2A (figure 1) appears complicated due to variations in lithology. The velocity decreases near 2.5 km depth indicating a change in pore pressure. A second velocity break near 3.5 km depth is due to change in lithology. In this well, the presence of overpressure cannot be inferred from large seismic stacking velocities because of the dominant change in velocities due to change in lithology. The shallow, low-velocity zone also interferes with accurate seismic velocity measurement at greater depths. Accurate pressure prediction from surface seismic data is difficult under such circumstances. Not all velocity changes due to overpressure are as abrupt as those shown in the 1A and 2A (figure 1). Well 2B (figure 1) shows a modest deviation from the normal velocity trend near 3.1 km depth that represents a change in mud weight. Well 2B was also chosen as a counterpoint to the previous examples. Close to 3.1 km depth, an increase in pressure correlates with a thick carbonate unit lying above a Paleocene shale unit whose velocity is lower than the overlying carbonate. For many cases, mechanisms that induce overpressure after compaction, and possible cementation, do not necessarily lower the velocity sufficiently to produce an obvious imprint.

Wells 3A and 3B show the normal compaction gradient in terms of pore pressure but sharp change in velocity at lithological boundaries and at depositional breaks can be clearly demarcated in velocity profiles (figure 1). An important observation about well 3B is that the increase in interval velocity at a depth of 1.75 km which corresponds to a smaller pack of sand lying between shale sequences is clearly seen. Generally, at this depth sands and shales exhibit same interval velocity but due to some erosional phenomena in this area, sand shows much higher velocity than shale. No abnormal pressure is encountered in this area.

2.2 Average velocity trend from six wells

Normally, pressure predictions are based on point measurements (based on well data only), that is, formation velocities at particular depths. Average velocity represents the total depth from a datum divided by the total one-way transit time of a seismic signal (Al-Chalabi 1974). Also, average velocity is closely related to seismic stacking velocity (Al-Chalabi 2014). Stacking velocity does not always need to be converted to interval velocity to infer the pressure anomalies and for lithological breaks. The knowledge of factors influencing the average velocity aids in picking and performing quality control of stacking velocities for pressure prediction, particularly in the presence of noise in data.

While dealing with real data, signal to noise ratio of the data is of paramount importance. Taking this fact into consideration, VSP checkshot data has been utilized here because it gives us direct time-depth values irrespective of bore-hole conditions. Missing sonic values at shallow depths, in washout zones, or near casing points lead to uncertainty in time-depth relationships because depth integration is required over all intervals while each check shot is an independent measurement and errors in shallow measurements do not affect the deeper values. Also, VSP data is relatively noise free in comparison to sonic. Figure 2 shows the average-velocity curves derived for the six wells shown in figure 1. All of the important trends observed in interval velocity are also present as slope changes in the average velocity plot of VSP data. The trends of the curve can be classified into four types:

i. An increase in slope (towards the vertical) indicates a reduction in interval velocity.
ii. A decrease in slope (towards the horizontal) indicates an increase in interval velocity.
iii. A sharp slope break indicates an abrupt interval-velocity change.
iv. A smooth transition in the slope of the average velocity implies the same in interval velocity.

Thus, the average velocity can be used as a tool to measure the changes in the interval velocity. The slope derived from the average velocity trend gives an idea about appropriate filtering of interval velocity across the layer boundaries. It is also much simpler to handle the average velocities, even if the data is noisy.

Based on the above criteria of interval velocities and the corresponding average velocities in high pore pressure environment, well 1A shows a reasonable relationship in terms of a sharp increase in slope (moves towards the vertical). This corresponds to a reduction in interval velocity which is very well visible from sonic interval velocities to VSP average velocities. (In well 1A only, a zone of more than 1 km shows a drop in interval velocity due to high pore-pressure). Due to close relationship of average and rms velocities (Al-Chalabi 1974) this observation can be utilized in seismic data re-processing only if we know an optimum time-depth relationship between two types of datasets. Well 1A has been selected to estimate the background shale trend in this area (Jindal et. al. 2016).

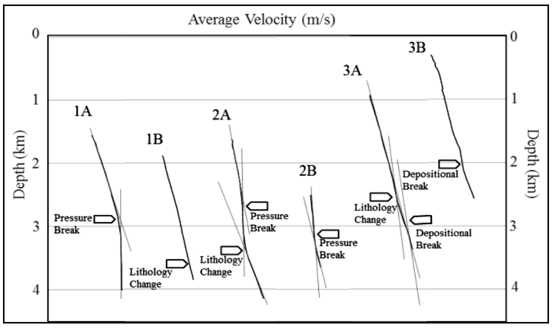

Figure 2. *The Average velocity curves for the six wells shown in figure (1) using VSP checkshot data. The slope breaks indicate changes in the interval velocity trends associated with changes in deposition, lithology and pore pressure.*

Figure 3 shows the time-depth relationship (figure 3a), the average velocity (figure 3b) and the interval velocity (Figure 3c) derived from the VSP from offshore wells of Mahanadi basin. Well-1A data is starting from 1.4 second TWT while well-2A is starting from 1.8 second TWT from mudline. The onset of over pressure is seen on a time-depth curve as a deviation from the trend in the shallower data (well 1A, WB – 40.3m). The effect, however, is more pronounced when the checkshots are converted to average velocity. The break in slope of the average velocity is correlated with overpressure similar to the curves in figure 2.

Extreme interval-velocity excursions implied by check shot data have been verified with the sonic log data. Check shot velocity information has been smoothed before its use to calibrate the sonic log. Overall velocity trends are still evident in an interval-velocity curve derived from check shot data. Due to above discussed properties, check shots provide data which is very well suited to test various equations used to represent the normal compaction trend for velocity versus depth.

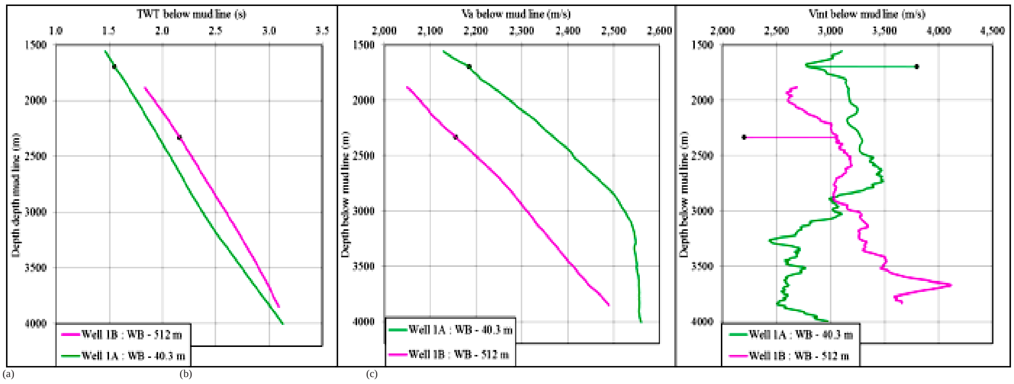

Figure 3. *(a) time-depth relationship b) the average velocity and c) smooth interval velocity derived from two wells of basin-1 (Water bottom: 512m and 40.3m). Geological age markers are plotted on data using black dots.*

Several techniques are available, ranging from drilling rates to resistivity logs, for predicting pore pressure on the basis of a deviation from a normal compaction trend. Seismic velocity measurements using differences in move out, however, seldom have the resolution necessary to separate lithology on a fine scale. Given the wide range in both sand and shale velocities possible at a given depth, however, such a sand/shale crossover is hard to observe on a single sonic log.

2.3 Some empirical models for time-depth conversion

The technique of time-depth modeling for inferring velocity model from interval velocities in high-pore pressure zones has been developed by Bell (2002). These models help to determine the response of different models on observed velocities. Model response has been analyzed by converting velocity to its corresponding slowness which relates it with the primary porosity of the rocks.
The following properties are desirable in an empirical model to characterize the noisy data:

i. The model parameters should be fairly insensitive to the range of the data because well data does not cover the entire range of seismic times.
ii. A consistent value of the parameters should be obtained when fitting the data with mathematically equivalent statements. For example, using sonic transit time (d_s) rather than V_i.
iii. There should be a bias towards small number of parameters to make it simpler while transforming between seismic domain to well domain.

Four two-parameter models have been analyzed all of which yield a reasonable starting value of V_0 = 1500 m/s at zero depth. In the following, k is the rate of change of velocity, T is two-way travel time, V_i is the interval velocity and V_a is the average velocity. Based on the requirements of empirical model for depth-time-velocity relationships, four models have been selected for testing. These models are based on linear and exponential functions derived by Slotnick (1936).

1. Model-1 : A linear interval velocity model in depth

$$V_i = V_o + kZ \tag{1}$$

2. Model-2 : A linear interval velocity model in time (two-way-time)

$$V_i = V_o + kT \tag{2}$$

3. Model-3 : An average velocity model in time (one-way-time)

$$V_a = V_o + kT/2 \tag{3}$$

4. Model-4 : An exponential interval velocity model in time (one-way-time)

$$V_i = V_o e^{kT/2} \tag{4}$$

Above discussed four models were tested on well 1A (water bottom: WB-40.3m), which represents the highest pore-pressure out of studied six wells.

2.4 Model-1

Figure 4 displays the Model-1 from well 1A. The data are displayed as slowness (ds) (Figure 4a) and as velocity on a linear scale (Figure 4b). Coefficients for the curves were determined from least-squares fits of the original check shot time-depth data near 2.8 km. A linear fit on velocity data shows a good agreement with the observed background shale trend while it shows slight deviation in the slowness curve. Here the slowness curve represents the sonic curve equivalent to velocity plot shown in figure 4b. As discussed previously, velocity slowness is an indirect indicator of primary porosity of the area. Thus, a good fit is required in slowness domain for its further use in well prognosis, while at the same time, a good time-depth conversion is needed for its use in seismic data reprocessing.

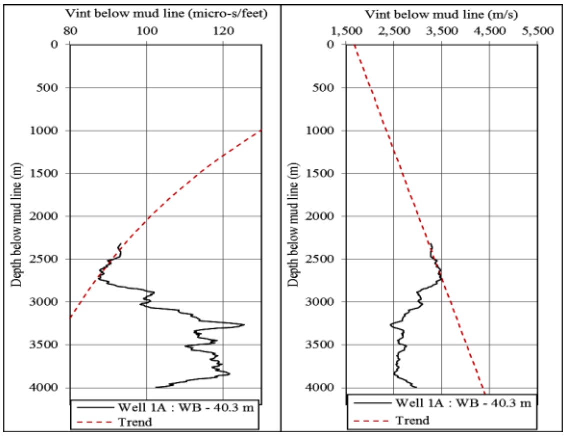

Figure 4: *Model-1: Linear interval velocity model in depth. (a) The plot of sonic curve (slowness in µs/ft) with depth; and (b) the plot of interval velocity with depth*

2.5 Model-2

Figure 5 displays the model-2 from the same well (1A). The data are displayed as slowness (ds) (Figure 5a) and velocity on a linear scale (Figure 5b). Similar to model-1, coefficients for the curves were determined from the least-squares fit to the original check shot time-depth data near 2.8 km. Trend line fit on velocity data agrees with the observed background shale trend represented by red dotted line in figure 5a. Here, the interval velocity and slowness have been plotted against the two-way-travel time. This model does not show much different results from model-1.

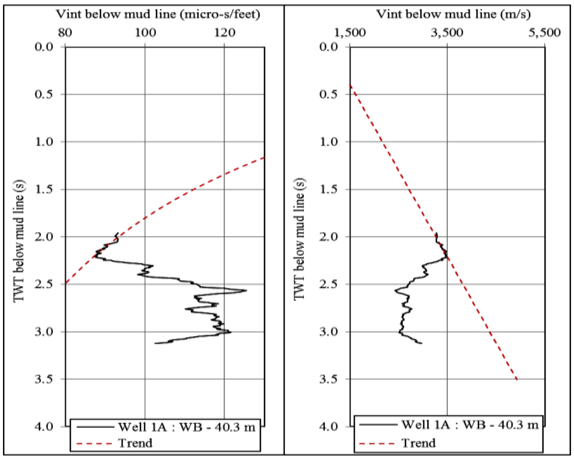

Figure 5: *Model-2: Linear interval velocity model in time (TWT- two way travel time). (a) The plot of sonic curve (slowness in µs/ft) with TWT; and (b) the plot of interval velocity with TWT*

2.6 Model-3

Figure 6 displays model-3 for well 1A. The data are displayed as average velocity (V_a) versus one-Way-Travel (OWT) time (Figure 6a) and interval velocity (V_i) (Figure 6b) versus OWT, both plotted in a linear scale. The coefficients for the curves were determined from least-squares fit to the original check shot time-depth data near 2.8 km, similar to those computed for other two models. Trend line has been calculated on average velocity versus OWT time curve. Trend line fit on average velocity data shows an agreement with the observed background shale trend. Interval velocity shows deviation from mathematically equivalent trend line compared to those estimated for average velocities. This might be because of noise present in data which gets averaged out in case of average velocities. Figure 6b shows that average velocity slope changes significantly at high-pressure conversion point which deviates it away from normal compaction trend. Beyond this point they begin to diverge significantly. That has implications for pore-pressure prediction schemes based on the ratio of the normal trend and the actual value at a given depth.

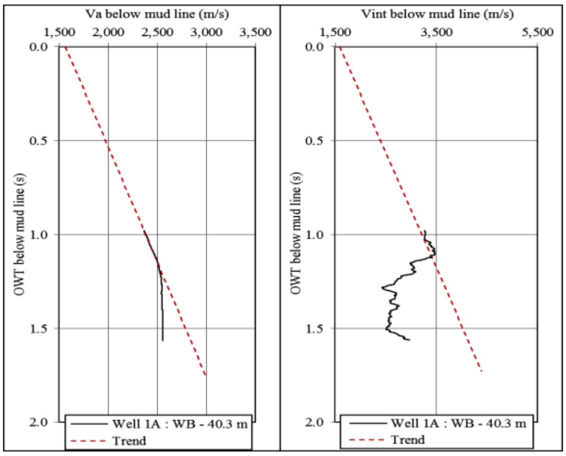

***Figure 6.** Model-3: Linear average velocity model in one-way time (a) The plot of average velocity with OWT; and (b) the plot of interval velocity with OWT.*

2.7 Model-4

Figure 7 shows the model-4 from well 1A. The slowness (ds) is plotted on a semi-log scale (Figure 7a) and the velocity on a linear scale (Figure 7b). The Exponential trend line fit on velocity data shows a good agreement to the observed background shale trend. Here, interval velocity and slowness have been plotted against the one-way-travel time. This model also shows results similar to those produced for model-1 and model-2.

3. Discussions

Figure 8 shows the various curves predicted as an average velocity function of two-way time. The input data range was approximately 1.5–2.3s. There is significant variation in values extrapolated into the region of overpressure. The exponential model using parameters fit to interval velocity versus one-way-time from Figure 5, is clearly a poor representation of the data in this form. The velocity profile obtained from fitting the exponential function to velocity-depth data does not yield a suitable equation for converting from seismic time to depth. Of the four models under consideration, only the exponential expression shows such a large variation where fitting mathematically equivalent expressions for vertical two-way travel time vs. depth rather than velocity vs. depth.

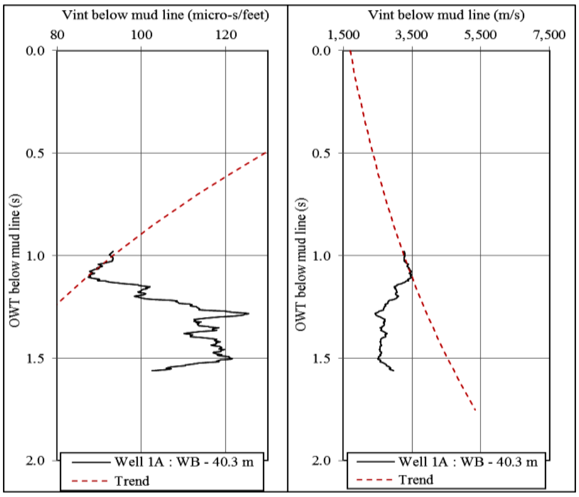

***Figure 7.** Model-4: Exponential interval velocity model in time (OWT- One way travel time). (a) The plot of sonic curve (slowness in µs/ft) with OWT; and (b) the plot of interval velocity with OWT*

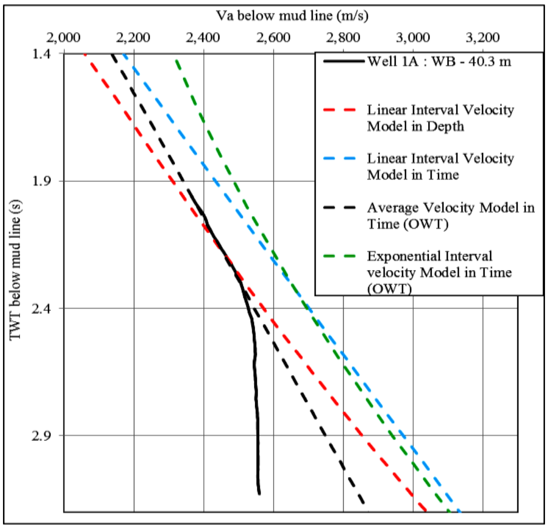

***Figure 8.** Average velocity curve as a function of two-way-time, shows that exponential relation (model-4) is not an appropriate relationship for time-depth conversion. While, model-3; Average velocity model in one-way time, show a good to the background shale trend*

The best fit appears to be an average velocity model in one way time, which yields a straight line as a function of time. Also, there is an indication for this well that none of the curves adequately represent the data at both shallow and intermediate depths. That could be due either to a change in the depositional history, that is, the rate of compaction, or a shortcoming of the empirical models. Additional data imply the former and support the linear time relationship as the best overall empirical fit for both time-depth conversion and prediction of interval velocity trends within zones of normal pressure. Coefficients for model-3 are; V_o=1566.7 m/s, k = 815.43. So, background trend equation can be written as:

$$V_a = 1566.7 + 815.43T/2 \qquad (5)$$

4. Conclusions

The objective of this study was to investigate various time-depth models suitable to high pore-pressure environment. A few offshore wells sonic and VSP data were analyzed for time-depth modeling. High correlativity of interval velocity boundary with average velocity slope change in high pore-pressure environment provided an opportunity for analyses of well 1A (which encountered highest pore-pressure in this area). Considering the fact that decreases in interval velocity is evident on well data can be indicative of high-pressure boundaries on seismic data. This is however true, only if it provides a consistent fit to both time-depth and velocity-depth data.

According to the analysis average velocity model in one-way time turned out to be the best model for time-depth conversion for high pore pressure environments of offshore east coast of India. This model can be used for understanding background normal compaction trend in this area due to its direct relationship with the primary porosity. These results are directly supported by equivalent expressions for vertical two-way travel time versus average velocity rather than velocity versus depth. A close association of the average velocity with the RMS velocity allows the use of average velocity model while dealing with surface seismic data.

One of the future tasks would be to apply the average velocity model on stacked volume of surface seismic data to convert from time to depth domain. A pore-pressure volume can also be generated with the help of 3D geological model and geomechanical modeling. This will serve to provide an improved visualization of overpressure generation in the entire seismic volume and safer and economic drilling of development wells in this region.

From additional data of different basins, we found that lowering of velocity may not be always due to the presence of high pore-pressure. It might be because of change in lithology or presence of erosional boundaries.

Acknowledgements

Authors thanks E & P (Petroleum) division of Reliance Industries Limited for allowing publishing this work.

References

[1] Bruce B., G., Bowers G. L., “Pore pressure terminology”, The Leading Edge, PP. 170–173, 2002

[2] Hottman C. E., Johnson R. K.,” Estimation of formation pressures from log derived shale properties”, Journal of Petroleum Technology, PP. 717 – 722, 1965

[3] Bell D. W., “Velocity estimation for pore pressure prediction”, AAPG Memoir, 76, PP. 217-233, 2002

[4] Pennebaker E. S., “Seismic data indicate depth and magnitude of abnormal pressure”, World Oil, 166, PP. 73-82, 1968

[5] Bowers G. L., “Pore pressure estimation from velocity data: Accounting for overpressure mechanisms besides undercompaction”, IADC/SPE Drilling conference proceedings, PP 515-530, 1994

[6] Jindal N., Biswal A. K. and Singh K. H.,”Time-depth modeling in high pore-pressure environment, offshore east coast of India”, AAPG Annual Convention and Exhibition, 19-22 June, Calgary, Alberta, Canada, 2016

[7] Al-Chalabi M., “An analysis of stacking, rms, average, and interval velocities over a horizontally layered ground”, Geophysical Prospecting, 22, PP. 458-475, 1974

[8] Al-Chalabi M., “Instantaneous Velocity Modeling. In: Principles of Seismic Velocities and Time to Depth Conversion”, EAGE Publications, HOUTEN, The Netherlands, PP. 303-364, 2014

[9] Osborne M. J., R.E. Swarbrick, “Mechanisms for generating overpressure is sedimentary basins: a re-evaluation”, AAPG Bulletin, 81, PP. 1023-1041, 1997

[10] Slotnick M. M., “On seismic computations with applications”, Geophysics, 1, PP 9-22, 1936

[11] Sayers M., “An introduction to velocity-based pore-pressure estimation”, The Leading Edge, PP. 1496–1500, 2006

[12] R.C. Fuloria R. C., “Geology and hydrocarbon prospects of Mahanadi Basin, India”, Proceedings of Second Seminar on 13 Petroliferous Basins of India, Indian Petroleum Publishers, Dehra Dun, India, 1, PP. 355-369, 1993