J. Ind. Geophys. Union (March 2018)
v.22, no.2, pp: 128-137

Stress Orientation from Image log and Estimation of Shear Wave Velocity using Multiple Regression Model: A Case Study from Krishna-Godavari basin, India

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ABSTRACT

Formation Micro Imager (FMI) logs from four boreholes located in the Krishna-Godavari (K-G) basin, covering an area of about 3760sq km onshore, are analyzed to identify natural fractures and breakouts. These features are used to calculate the in-situ maximum and minimum horizontal stress orientation at different depth intervals in the wells. The orientation of maximum principle horizontal stress (S_H) obtained from orientations of breakouts and drilling induced fractures varies from N14.54^{0}E to N21.84^{0}E for the four wells. The dip of natural fracture varies from 4.83^0 to 29.31^0 with a dominating mean azimuth N9^{0}E. The orientation of S_H is in close agreement with the regional NNE trend of the horst-graben, the K-G basin. In addition to stress directions, the mechanical properties of the formations, like Young's modulus (Y), bulk modulus (K), shear modulus (G), Poisson's ratio (σ) and unconfined compressive strength (UCS) are estimated from the density and P-and S-wave velocity (Vp and Vs) log data. Further, correlation between Vp and Vs is examined by multiple regression analyses with squared multiple correlation coefficient (R^2) varying from 0.92 to 0.96. The models developed by multiple regression analysis for Vs can be used to estimate elastic moduli and rock strength for other wells in the K-G basin.

Key words: FMI log, Breakout, Drilling induced fracture, Natural fracture, Stress orientation, Rock mechanical parameters, Shear wave velocity, Krishna-Godavari basin.

INTRODUCTION

Borehole breakouts and drilling induced fractures have long been recognized as stress-induced features because we can use information on their azimuth to determine orientations of in situ principal stresses (Nelson and Hillis, 2005; Nelson et al., 2005; Tingay et al., 2009; Nie et al., 2013). Information of in situ stresses plays an important role in evaluation of seismic risk, and analysis of regional and tectonic activities (Zoback, 1992; Bell, 1996; Trautwein et al., 2010). A thorough understanding of in situ stress conditions and rock properties, such as compressive strength, elastic moduli and anisotropy are required to optimize the wellbore design (Das and Chatterjee, 2017). In any sedimentary basin, these rock properties can be derived from the P- and S- wave velocities. Determination of mechanical properties of rocks is important for a variety of reservoir engineering purposes like hydraulic fracturing, estimation of removable reserves, prediction of wellbore stability and subsidence. No core sample and seismic data are, however, available; only image log, velocity log and conventional logs are available to compute in-situ stress and rock properties. Therefore, in this paper, we focus on (a) identification of breakout, drilling induced fractures and natural fractures from image log, (b) determination of in-situ stress orientation, (c) estimation of rock mechanical parameters and (d) regression models for prediction of S-wave velocity. The S-wave velocity is important in the study of seismic inversion and petrophysical evaluation, particularly for estimation of geomechanical properties. The P-wave and S wave velocities and density values are used to estimate the shear modulus (G), Young's modulus (Y), bulk modulus (K), Poisson's ratio (σ) and unconfined compressive strength (UCS) of rocks in Krishna-Godavari (K-G) basin.

STUDY AREA

The K-G basin developed at the confluence of the Krishna and Godavari rivers at the east coast of India form the largest basin under the eastern Continental Margin of India (ECMI) (Figure 1). It occupies an area of about 20,000 km^2 onland and another 13,000 km^2 offshore (Gupta, 2006). K-G basin encompasses large areas both onland and off shore including those located in deep waters. The basin itself came into existence following rifting along ECMI craton during early Mesozoic (Sastri et al., 1973). Both the onland part of the basin and its off shore host a large number of structural traps that have been mapped and a large number of them established through drilling (Rao, 2001). Enhanced activity for hydrocarbon exploration in the K-G basin within the past decades has emphasized the need for a better understanding

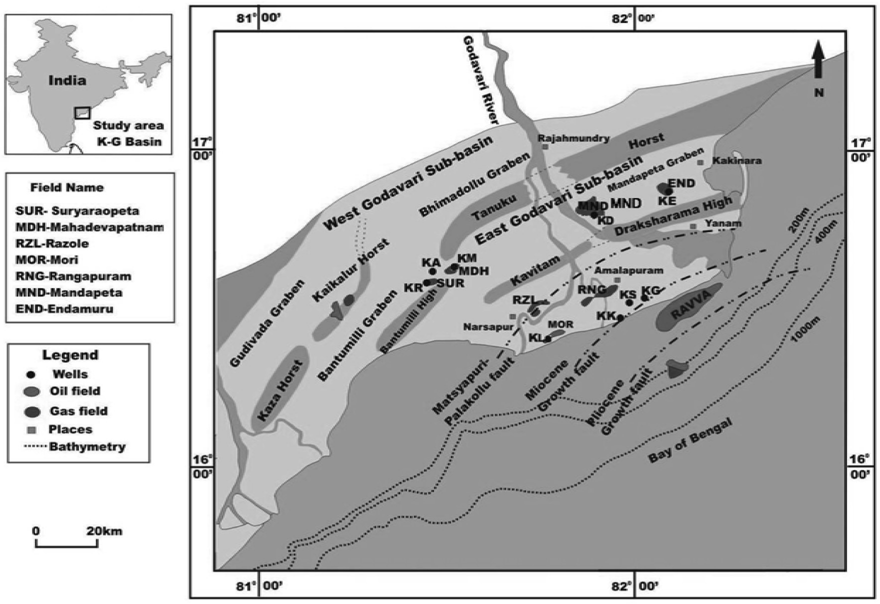

Figure 1. The map illustrates locations of nine wells distributed in the oil/gas fields of Krishna-Godavari basin (after Rao, 2001). Out of these nine wells, data of the four selected wells (KA, KS, KD and KL) are analysed in this study.

of the regional stress regime for the ECMI, in general, and for the K-G basin in particular. Using 4-arm dipmeter caliper log data from 20 wells, a maximum horizontal in situ stress, varying from N54^{0}E to about N-S orientation, was reported by Chatterjee and Mukhopadhyay (2002). In the present study, our aim is to investigate the orientation of horizontal in situ stress from breakout, drilling induced and natural fractures using Formation Micro Imager (FMI) data of four wells; KA, KL, KS and KD drilled by ONGC covering an area of 2005 sq. km in the onshore K-G basin (Figure 1). We also investigate mechanical properties of rocks from five wells; KA, KR, KK, KG and KE distributed in the 3760 sq km area of this basin. The well KA located at the west-Godavari sub-basin encountered the Raghavpuram Shale formation. The wells KS and KL located in the east-Godavari sub-basin have penetrated the Narsapur Claystone, Matsyapuri Sand formation overlying the Vadaparru Shale. The well KD in the same sub-basin encountered the Mandapeta and Gollapalli sandstones overlain by Raghavapuram shale formations. Vertical stress, horizontal stress, pore pressures and fracture pressures were earlier reported for this part of the K-G basin (Singha and Chatterjee, 2014). Knowledge of all these parameters including rock strength is important to understand fracture characteristics of rocks under the stresses induced by hydraulic fracturing for well stimulation (Gray et al., 2012).

Fracture and In-Situ Stress Orientation

Stresses in the Earth can be defined in terms of magnitude and orientation of three principal stresses: maximum, intermediate and minimum. For a vertical well (as in the present study) and for a normal faulted stress regime, the first principal stress is considered to be vertical (S_v), corresponding to the weight of the overburden, the second principal or intermediate stress as well as the third principal stresses are referred to S_H and S_h indicating the maximum and minimum horizontal principal compressive stresses, respectively. S_H orientation has a significant implication on subsurface fluid flow and fault reactivation (Barton et al., 1988; Tingay et al., 2010a, b) and can be determined from borehole breakouts and drilling induced fractures interpreted from the FMI logs.

Borehole Breakout

Figure 2 shows the typical breakout signatures at several depth intervals of the selected four wells. The well KD in east Godavari sub-basin has penetrated the oldest sediments (Permo-Triassic through Cretaceous sequences) in the K-G basin. The breakouts are observed in this well at depths between 2395m and 2632m, corresponding to a total length of breakout for 114 m. This depth range is characterized by a mean S_H orientation N19.01^{0}E. The well KL has breakouts of 6 m length at a depth interval 1101-1350m characterizing a mean S_H N19.24^{0}E in the Oligocene sediments. The well KS has breakouts at depths between 1300m and 1311m for a length of 8m penetrating the sediments of Oligocene to Miocene with S_H orientation N14.54^{0}E (Singha and Chatterjee, 2014; Singha and Chatterjee, 2015). The deepest well KA, located within 60 km from the well KD in the west-Godavari sub-basin penetrating the early Cretaceous sequences, yields S_H orientation N20.68^{0}E.

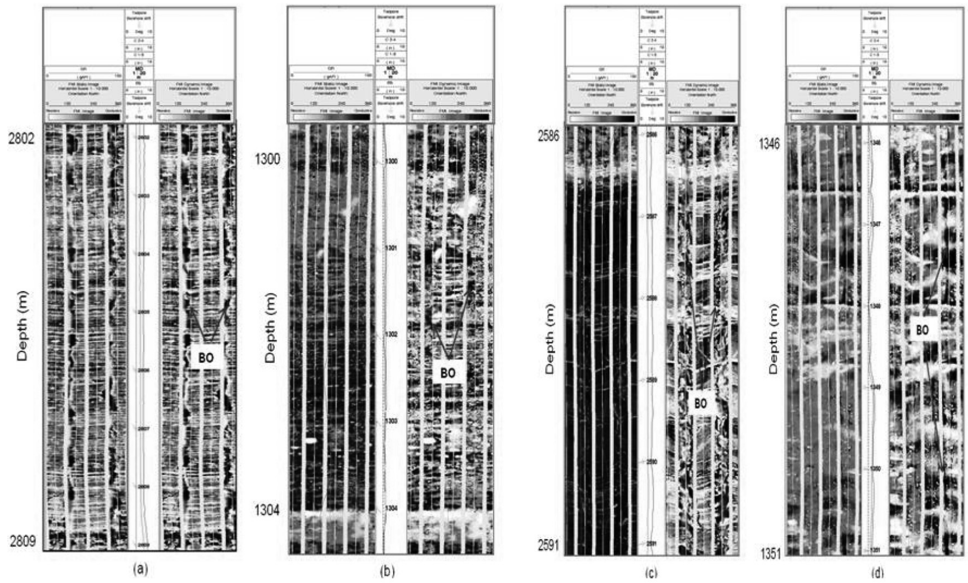

Figure 2: Breakouts observed at selected depth intervals for the wells: (a) KA, (b) KS, (c) (KD) and (d) KL.

Table 1: The orientation of maximum horizontal stress obtained from breakouts and drilling induced fractures observed from FMI logs, Krishna-Godavari basin.

Wells	Depth interval (m)	Length (m)	Orientation from North (degree)		Azimuth of S_H (degree)		Name of Field	Formation	Geological age
			Azimuth	Mean	Mean	s.d			
Breakout observation									
KA	2800-2807	7	114.14	110.68	N20.68E	±2.76	Mahadevapatnam	Raghavapuram Shale	Early Cretaceous
	2808-2819	11	110.19						
	2820-2830	10	108.82						
	Total	28							
KL	1101-1104	3	291.11	289.24	N19.24E	±2.64	Mori	Narsapur Claystone	Oligocene
	1346-1350	3	287.37						
	Total	6							
KS	1300-1303	3	104.65	104.54	N14.54E	±0.12	Rangapuram	Matsyapuri Sandstone	Oligocene to Miocene
	1306-1311	5	104.48						
	Total	8							
KD	2395-2413	28	106.75	109.01	N19.01E	±1.34	Mandapeta	Gollapalli Sandstone	Jurassic to Early Cretaceous
	2421-2448	27	109.86						
	2451-2467	16	108.86						
	2476-2482	6	108.33						
	2521-2537	16	110.82					Mandapeta Sanstone	Permo Triassic
	2581-2592	11	109.75						
	2622-2632	10	110.00						
	Total	114							
Drilling Induced Fracture observation									
KL	1101-1105	4	23.53	21.84	N21.84E	±5.52	Mori	Narsapur Claystone	Oligocene
	1349-1350	1	209.07						
	1351-1352	1	31.84						
	1445-1448	3	200.43					Matsyapur Sandstone	Oligocene to Miocene
	1558-1565	7	199.03						
	Total	16							

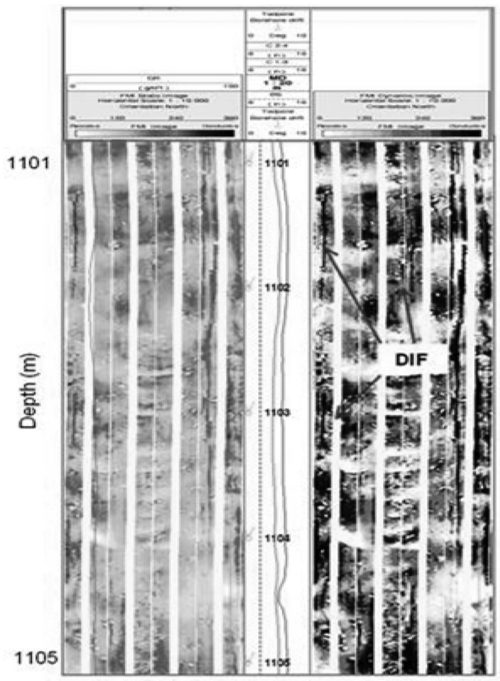

Figure 3: Drilling induced fractures in the selected depth interval are shown.

Drilling Induced Fracture (DIF)

Drilling induced fractures (DIFs) are created when the stresses concentrated around a borehole exceed that required to cause tensile failure of the wellbore wall (Aadnoy, 1990). DIFs typically develop as narrow sharply defined features that are sub-parallel or slightly inclined to the borehole axis in vertical wells and are generally not associated with significant borehole enlargement in the fracture direction (Bell, 1996). The DIFs are only observed for a length of 14m at depth interval 1101-1565m in the well KL (Figure 3). The S_H orientation is N21.84^{0}E in sediments of Oligocene to Miocene. The mean orientation of S_H of the selected four wells is sub-parallel to the NNE regional horst-graben trend.

An average or mean breakout/DIF orientation is calculated as a 'length weighted average breakout/DIF orientation'. Table 1 lists the well identification, depth interval, length, azimuth, mean breakout/ DIF orientation for the given depth interval, and the mean azimuth of S_H for the individual well with standard deviation (s.d), name of oilfield, formation with geologic age. Figure 4 displays the breakout and DIF orientations with depth including the rose diagram indicating the mean S_H direction for the four wells. The S_H orientation obtained from the breakout in well KL differs by 2.6^o from that obtained by the DIF.

3.3. Natural Fracture

A fracture is a surface along which a loss of cohesion in the rock texture has taken place. Minerals may fill the entire fracture, converting an open fracture to a healed or sealed fracture. In this study natural fractures are subdivided into open fracture, partially open fracture and resistive fracture (Rajabi et al., 2010). The fractures are observed on image logs in each wells excepting the well KA. The fluid loss during drilling suggests existence of natural fractures and open or partially open fractures are permeable in-situ. Three types of natural fractures are generally observed; these are: (i) open fracture (OF), which is a resistive fracture, free from fluid and yields white image,(ii) closed fracture (CF), which is low resistive, fluid filled and yields black image, and (iii) partially open fracture (POF), which is moderate resistive, partially fluid filled and yields black-white image. The typical fractures obtained from image logs at the three selected wells (Figure 5) are counted to be 44, 24 and 50 in the KL, KS and KD wells, respectively. Fractures are mostly observed in Narsapur claystone in KL, in Matsyapuri sandstone in KS and in Mandapeta and Gollapalli sandstones in KD, respectively.

The orientations of natural fractures with dips are plotted in stereonet for the wells KL, KS and KD (Figure 6a, b and c). These plots show the distribution of CF, OF and POF in these wells. The dip of the OF and POF varies from 7.8^0 to 29.31^0 in well KL, 4.83^0 to 26.91^0 in well KS and 6.03^0 to 22.62^0 in well KD, respectively. The azimuths of open fractures in well KL, KS and KD vary from N6^{0}W to N16.62^{0}E, N45.69^{0}W to NS and N7^{0}W to N31.85^{0}E, respectively. Mean azimuth of OF is orientated N5.31^{0}E in well KL, N22.85^{0}W in well KS and N12.85^{0}E in well KD, respectively. The OF as well as POF for the three wells are oriented dominantly in NNE with a few in NNW. Majority

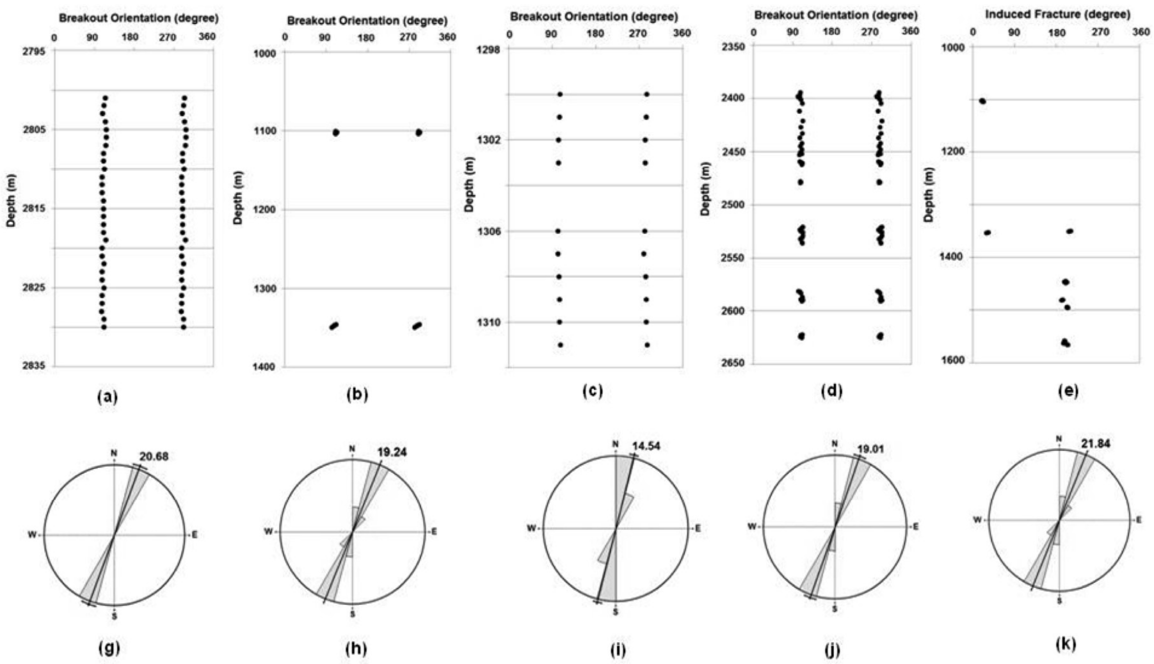

Figure 4: Breakout orientations at the available depth intervals for the wells (a) KA, (b) KL, (c) KS and (d) KD, and (e) orientations of DIF at depths for the well KL are shown. The rose diagrams depict mean breakout horizontal stress (S_H) for the wells: (g) KA, (h) KL, (i) KS, (j) KD, and (k) DIF S_H orientation for the well KL.

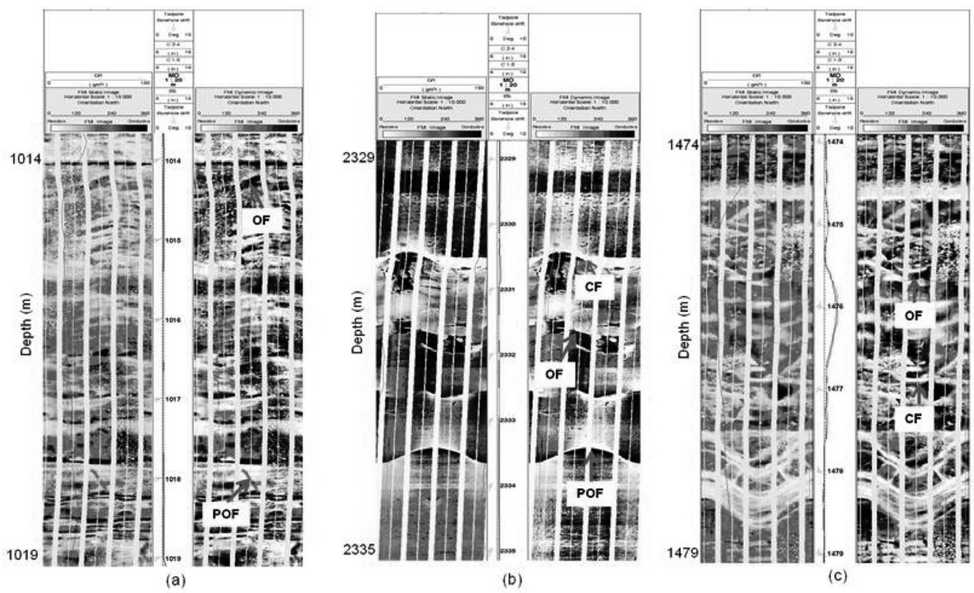

Figure 5: The natural observed fractures CF (closed fracture), OF (open fracture) and POF (partially open fracture) in image logs at selected depth intervals in wells (a) KS, (b) KD and (c) KL.

of the OF follow the mean S_H orientation with a maximum deviation of about 10^0.

Azimuths of the natural fractures interpreted from the FMI are dominantly in NNE-SSW with a few in NNW-SSE, and they more or less follow the trend of the faults in the area. The faults and natural fractures are genetically related and are developed under the same stress conditions (Gupta, 2006).

COMPUTATION OF ROCK MECHANICAL PARAMETERS

The orientation of S_H, knowledge of rock mechanical properties and magnitude of in-situ stress with pore pressure are important parameters for planning both drilling and production strategies. Using well logs to predict formation mechanical properties is an indirect technique.

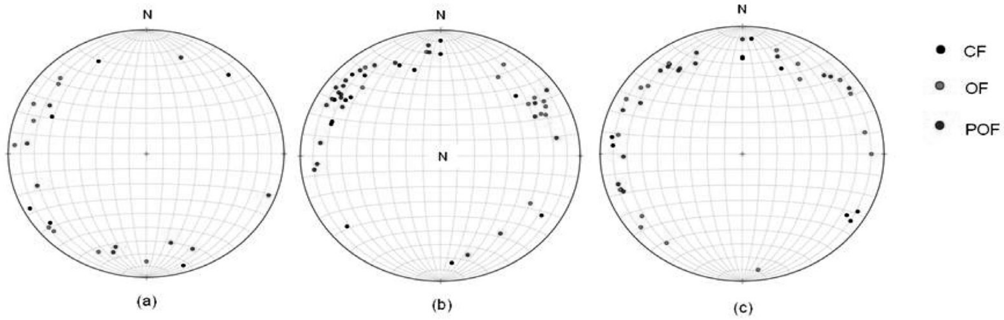

Figure 6: The Stereonet plots show fracture dip and azimuth at the wells (a) KL, (b) KS and (c) KD. CF, Closed Fracture, OF, Open Fracture and POF, Partially Open Fracture.

Table 2. Rock mechanical parameters of geological formations for five wells in K-G basin.

Formation	**Depth Ranges in Well**		**Shear Modulus (GPa)**	**Young's Modulus (GPa)**	**Bulk Modulus (GPa)**	**Poisson's Ratio**	**UCS (MPa)**
	Well	**Depth interval (m)**	**Average**	**Average**	**Average**	**Average**	**Average**
Matsyapuri Sandstone	KK	1988-2380	4.8	12.6	14.4	0.35	37.4
	KG	1095-1400					
Vadaparru Shale	KK	2380-2570	4.9	13.1	23.3	0.34	38.1
Raghavapuram Shale	KR	2023-2424	9.2	23.9	19.0	0.29	62.8
	KA	2800-2830					
	KE	1763-1938					
Gollapalli Sandstone	KE	1938-1980	13.2	31.1	16.5	0.17	75.1
Kommugudem Formation	KE	1980-2116	22.4	56.1	41.8	0.26	74.2

However, the method offers several benefits including cost, continuous estimations of mechanical properties with depths and prevalence of log data. The most commonly used method for deriving elastic mechanical properties from logs is based on relations expressing these properties in terms of acoustic velocities. Due to lack of core samples, we are not able to correlate the static modulus and dynamic modulus. The rock mechanical parameters for five wells: KA, KR, KK, KG and KE have been computed from sonic logs of Vp and Vs (Singha and Chatterjee, 2017).The unconfined compressive strength (UCS), elastic moduli such as: shear modulus (G), Young's modulus (Y), bulk modulus (K) and Poisson's ratio (σ) have been estimated from V_P ,V_s and density (ρ) log data using the equations given by Mohammed and Zillur (2001) and by Potter and Foltinek (1997):

Poisson's ratio, $\sigma = \frac{1}{2}\frac{((V_p/V_s)^2-2)}{((V_p/V_s)^2-1)}$

Shear modulus, $G = V_s^2\rho$

Young's modulus, $Y = 2 * G(1+ \sigma)$

Bulk modulus, $K = \rho * \left(V_p^2 - \frac{4}{3}V_s^2\right)$

And Cohesive Strength (S_0) as

$S_0 = 0.025 * 10^{-9}\frac{Y}{K}[0.008 * Vsh + 0.0045(1 - Vsh)]$,

where Vsh is the clay content.

Unconfined Compressive Strength is therefore given by:

$UCS = \frac{S_0}{0.289}$

The values G, Y, K, σ and UCS in these five wells vary with depth as well as with lithology as listed in Table 2.

RESULTS AND DISCUSSION

The variations of these parameters are mostly constant for the well KA at a short depth interval 2800-2830m.The breakouts observed for ~28m length indicates shear failure due to relatively low UCS of about 60 MPa with respect to the compressive hoop stress developed at the borehole wall (Barton et al., 1988). Below the breakout, low poison ratio is observed indicating presence of gas sand. The Raghavapuram Shale at a depth interval 2010-2420m in the well KR is characterized mostly with low G, Y, K values and σ of 0.35. This well has penetrated gas bearing sands with low σ of 0.11 and high resistive value at depth interval 2365 to 2378m. The variation of elastic parameters values at

Table 3. Range of dependent and independent variables for predicting shear wave velocity (Vs) using multiple linear regression analysis.

Wells	Depth interval (m)	P-wave (m/sec)	S-wave (m/sec)	Vsh	Φ
KA	2800-2830	3644-3885	2035-2159	0.51-0.77	0.006-0.05
KR	2023-2429	2529-5242	738-2338	0.002-0.92	0.03-0.56
KM	457-2512	1932-5354	1204-2950	0-0.70	-
KK	1988-2577	2511-2449	1027-2778	0.02-0.63	0.03-0.31
KG	1095-1399	1729-4428	376-2208	0.11-0.46	0.1-0.44
KE	1763-2116	2737-6044	1252-3931	0.02-0.81	0.05-0.54

Vsh, clay content and ϕ, porosity

Table 4: Summary of multiple regressions for prediction of shear wave velocity (Vs).

Model no.	Independent Variables	Coefficient	Standard Error	t-value	Significance
Model 2 for Vs2	Constant	-559.75	25.47357	-21.9737	5.96E-84
	Vp	0.71	0.008293	85.14415	0
	Vsh	-202.20	33.16041	-6.09775	1.68E-09
Model 3 for Vs3	Constant	-257.709	39.21033	-6.57247	8.97E-11
	Vp	0.677533	0.00837	80.94516	0
	Vsh	-376.223	36.06393	-10.4321	5.81E-24
	ϕ	-783.87	80.3058	-9.76107	2.49E-21

Vp, P-wave velocity, Vsh, clay content and ϕ, porosity

depth interval 1980-2570m demonstrates the characteristic signatures of rock mechanical properties in shaly sands in Matsyapuri Sandstone Formation. It is observed that the Vadaparru Shale in this well is characterized by continual increase of elastic moduli and UCS. The least value of G, Y, K and UCS are observed in the well KG at a depth interval 1090-1400m in the Matsyapuri Sandstone Formation. Shale lamina is characterized by high Poisson's ratio of 0.44 whereas gas producing layers are characterized by low Poisson's ratio below 0.18. The value of σ varies from 0.32 to 0.47 in the Raghavapuram Shale with lowering of its value down to 0.12 in the Gollapalli Sandstone Formation, and then again-increases in the Kommugudem Formation. Gas producing zone is characterized by low Poisson's ratio at depth interval 1939m - 1958 m in the Gollapalli Sandstone. The signature of dynamic elastic moduli and UCS suggest the lithofacies changes from shale-dominated to sand-dominated rocks.

S-Wave Velocity Estimate from Regression Model

The information on density, sonic P and S wave velocities are to be known in order to determine the rock mechanical properties from well log data. The P and S wave velocities and density values are used to estimate the elastic moduli for rock strength and geo-mechanical modeling (Singha and Chatterjee, 2015), which are useful for the determination of maximum and minimum horizontal stresses. However, the absence of the dipole shear sonic logs imposes severe limitations to such applications. We propose regression models for computation of S wave velocity from the four wells KA, KG, KK and KE. Sandstones, shaly sandstones and shales comprise a major component of the K-G basin and are of significant relevance to hydrocarbon reservoir. Many theoretical/experimental models exist considering the effects of porosity (ϕ), clay content (Vsh), pore shape, fluid, and matrix moduli on the elastic properties of rocks (Gassmann, 1951; Mavko and Nur, 1978; Castagna et al., 1985; Eberhart-Phillips et al., 1989). Therefore, in order to establish predictive models among parameters, simple regression between Vp and Vs has been performed in the first stage of analysis and displayed in Figure 8a.The linear regression relation between Vp and Vs with R^2 of 0.92 resembles the relation given by Castagna et al. (1985). Multiple regression analyses have been carried out to correlate the Vs with Vp, Vsh as well as with Vp, Vsh and ϕ for the four wells. The clay content and porosities have been derived from the following equations:

$Vsh = (GR-GR_{min})/(GR_{max} - GR_{min})$ where GR = gamma ray log reading at any depth, GR_{min} = minimum gamma ray reading, GR_{max}= maximum gamma ray reading and porosity $(\varphi) = \frac{(\rho_{ma} - \rho)}{(\rho_{ma} - \rho_{fluid})}$

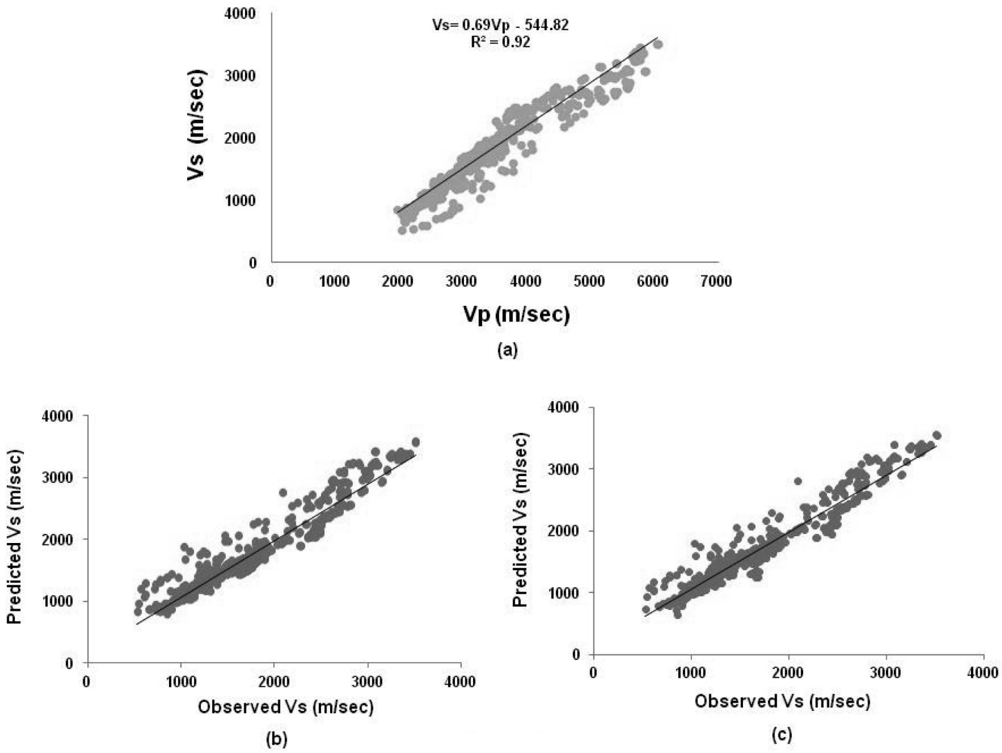

Figure 7: (a) Linear regression relation between Vp and Vs containing 796 observations of the four wells in the K-G basin, (b) correlation between 2nd model predicted Vs and the observed 796 Vs and (c) correlation between 3rd model predicted Vs and the observed 796 Vs.

ρ_{ma} = matrix density point = 2.71 gm/cc, ρ_{fluid} = density of fluid= 1gm/cc and ρ = density log data of rock in gm/cc

Table 3 shows the well name, depth interval, Vp, Vsh, ϕ and Vs for the multiple regression statistical analysis. The well log data are sampled averaging the log values at depth intervals of 1.8m or less without losing the information for each lithology. Analysis of variance (ANOVA) is a technique that analyzes the relationship between a dependent variable and two/three independent variables using IBM SPSS Statistical Software, version 21.0. The ANOVA model is the simplest linear statistical model with independent variables (Gelman, 2005). The independent variables namely, Vp, Vsh and ϕ are three different groups in this analysis.The squared multiple correlation coefficient (R^2) between the observed and predicted values is a good indicator to check the prediction performance of the model.

The linear regression models for computation of Vsare as follows:

Model 1: Vs predicted = 0.69Vp – 544.82 with R^2 = 0.92

Model 2: Vs Predicted = 0.71Vp - 202.20Vsh – 559.75 with R^2= 0.95

Model 3: Vs Predicted = 0.68Vp – 376.22Vsh – 783.87ϕ – 257.709 with R^2 = 0.96

All obtained relations are found to be statistically significant according to the Student's t test at 95% confidence level. Table 4 explains the coefficients of models, standard errors, t-value with significance level. The correlation between observed Vs and predicted Vs for models 2 and 3 are illustrated in (Figures 7b and c).

Validation

The models are validated with the Vs log for the wells KR and KM respectively (Figures 8a, b). The model estimated results match reasonably well with the observed Vs log for these wells. The information on Vs for well KM is not available continuously with depth. Variations between model predicted Vs and observed Vs are observed at depths 2360-2370m in well KR and at shallower depth from 450 to 650m in well KM. Despite little scatter, trends indicate that Vs decrease with increasing clay content and porosity. Model 1 predicts the Vs in clean sand without clay content. In water filled clean sand, model 1 estimates Vs with better precision. In shaly sand, the model 2 estimates better results considering the effect of clay content. Since velocity decreases with increasing porosity, the model 3 reflects the clay and porosity effects.

CONCLUSIONS

The orientation of S_H determined within the four wells in the K-G basin is consistent and is considered to be

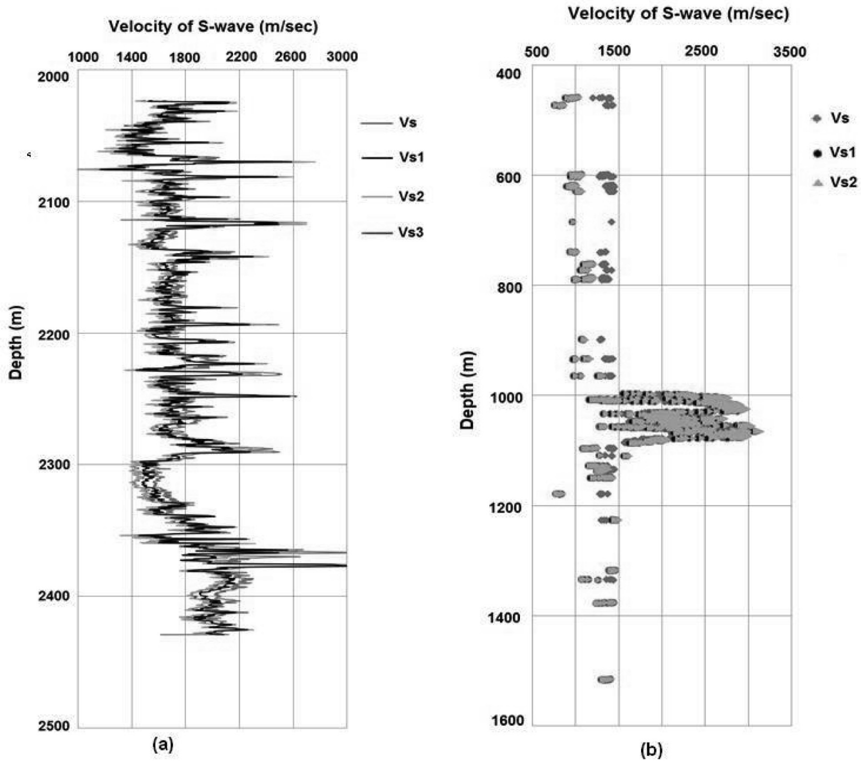

Figure 8: Validation of three models for (a) well KR and (b) well KM. The 3rd model predicted Vs for well KM could not be obtained due to non availability of density logs. Vs**:** Observed Vs from log, Vs1**:** predicted Vs from model 1, Vs2**:** predicted Vs from model 2, and Vs3**:** predicted Vs from model 3.

more reliable than the existing knowledge. The mean S_H orientation determined at N18.6^{0}E conforms with the known NNE-SSW maximum horizontal stress (Chatterjee and Mukhopadhyay, 2002). The orientations of open fractures at various depth intervals estimated from FMI log are in close agreement with the estimated S_H from the breakouts and DIF with a maximum deviation of 10^0. The estimated dynamic elastic moduli and UCS in the selected five wells would be useful in development of geo-mechanical models in this basin. The breakouts are associated with a relatively low strength rock as observed from the well KA. The gas bearing zones are characterized by low Poisson's ratio in the wells KK, KG and KE. Estimation of Vs considering the effect of clay and porosity yields precise dynamic elastic moduli and UCS. This model would be useful in other wells of the basin maintaining mud weight, well casing deign, hydro-fracturing and stimulation (Rickman et al., 2008). The models may be further refined with velocity information from offshore wells and incorporating confining pressure and pore pressure corrections.

ACKNOWLEDGEMENTS

Authors are very thankful to ONGC, Dehradun for providing us the well log and geologic information. Authors also acknowledge the financial support from the Department of Science and Technology (DST-INSPIRE) and Ministry of Earth Science through the R&D project MoES /P.O./(Seismo)/1(138) 2011 dated 9.11.12.Authors thank Dr.Suman Paul and Dr.J.R.Kayal for objective evaluation and useful suggestions. Thanks are also due to Dr.M.R.K.Prabhakara Rao and Chief Editor for final refinement and apt editing.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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Received on: 14.09.2017; Revised on: 6.10.2017; Re revised on: 30.10.2017; Accepted on: 13.11.2017