



# Pore Pressure Prediction a Case Study in Cambay Basin

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## Abstract

Any method that intends to minimize the uncertainty and enhances the preparedness to deal critical situation has always drawn attention in subsurface exploration. Showing no exception, in oil and gas drilling industry, pore pressure prediction has always been of immense importance as it provides insights to deal with probable high pressure zone, which are capable of creating disasters. The present study is an attempt to minimize such uncertainty in one of the exploration block of Indian Oil Corporation Limited in Cambay Basin where data availability is limited. With the limited data available in the nearby wells within the block and outside it, a study has been carried out which indicates the study area is likely to be in normal hydrostatic pressure regime. Accordingly, all drilling plans have been lined up. However, the model will be updated after drilling of the 1<sup>st</sup> well.

## Concept

Formations penetrated during the drilling of an oil and gas well exhibit pressure which may vary in magnitude depending on geological setting, depth of occurrence, location and proximity to other structures.

### 1. Hydrostatic Pressure

Hydrostatic pressure is defined as pressure exerted by a column of fluid. This pressure is function of average fluid density and depth or vertical height of the fluid column.

$$p(z) = \frac{1}{A} \int_{-z_0}^z dz' \iint_A dx' dy' p(z')g(z') = \int_{-z_0}^z dz' p(z') g(z')$$

p is the hydrostatic pressure (Pa),

$\rho$  is the fluid density (kg/m<sup>3</sup>),

g is gravitational acceleration (m/s<sup>2</sup>),

A is the test area (m<sup>2</sup>),

z is the height (parallel to the direction of gravity) of the test area (m) &

z<sub>0</sub> is the height of the zero reference point of the pressure (m).

Further simplifying assuming (a) since many liquids can be considered incompressible, a constant density throughout the liquid is assumed. (b) Since the height h of the fluid column between z and z<sub>0</sub> is often reasonably small compared to the radius of the Earth, one can neglect the variation of g. Under these circumstances, the integral boils down to the simple formula:

$$\rho = \rho gh,$$

### 2. Overburden Pressure

The overburden pressure is defined as the pressure exerted by the total weight of the overlying formations above the point of interest. The total weight is the combined weight

of the formation solids (rock matrix) and formation fluids in the pore space. The density of the combined weight is referred to as bulk density.

### A. Methods for determining Overburden Pressure

#### (i) Extrapolated density

Density is extrapolated up to mud line using the following geometric fit.

$$\rho_{\text{extrapolated}} = \rho_{\text{mudline}} + A_0 \times (\text{TVD} - \text{AirGap} - \text{WaterDepth})^\alpha$$

Where

$\rho_{\text{mudline}}$  is the density at the sea floor or ground level;

$A_0$  and  $\alpha$  are fitting parameters.

#### (ii) Amoco empirical relation

The average bulk density below the sea floor is estimated by an empirical equation obtained from statistical data from the Gulf of Mexico.

$$\rho_{\text{Amoco}} = \rho_{\text{mudline}} + [(\text{TVD} - \text{AirGap} - \text{WaterDepth})/3125]^\alpha$$

Where  $\rho_{\text{Amoco}}$  is in ppg and all depths are in feet, and

$\rho_{\text{mudline}}$ : mud line density in ppg (default 16.33 ppg)

a: exponent coefficient (default 0.6)

#### (iii) Gardner density from sonic or seismic

$$\rho_{\text{Gardner}} = a \times V^\beta$$

Where  $\rho_{\text{Gardner}}$  is in g/cm<sup>3</sup> and  $\alpha$  and  $\beta$  are two fitting parameters named velocity factor and velocity exponent respectively, V is sonic or seismic formation velocity in ft/s.

In Gardner's original equation, a= 0.23 and  $\beta=0.25$

When compressional slowness is provided as an input, then it is converted into velocity before use in this equation.

#### (iv) Miller density

Miller density is calculated from porosity as follows:

$$\rho_{\text{Miller}} = \rho_{\text{matrix}} (1 - \phi_{\text{Miller}}) + \rho_{\text{water}} \phi_{\text{Miller}}$$

with :

$$\phi_{\text{Miller}} = \phi_a + \phi_{bc}^{(-k \cdot (\text{TVD} - \text{AirGap} - \text{waterDepth})^n)}$$

and where depth is in ft, bulk density in g/cc and:

$\rho_{\text{matrix}}$ : matrix density (default 2.65 g/cc)

$\rho_{\text{water}}$ : density of pore water (default 1.03 g/cc)

$\phi_a$  : sediment porosity at great depth

$\phi_b$  : sediment porosity fitting parameter equal to mud line porosity minus  $\phi_a$

K: porosity decline parameter

N: curvature parameter

#### (v) Constant density

In this mode, the user can create a density curve which has a constant value along depth.

#### B. Overburden stress calculation

The overburden stress is calculated from the bulk density as below:

$$\sigma_v = g \int_0^{\text{TVD}} \rho_b(z) dz$$

where

-  $\sigma_v$  is the vertical stress / overburden stress at depth TVD

-  $\rho_b$  is the bulk density (including the water section above sea floor.

- g is the gravitational constant.

The input for the overburden stress estimation is the "best density", which is often a composite log from actual density measurement and a synthetic density where no density log is available (RBCP\_COMP).

#### Pore Pressure

Pore pressure is the pressure on the fluids in the pore spaces of the rock. However, the above definition stands good for a reservoir rock like sandstone. For shale that has extremely small pores, intense chemical effects, dominance of bound water, make this easy definition unsatisfactory. Better answer for shale pore pressure is the fluid pressure in permeable zone in long-term equilibrium with the shale. This answer reflects the hazard that elevated shale pressures bring to drilling operations.

Depending on the magnitude of the pressure, it can be described as either being normal or abnormal or subnormal.

**A. Normal Pore Pressure** - Normal pore pressure is the pressure exerted by the column of the fluid extending from the surface to the subsurface being considered.

Normal pore pressure is not constant. The magnitude of normal pore pressure varies with the concentration of dissolved solids, type of fluids, gases present and temperature gradient.

**B. Abnormal Pore Pressure** - Abnormal pore pressure is defined as any pore pressure that is greater than hydrostatic pressure of the formation water occupying the pore space. Abnormal pore pressure is sometimes referred to as overpressure or geo-pressure. Abnormal pressure is thought of as being made up of normal hydrostatic component plus an extra amount of pressure. This excess pressure is the reason why surface control equipments (e.g. BOPs) are required when drilling oil and gas in wells.

The **cause** of abnormal pressure is attributed to a combination of various geological, geochemical, geothermal and mechanical changes. However for any abnormal pressure to develop there has to be an interruption to or disturbance of the normal compaction and de-watering.

**C. Subnormal Pore Pressure** - Subnormal pore pressure is defined as any formation pressure that is less than the corresponding fluid hydrostatic pressure at the given depth.

**Subnormal** pore pressures are encountered less frequently than abnormal pore pressure and are often developed long after the formation is deposited. Subnormal pressure may have natural cause related to the stratigraphic, tectonic and geochemical history of an area or may have been caused artificially by the production of reservoir fluids.

- Depositional effects
- Diagenetic effects
- Tectonic effects
- Structural causes
- Thermodynamic effects

**D. Importance of Pore Pressure** - Uncertainties cannot be avoided but preparedness to tackle the situation becomes very important. Pore pressure prediction is very important to determine the mud weight with which drilling is to be carried out. Improper analysis may lead to the following:

- a. If the pore pressure is underestimated i.e. if mud weight is less than pore pressure, problems like caving, flows from Formation to wellbore, kicks, blowout, all threatening hole stability and safety issues.
- b. If pore pressure is overestimated and actually if it touches fracture pressure of a Formation again hole stability is threatened and Formation is damaged. Furthermore, high mud weight damage the Formation (reservoir) hence basic purpose of well is not met.
- c. Improper analyses of pore pressure, fracture pressure and overburden pressure leads to drilling complications like stuck pipe/lost in hole, low ROP (rate of penetration)

because of unnecessary high mud weight, improper casing design all leading to additional time for drilling operations and results in high cost implications.

## E. Pressure Prediction Methods

Several methods of pressure prediction are available. These methods can be logically grouped as follows:

- Areal analysis from seismic data
- Offset well correlation
- Log analysis
- Drilling parameter evaluation
- Production or test data
- Real time evaluation

### (i) Seismic Analysis

Geophysical method such as seismic can be used to detect presence and top of the abnormally pressured formations and to evaluate the magnitude of pressures. The techniques are similar to acoustic well logging but utilize different frequencies and wavelength.

The interval velocity from seismic profiles is the reciprocal of the interval travel time. The reciprocated values can be plotted v/s depth to indicate the presence of abnormal pressures. A normal environment exhibits increase in velocity as compaction occurs. Therefore the travel time should decrease. An abnormal pressure zone has lower velocities than normal pressure zone for the specific depth and causes higher travel times.

### (ii) Log analysis

Log analysis is a common procedure for pore pressure estimation in both offset wells and while well drilling. New MWD (measurement while drilling) tools implement log analysis technique in a real time drilling mode. The techniques use the effect of the abnormally high porosities on rock properties such as electrical conductivity, sonic travel time and bulk density. Both the resistivity (reciprocated conductivity) log and the sonic log are based on these principles. Log dependent primarily on porosities for its response and can be used in a quantitative evaluation of formation pressures.

Resistivity log was originally used in pressure prediction. Log response is based on electrical resistivity of the total sample, which includes the rock matrix and fluid filled porosity. If zone is penetrated that has abnormally high porosity (and associated high pressure) then resistivity of the rock will be reduced due to greater conductivity of water than rock matrix (provided water is saline). Upon penetrating an abnormal zone a deviation of divergence is noted (from the normal trend). The degree of divergence is noted to estimate the magnitude of pressure.

### a. Eaton's Method

It is one of the most widely used pore pressure estimation method in the industry and is based on the Eaton's work in the

Gulf of Mexico. Eaton's method uses a semi logarithmic normal trend line. The various log measurements (R) used by the Eaton's Method are resistivity, sonic or seismic interval velocity.

Eaton assumes there is a normal pore pressure with a fixed gradient, and the pore pressure is calculated as below:

$$P_p = \sigma_v - (\sigma_v - P_{pnorm}) * a * (R/R_{norm})^n$$

Where:

R = measurement value

R<sub>norm</sub> = normal pore pressure

a = Eaton factor

n = Eaton exponent

Default values for a & n are 1 & 1.2 for Eaton method using resistivity and 1 & 3 using compressional slowness.

### b. Bowers Method

Bowers method accounts for overpressure generated by both under compaction, and pore fluid compaction (which may be caused by temperature changes, hydrocarbon maturation and / or clay diagenesis). The effective stress and pore pressure can be calculated as following :

$$\sigma'_v = (V - V_0/A)^{1/B}$$

$$P_p = (\sigma_v - \sigma'_v) / \alpha$$

Where:

V<sub>0</sub> = Velocity in ft/s at zero effective stress,

A, B are fitting parameters.

α = is the Biot constant.

### c. Traugott Resistivity Method

This method calculates Normal compaction trend line for resistivity based on an empirical model of decreasing porosity, then uses Eaton equation to calculate pore pressure based on resistivity. Uplift and tectonic stress can be taken into account in the calculation.

## 4. Fracture Gradient

Fracture gradient (FG), pressure required to induce fractures at a given depth is calculated from pore pressure and overburden gradient using the following formula:

$$FG = K * (\sigma_v - \alpha P_p) + \alpha P_p$$

Where α is Biot coefficient and K is called the stress ratio (unitless), which is horizontal effective matrix stress over the effective vertical stress.

All methods for calculating Fracture Pressure are only different in computation of value of K.

### A. Fracture Gradient / Pressure estimation

#### (i) Matthews & Kelley

In realizing that cohesiveness of rock matrix is usually related to matrix stress and varies only with degree of

compaction. Matthews and Kelley developed the following equation for calculating fracture gradients in sedimentary formations:

$$F = P/D + K_1 \alpha / D$$

where

- P= formation pressure at point of interest, psi
- D= Depth of interest, feet
- $\alpha$ = matrix stress at point of interest, psi
- $K_1$ = matrix stress coefficient for the depth at which value of  $\alpha$  would be normal matrix stress, dimensionless
- F= fracture gradient at point of stress, psi/foot

## (ii) Eaton

Eaton extended the concept of Matthews and Kelley to introduce Poisson's ratio into the expression of fracture pressure gradient,

$$F = S - D/P(v/1-v) + P/D$$

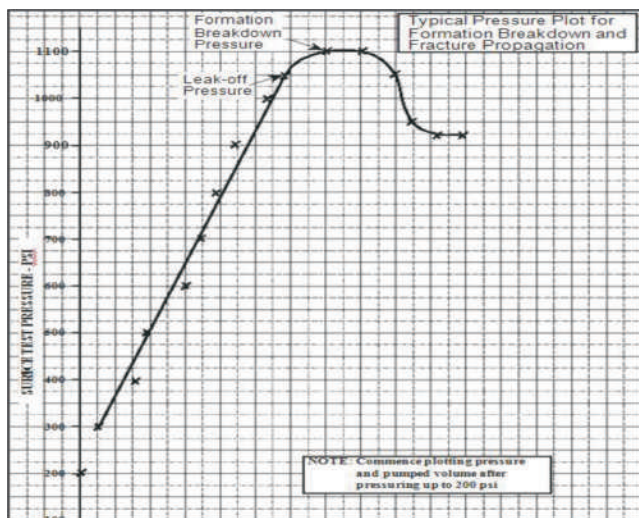
where

- P= wellbore pressure, psi
- S= overburden stress, psi
- D= depth, foot
- v= poisson's ratio
- F= fracture gradient, psi/foot

Eaton assumed that both overburden stress and Poissons ratio were variable with depth. Eaton's method or its modification is perhaps the most widely used procedure in the industry. It has proved successful in both onshore and offshore throughout the world.

## B. Field determinations of fracture gradient

The most common procedure used for determination of fracture gradient is leak off test (LOT). In the test the blow outs preventers are closed and then the pressure is applied incrementally to the shut in system until the formation initially accepts the fluid.



Volume Pump Vs Pressure plot

## Study Area

The area is located in the Broach Block of prolific Cambay Basin. Area was awarded to a company and it has carried out the 3D seismic data acquisition, processing and interpretation. Based on interpretation of exploration data five firm and two to mature category wells were identified for drilling (Fig. 1). Based on objectives, the depth range of proposed wells is varying between 1300 to 2000 mtr.

### 1. Available Data

The data available for Pore Pressure study are interval velocity (Fig. 2 & 3) and instantaneous velocity cubes for the whole block. From the same the respective velocities for the proposed wells are derived from seismic data.

Available wireline log data of the existing wells viz. M-3, M-1, A-1, AW-1 and Mi-1 are Gamma Ray, Spontaneous Potential and Density etc.. Sonic data is available only in M-3 which is used for calibration of pore pressure using Eaton's sonic method.

- o Compressional sonic data is available only in Matar-3 from 450m to Well Bottom.
- o Density and porosity data are not available up to surface in all wells.
- o Synthetic density is generated in upper section for all wells.
- o Information gathered about MDT and LOT data for nearby wells Ma-15, M-16, PRS-4 and SPD-1 have been used for calibration.

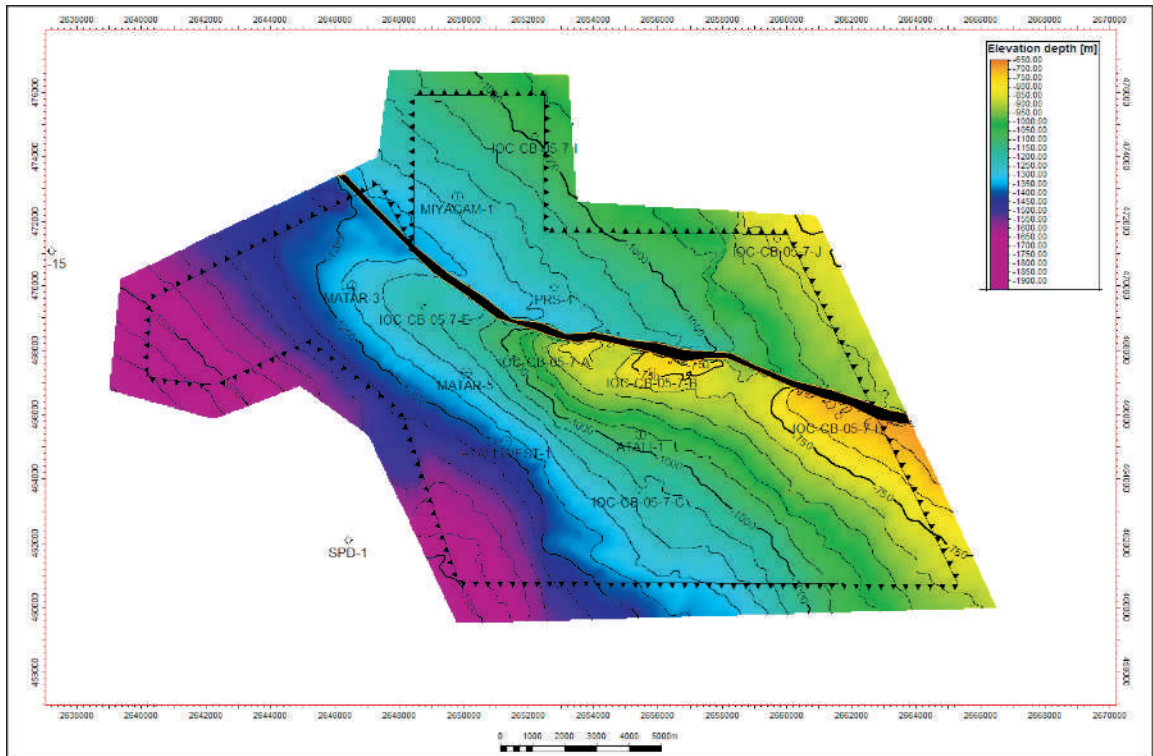
As per the data available and based on seismic interpretation, it is noticed that an axial fault (appears to be reverse fault) trending in NNW to SSE direction divides the block broadly in to two regions (Fig. 1). The northern part lies to the fault is uplifted and few Formations like Cambay Shale and Hazad are completely eroded because of upliftment. Hence, Mi-1 well, which lies on the northern side of fault, is used and calibrated for pore pressure study of Wells IOC-CB-05-7-I and IOC-CB-05-7-J.

M-3 is used for calibration of Pore pressure prediction of IOC-CB-05-7-E and IOC-CB-05-7-A and A-1 is used for IOC-CB-05-7-B, IOC-CB-05-7-C and IOC-CB-05-7-H.

Normal compaction trend line (NCTL) established in the wells represents the normal compaction trend for the area of interest and can be used for building the pore pressure cube and estimating the pore pressure profile at the planned well location.

## Methods & procedure Adopted

- A. **Lithology Determination:** Lithology Determination is important for Pore Pressure analysis for separating shale and non-shale rocks. It is very common for formations



**Fig. 1:** Location of wells in Study Area

penetrated in a well to exhibit distinct properties. To be able to create better model for pore pressure prediction, it is important to correlate and identify lithology. This is done using cut-offs on some logs, which are lithology logs (i.e. gamma ray, SP, density, porosity and deep resistivity).

**B. Overburden Stress Calculation:** Overburden stress is determined by two methods:-

- a. **Using Density Log** - Making a synthetic curve matching density (RHOB) log in the specified interval and then splice the two to generate a continuous log. Overburden stress (vertical stress) is computed by integrating synthetic density from 0 to TVD.
- b. **Interval Velocity** - Here, Interval velocity extracted from seismic data (Fig. 2 & 3) is used to determine density using Gardner's equation which is integrated to determine vertical stress.

**C. Pore Pressure Calculation:** Due to lack of data, methods used for pore pressure determination is Bowers method using compressional slowness or interval velocity. It is calibrated with mud weight data of offset wells. Since sonic data is available only in Matar-3, it is used for calibration in all wells.

Normal compaction trend line is established in the offset wells which represents the normal compaction trend for the area of interest and is used for building the Pore Pressure cube and estimating the Pore Pressure profile at the planned well location (Fig. 4 a, b and c).

**D. Fracture Pressure Calculation:** Fracture pressure profile is estimated using Mathews & Kelly Method and it is calibrated with the LOT data of some wells in the vicinity viz. Matar-15, Matar-16, PRS-4, SPD-1.

### Summary, Conclusions and Recommendations

- Gardner's equation is used to determine bulk density from interval velocity.
- Bowers method is used to calculate the pore pressure profile from compressional slowness as well as interval velocity and is calibrated with mud weight data available from offset wells and sonic data of Matar-3.
- Fracture pressure profile is estimated using Mathews & Kelly Method and is calibrated with LOT data of wells Matar-15, Matar-16, PRS-4 and SPD-1.
- Normal compaction trend line is established while estimating the pore pressure profile at the planned well locations and is in corroboration with offset wells.
- All proposed well locations appear to be in the normal pore pressure range.
- It is opined to update the model after the availability of the first exploration well drilling data to reduce the uncertainty in pore pressure estimation due to availability of less calibration data.
- The estimated range of proposed mud weight are tabulated in Table 1.
- Mud weight shall be carefully monitored while drilling the well IOC-CB-05-7-A and to be kept close to lower limit of mud weight due to observance of significant mud loss in well A-1 at 1800 mtr.

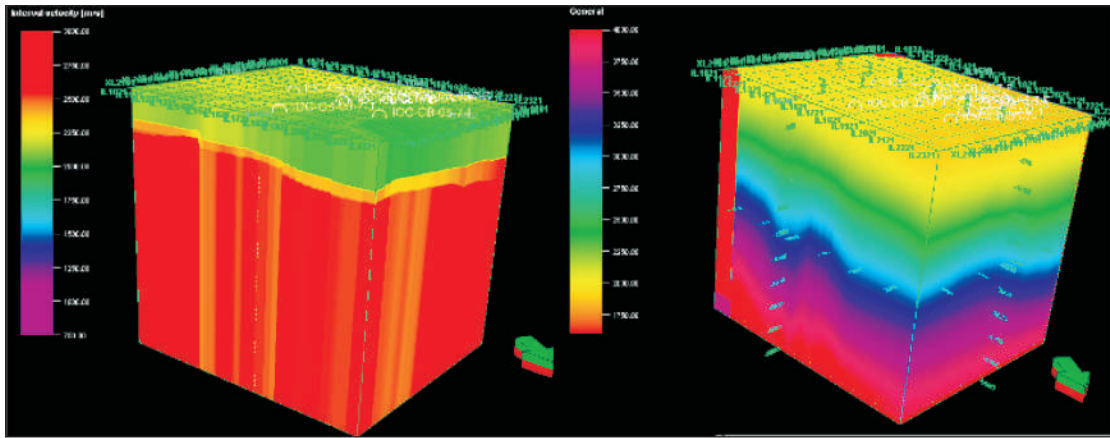


Fig. 2: Velocity Cubes obtained from seismic data in 2 separate model 3 layer model and 10 layer model

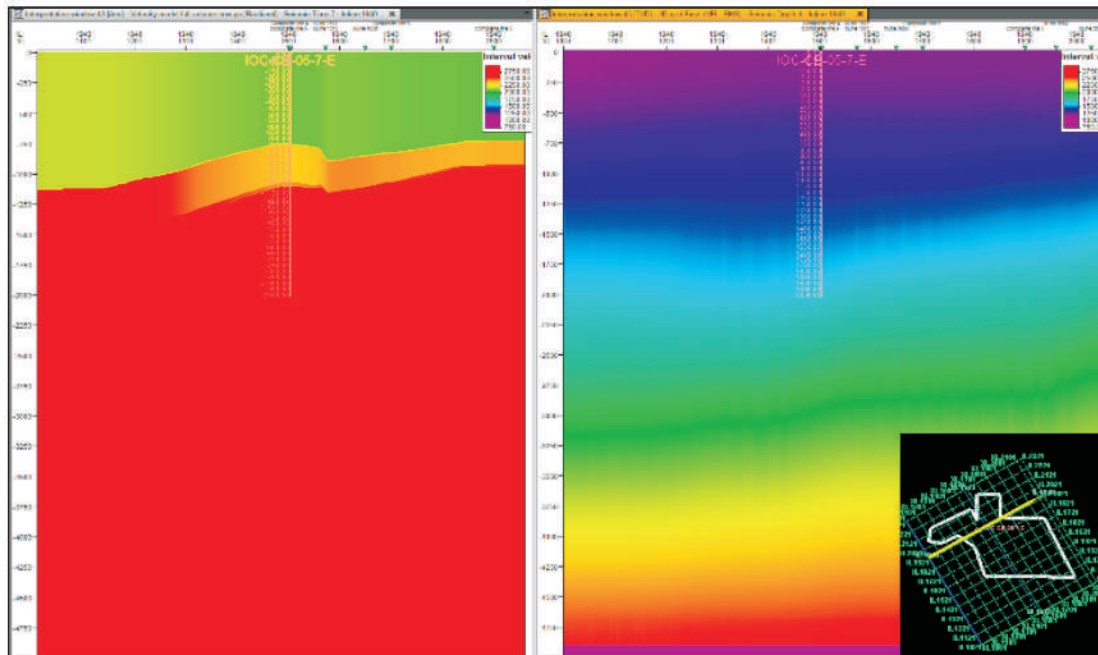


Fig. 3: Velocity sections obtained from seismic data in 2 separate model 3 layer model and 10 layer model

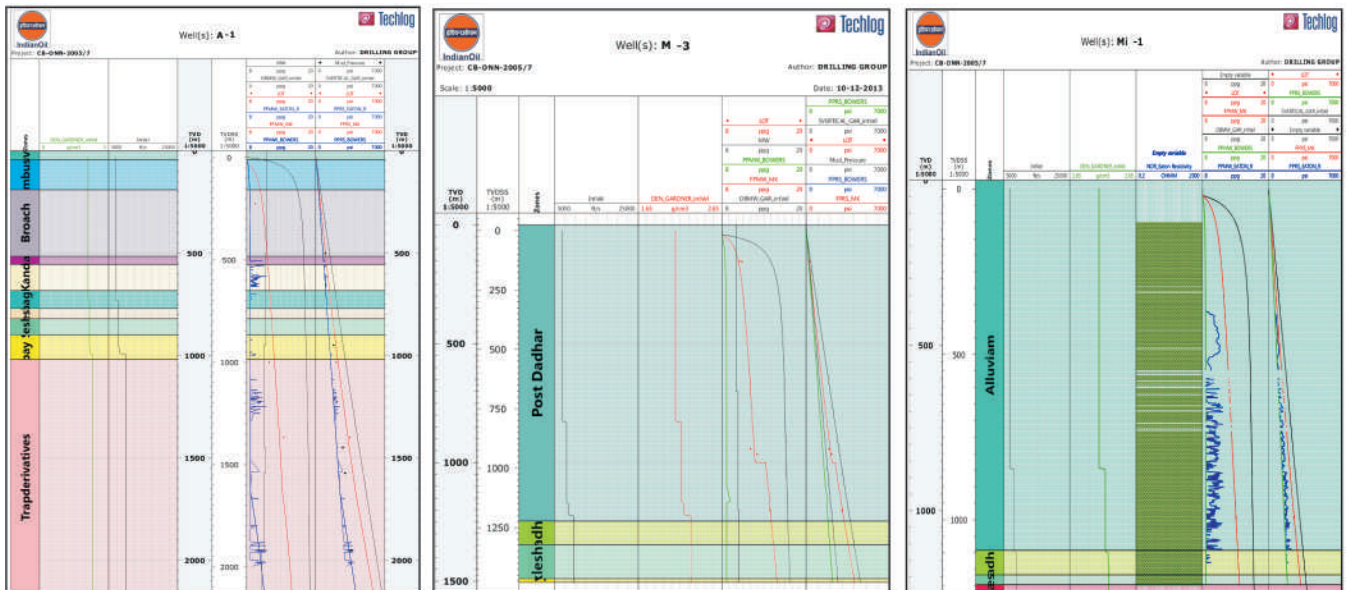
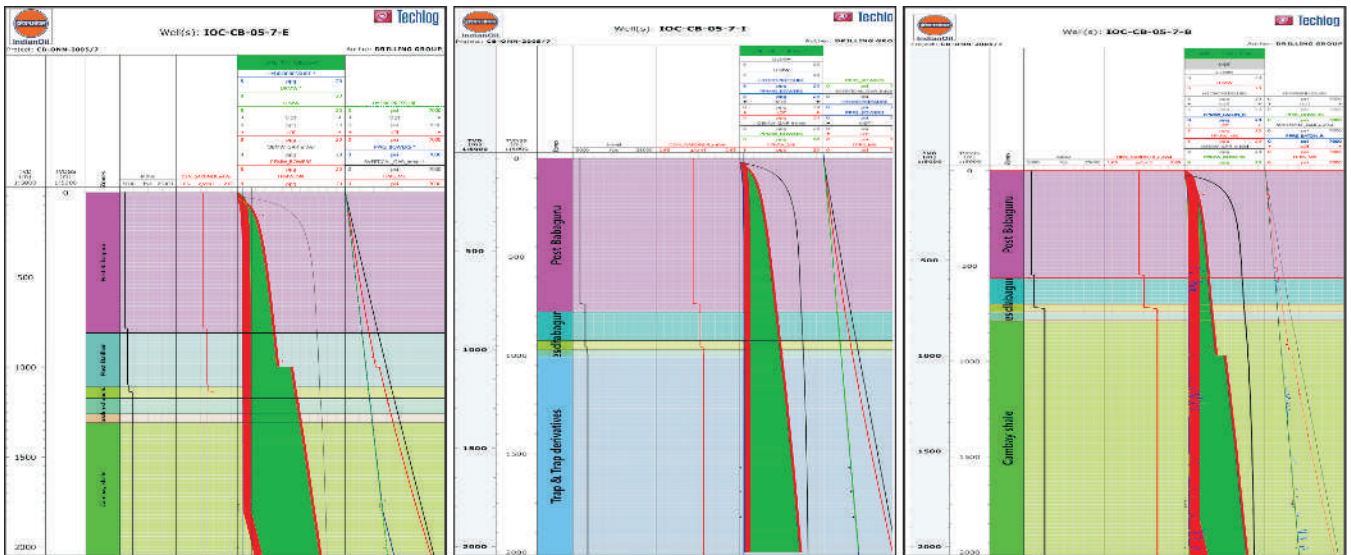


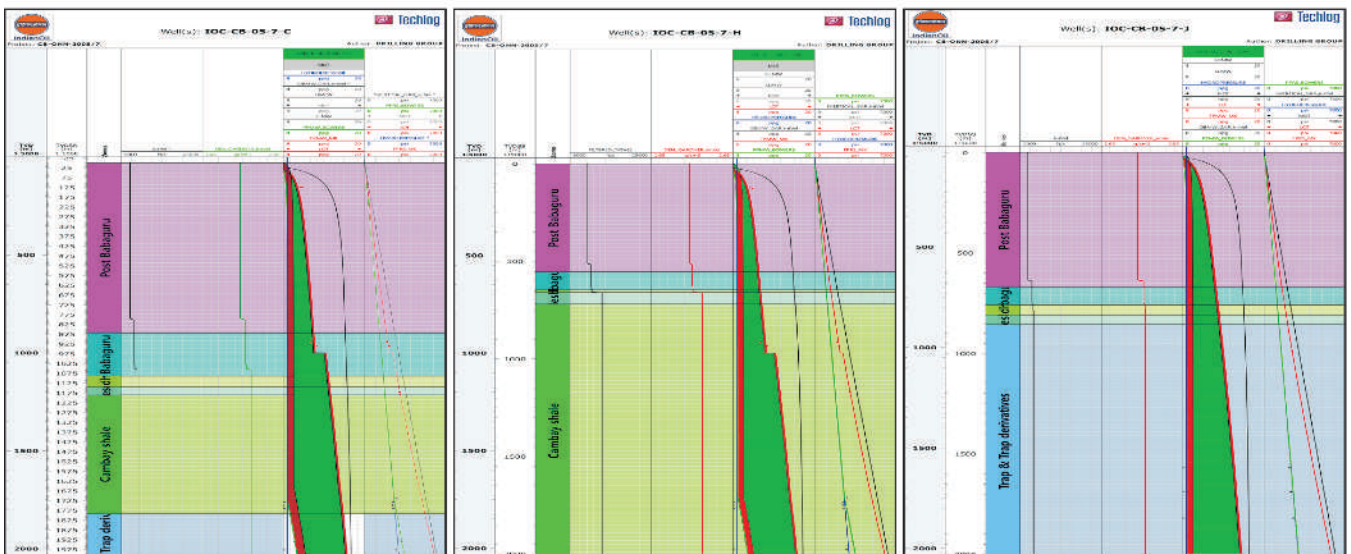
Fig. 4 a: Calibration of parameters in existing well A-1, M-3 and Mi-3 and applying the same for prediction in a proposed well

**Table 1:** Quantitative output of the study

Wells	Depth Range(m)	Estimated Formation Pressure ( PPG)	Proposed Mud Weight Range (PPG)	Remarks
E	0-150	8.4-8.6	8.75-9.2	Normal Pore Pressure Expected
	150-800	8.4-8.8	9.2-9.6	
	800-1245	8.4-8.8	9.6-10.2	
A	0-150	8.4-8.8	8.75-9.2	Hydrostatic head upto 1700 m. Max. Pore Pressure Expected is Hydrostatic+15-20 % at TD
	150-1000	8.4-8.8	9.2-10	
	1000-2000	8.8-10.4	10.0-12.0	
I	0-100	8.4-8.6	8.75-9.2	Normal Pore Pressure Expected
	150-1150	8.6-8.8	9.2-10	
B	0-150	8.4-8.6	8.75-9.2	Normal Pore Pressure Expected
	150-1200	8.6-8.8	9.2-10.2	
C	0-150	8.4-8.6	8.75-9.2	Hydrostatic Head is Expected
	150-1000	8.4-8.8	9.2-9.8	
	1000-1665	8.4-8.8	9.8-10.4	
H	0-150	8.4-8.6	8.75-9.2	Hydrostatic Head+5-10 % Pressure Expected
	150-1400	8.4-8.8	9.2-9.8	
	1450-1700	8.8-9	9.8-10.6	
J	0-100	8.4-8.8	8.75-9.2	Normal Pore Pressure Expected
	100-950	8.4-8.8	9.2-9.6	



**Fig 4 b:** Pore Pressure Prediction plots with safe mud window for proposed Wells E, I and B



**Fig 4 c:** Pore Pressure Prediction plots with safe mud window for proposed Wells C, H and J

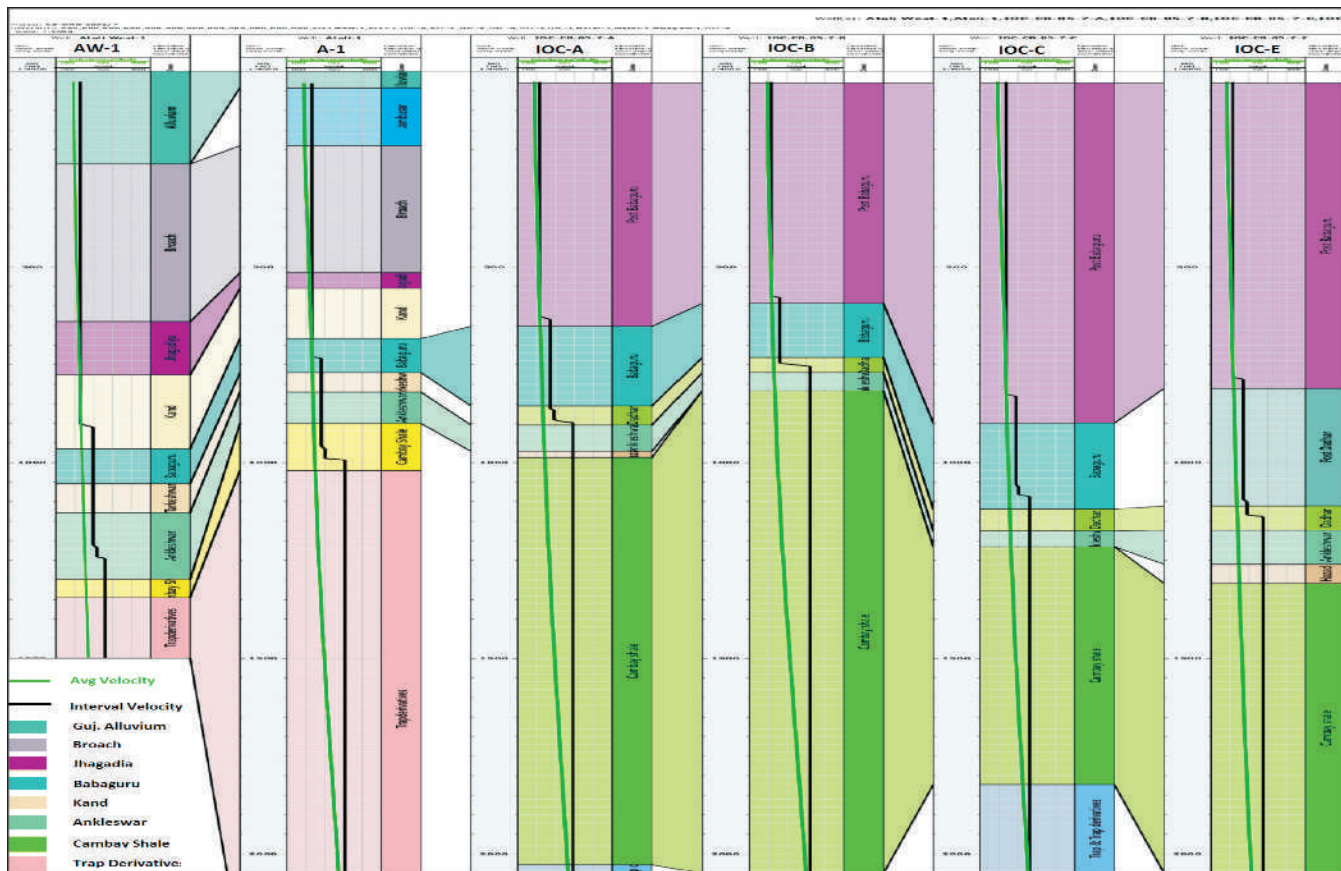


Fig 5 a: Correlation of wells (both existing & proposed) along with their velocity trends

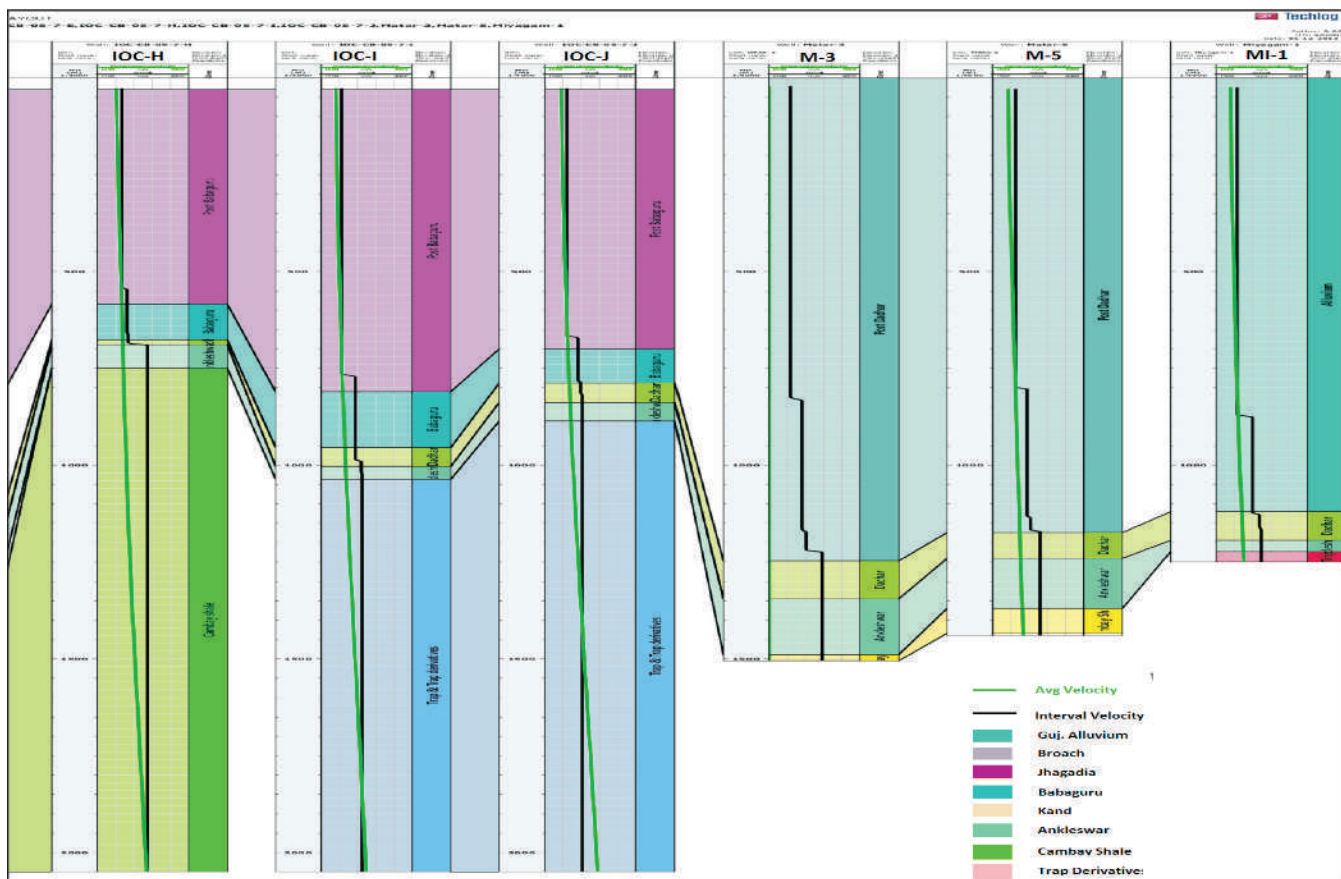


Fig 5 b: Correlation of wells (both existing & proposed) along with their velocity trends

- Safe mud window (as shown in Fig. 4b and c) to be used while drilling the wells.

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chlumberger Techlog 2013

## Author's Profile



**Rakesh Roshan Rana**

Rakesh Roshan Rana, a young geoscientist with 6 plus years of Upstream oil and gas industry experience. Topped North Orissa University in Graduation and completed M.Sc. Tech. from Indian School of Mines, Dhanbad in 2008. Joined Indian Oil Corporation on 14th July 2008, and currently working as an Operational Geologist for IOC's Operated blocks in Cambay Basin.



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Dr.C.Chandrashekhara worked with the upstream oil industry for the last 31 plus years in various facets of oil and gas exploration and production. With rich experience obtained during PSU career, started working from 2007 onwards with private oil and gas industry, for participation in NELP bid rounds, visit of data rooms of various companies and governments, preparation of prospectivity reports & submission of bids for NELP. Worked on resourcing LNG for India, exploring the options for power generation, Gas to Liquids plant, gas based power generation, fund raising for oil and gas properties acquisition etc. Presently with Indian Oil Corporation Limited as a Consultant Geophysicist.