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Modeling for Detection of in-situ Combustion through Acoustic Impedance response in Santhal Field; A Feasibility Study

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Summary

Santhal field, located in Mehasana block of Cambay basin, India, has heavy oil sandstone reservoirs of Eocene age, and requires combustion for producing them. A 3D seismic survey was carried out in year 2002-03 and has been analyzed to observe the effect of in-situ combustion on the acoustic impedance response. Gassmann fluid substitution modeling carried out to study change in velocity and density after the combustion suggests the feasibility of monitoring the fire front movement on acoustic impedance response arrived from seismic inversion. These changes in the velocity and density are validated by comparing log data of wells drilled after combustion with the nearby wells drilled before in-situ combustion. Seismic impedance response on sections passing through the wells where in- situ combustion is known to have taken place before acquiring the seismic data, show significant lowering of reservoir impedance, supporting the feasibility study. Considering the issue in achieving repeatability of 4D seismic survey due to change in seismic acquisition, processing technologies and surface conditions(Lumley, 2001), it may be advisable to follow reservoir characterization route through seismic inversion for each of the repeat survey rather than striving to achieve exact repeatability of time-lapse seismic surveys.

Keywords*: Heavy Oil, Burnt zone, Fire front monitoring, Fluid substitution modeling, Seismic inversion, Acoustic impedance*

Introduction

The Santhal Field was discovered in 1970 and was put on production in 1974 (Figure1). Combustion process was started for EOR processes in 1997 in northern Santhal field. A 3D seismic survey was carried out in year 2002-03. Fluid replacement modeling (FRM) is carried out to understand post combustion impedance responses for the burnt zone behind the fire front. In burnt zone, the pores space is thought to be occupied by mixture of nitrogen, CO_2 and air. It shows that the combustion has lowered the impedance significantly enough to map the burnt zones indicating the feasibility of monitoring fire front on seismic impedance response in time lapse seismic surveys. Kumar A et al, 2004 and Hossein Mehdi Zadeh et al, 2010, have shown the feasibility of tracking thermal front on the basis of 4D seismic survey in the contiguous Balol field.

Theory and Method

Sands are characterized by higher impedance than shale as seen on well log data (Figure2). 3D seismic data acquired in 2002-2003 over the field has been subjected to model based post stack seismic inversion. Sands are well brought out on impedance response arrived after inversion (Figure3) showing impedance parameter alone can be used for mapping reservoir facies.

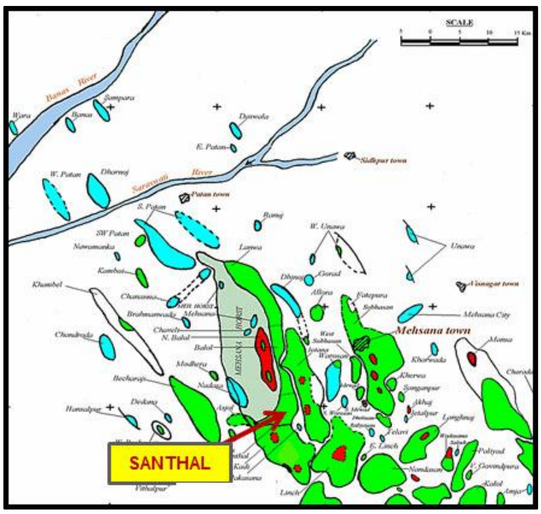

Figure1: Oil and Gas Fields of Mehsana Petroleum Province showing location of Santhal Field.

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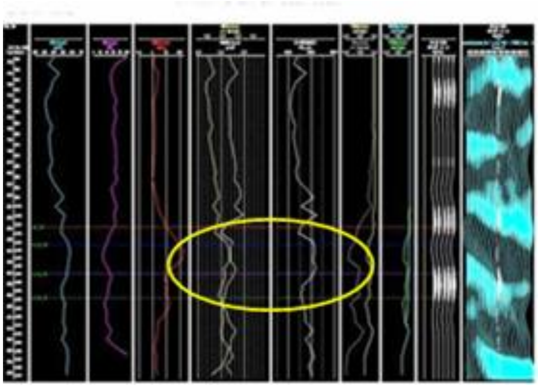

Figure2: Impedance from well log data (well-A) at seismic scale showing high impedance at pay sands.

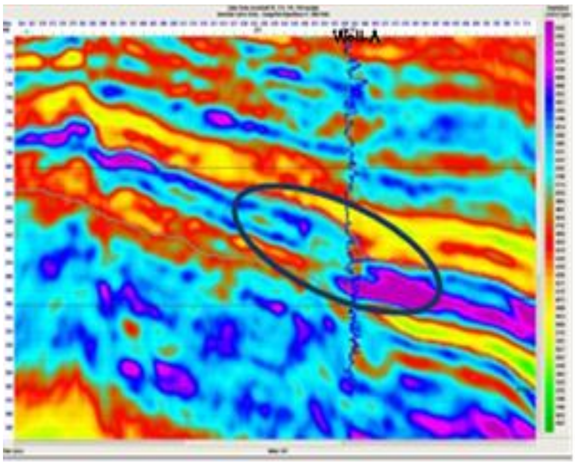

Figure3: Impedance Section passing through well - A.

Heavy oils behave as solids at low temperatures and as liquids at high temperatures. Both Vp and Vs of heavy oil sands decrease significantly with increasing temperature (De-Hua Han et al, 2008). Changes in pressure and saturation also affect the velocities and density of the reservoir and thus alter the impedance (Han D et al, 1997; Hedlin K et al, 2001; Bentley et al, 2000).

Fluid Replacement Modeling (FRM) has been carried out to see the feasibility of monitoring the fire front through impedance parameter.

Gassmann fluid substitution

The acoustic impedance of the rocks is multiplication of compression velocity Vp (P-wave) and density. Seismic parameters Vp (P-wave) and Vs (S-wave) are related with rock parameters by following relations.

$$Vp = [(k+4/3\mu)/\rho]^{1/2}$$

$$Vs = (\mu/\rho)^{1/2}$$

Where k, μ and ρ are the bulk modulus, shear modulus and bulk density of the rock respectively. The effect on seismic parameters after combustion is worked out using Biot-Gassmann equation; the most commonly used method for fluid replacement.

Gassmann equations

$$K = Kd + \frac{(1 - K_d/K_m)^2}{\Phi/K_f + (1-\Phi)/K_m - K_d/K_m^2}$$

$$\mu = \mu_d$$

where *K* is the bulk modulus of a fluid filled rock, *Km*, the bulk modulus of the solid grains(mineral matrix), *Kf* , the bulk modulus of the fluid mixture occupying the pore space, *Kd* , the bulk modulus of the dry rock frame and φ is porosity of the rock. μ_d is the shear modulus of dry rock.

The bulk modulus K_f of a fluid mixture can be calculated using Wood's equation :

$$1/K_f = S_w/K_w + S_o/K_o + S_g/K_g$$

where K_w, K_o and K_g are the bulk modulus of water, oil and gas respectively . S_w, S_o and S_g are the saturations of water, oil and gas in pore spaces, respectively.

the bulk density ρ_f of fluid mixture is given by :

$$\rho_f = S_w\rho_w + S_o\rho_o + S_g\rho_g$$

where ρ_o, ρ_g and ρ_w are the densities of oil, gas and water respectively.

A Producing well-C which was logged before the combustion was started is selected as candidate for feasibility study of detecting in-situ combustion through acoustic impedance (Figure4).

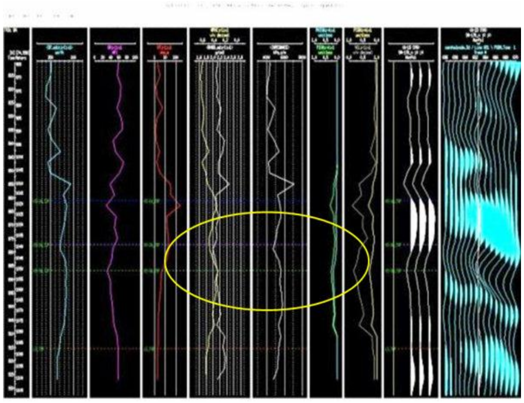

Figure4: Impedance from well log data (well-C) at seismic scale.

Parameters before combustion

Gassmann equation shows K_d is required to be known for calculating seismic parameters Vp, Vs and density after fluid substitution. For this K, K_m, K_f, and porosity Φ are required to be known.

K is calculated from Vp, μ and ρ; where in this case Vp and ρ are available from well log data. In the absence of shear wave logs, Castagna's (1985) mud-rock line is used to generate the Vs log from Vp and thereby μ is calculated from Vs and density ρ.

Density ρ of the reservoir is the sum of ρ_d (dry dock density) and ρ_f multiplied by porosity Φ. With known density and distribution of fluid saturations, porosity is calculated.

K_m for sand stones is a standard parameter as 36 Gpa. K_f is calculated from wood's equation. Ko for heavy oil is calculated for reservoir parameters API=17, pressure 10Mpa, temp70^{o}C and minimal GOR value from Batzle and Wang relations. Ko, Kw, So as 32% and Sw as 68% are inputted in wood equation and K_f is calculated.

Once K_d made available from Gassmann equation, K is calculated in post combustion scenario for reservoir rock behind the fire front from Gassmann equation.

Parameters after combustion

$K_{m,}$ k_d and porosity Φ remain the same. Post combustion K_f has been calculated for

a) 20% of gas saturations at the pressure 10Mpa and temperature of 300^{o}C and
b) 100% saturation of mixture of gases for the same pressure and same temperature for the burnt zone behind the front.

Post combustion ρ is calculated using density of individual fluids and their saturation distribution from ρ_d and porosity Φ. K is calculated from above post combustion parameters using Gassmann equation. With available K, density and μ parameters post combustion Vp is calculated. The parameters before and after combustion are shown in Figure5.

Discussions

Wood equation shows substantial lowering of fluid bulk modulus and density after substitution of gas in both the cases and therefore lowering of K is expected from Gassmann equation (Figure5), this resulting in decrease in P-wave velocity and density by 15-20% whereas S-wave velocity was not affected much (Figure6). The lowering of impedance is significant enough to map the combustion zones on seismic derived impedance response.

Decrease in P wave velocity is more for 20% gas saturation as compared to P wave velocity for 100% gas saturation. The gas saturation values were chosen judiciously, as they correspond to pre-combustion (0%) and post-combustion (100%) cases.

The data slice generated over reservoir interval from impedance volume shows quite low impedance over producing area in the northern part (Figure7). Anomalies observed in the northern part of Santhal field (in-situ combustion started first) are caused by gas saturation within the reservoir zone as in this area in-situ combustion started in 1997 well before the acquisition of seismic data. Since well log data is available for the post and pre combustion case in the central part of Santhal Field, the realistic change in density between well-D (drilled in 2010) and well-E (drilled in1995) is observed (Figure8), validating the results obtained from FRM .

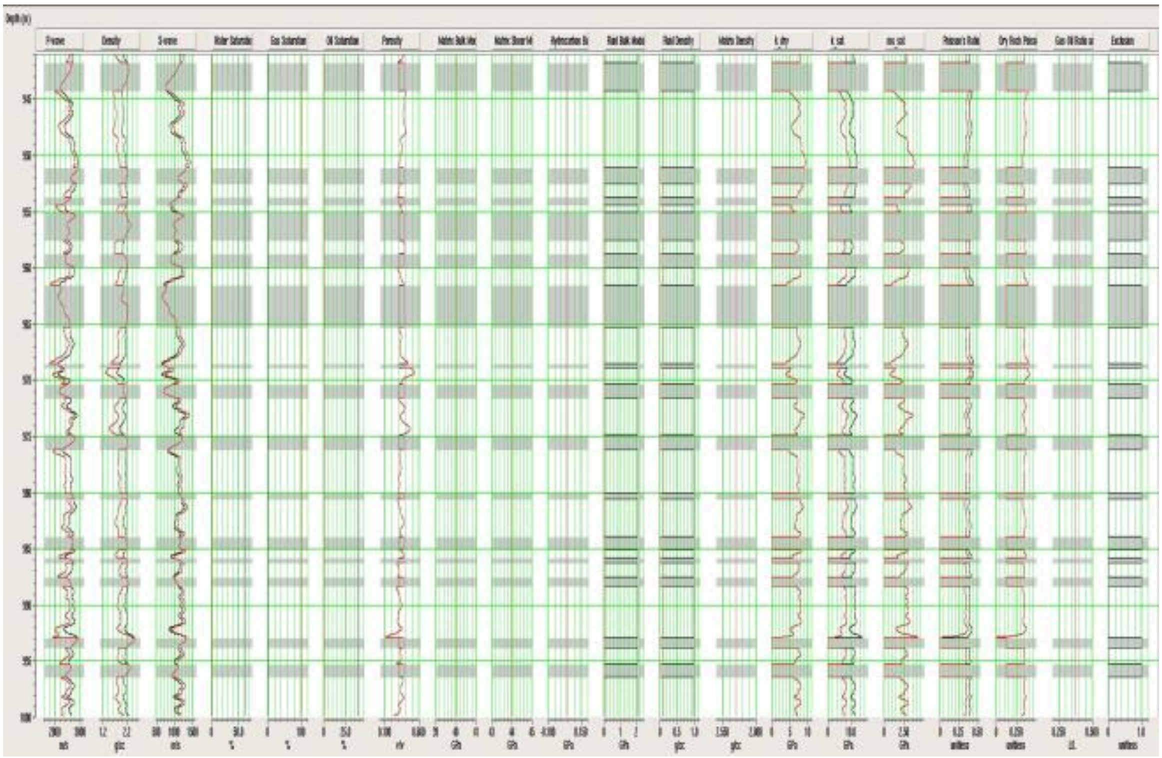

Figure5: Parameters before and after Gassmann fluid substitution showing lowering of fluid bulk modulus , fluid density and K_sat —— corresponds to original log and —— corresponds to modified log.

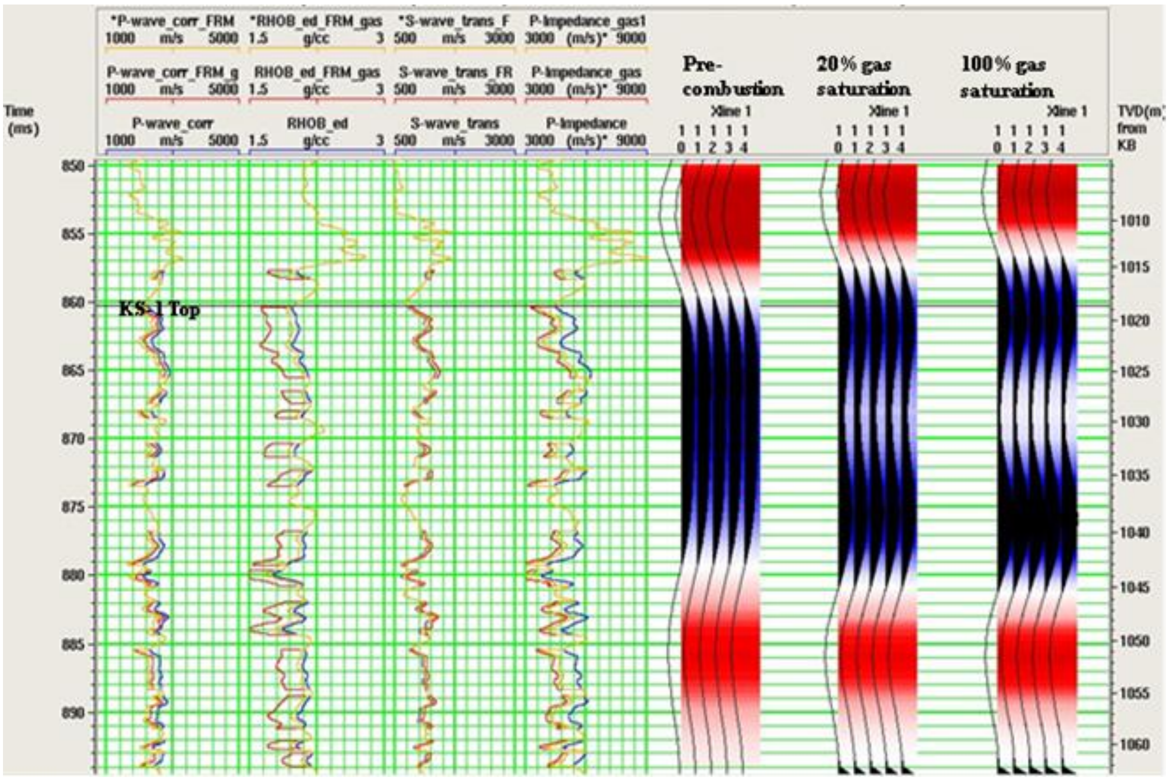

Figure6: P-wave, S-wave, density and computed impedance logs before and after Gassmann fluid substitution along with synthetic sections. —— Pre combustion, —— 20% gas saturation and —— 100% gas saturation.

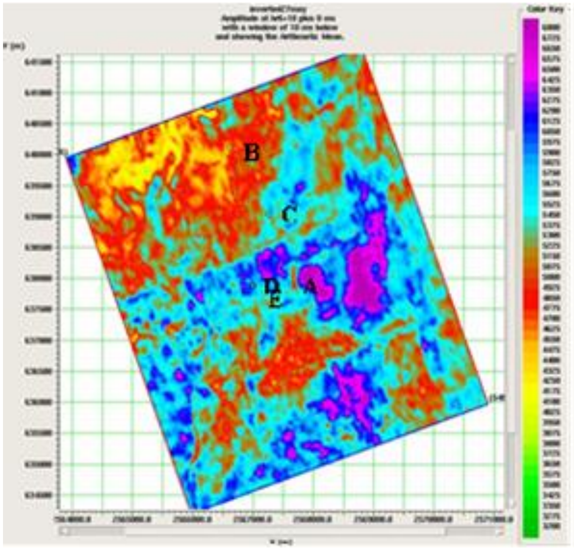

Figure7: Horizon slice at reservoir top showing lower impedance in Northern part where in-situ combustion started well before 3D data acquisition.

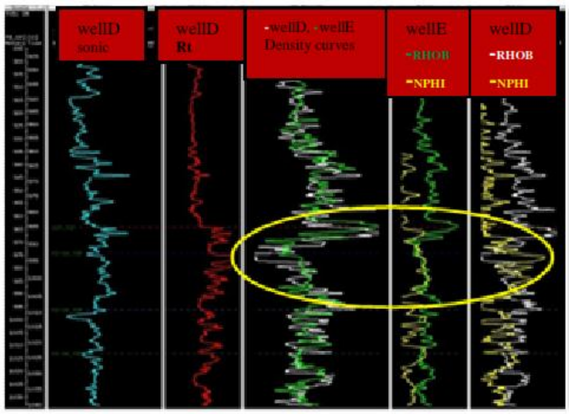

Figure8: Comparison of log data of well-D (2010) and well-E (1995) validating the result of Gassmann Fluid substitution.

Seismic impedance response at few of the well locations where in-situ combustion was initiated before acquiring the seismic data has been studied. Well-B is such a well shown with the data logged before combustion started in Jan 1999. It is understood that significant amount of in-situ combustion has taken place before 2002-03. Well logs at seismic scale show high impedance corresponding to reservoir (Figure9) and significant amount of impedance lowering on impedance sections is expected after combustion. Impedance sections passing through these wells show significant lowering of impedance (Figure10) than the impedance of the interpreted reservoir sands in up dip. Higher acoustic impedance (≥6000) on seismic is interpreted to be given by yet un-drained portions of the reservoir.

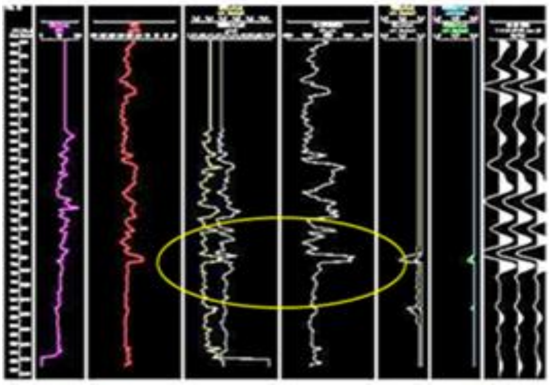

Figure9: Impedance from well log data at seismic scale (well-B)

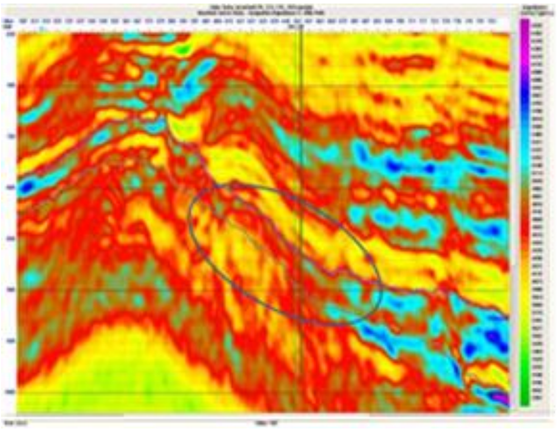

Figure10: Seismic derived Impedance response passing through well-B showing post-combustion significant lowering of impedance at pay sand level.

Conclusions

Gassmann fluid substitution shows lowering of impedance by 20% which is quite significant for monitoring fire front and mapping the residual oil. It is concluded that the geobodies with high acoustic impedance represent as yet un-drained portions of the reservoir.

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