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Synergetic Approach for Geomechanical Modelling Integrated with Rock-Physics, Image Log Data & Pre-Stack Inversion in Tertiary Sequence Sediments in Western Offshore Basin, India - A Case Study

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Abstract

Understanding of stress state (both magnitude & direction) plays critical role in every aspect of a hydrocarbon field development starting from early exploration to field abandonment. Vertical and lateral distribution of pore pressure and in-situ principal stresses are preliminary input parameters for Geomechanical modelling which provides in-depth insights into variation of local stress field contributing to well stability, proper drilling fluid and casing design. Recently ONGC has made hydrocarbon discoveries in Kutch-Saurashtra offshore basin which leads to increase in exploration and production activities and need for robust Geomechanical model to drill up-coming wells without NPT (non-productive time).

The present paper has brought out 1-D Geomechanical model comprising of pore pressure, elastic properties (Poisson's ratio, Young modulus), strength parameters (unconfined compressive strength, tensile strength, friction angle) and magnitudes and direction of in situ stress in the nine key wells based upon comprehensive petro-physical evaluation, rock physics modelling and understanding of resistivity image log, interpretation of fast/slow shear sonic waveform and pre-stack inversion of seismic data of tertiary sediments of Kutch-Saurashtra area.The computed values of overburden gradient (OBG) have been found in the range of 7-19 ppg. The estimated pore pressure has been observed hydrostatic though out depth in different formations and has good match with formation pressure data/MDT data. The magnitudes of principal stresses were computed using poro-elastic model. The values of minimum principal stress (Shmin) have been observed 12-14 ppg and calibrated with leak off test (LOT)/XLOT data. The maximum principal stress (Shmax) has been validated with stress polygon method. The derived elastic properties are also validated through laboratory measured values on the core samples. The direction of Shmin have been estimated through understanding of borehole failure i.e. breakouts identified from oval shape of borehole diameter in calipers log C1 and C2 in formation micro imager (FMI) and values are 95-115 degree in the four studied wells. The estimated values of fast shear azimuth (FSA) indicative of maximum stress direction from sonic scanner tool are 5-25 degree are perpendicular to the breakout direction and validating each other. The same stress direction has also been found in world stress map of Kutch-Saurashtra area corroborates the present study. The 1D MEM results also validated with drilling events and borehole failure. The 1D MEM outputs have been successfully used for calibration of 3D pore pressure, stresses, elastic properties and strength parameters at well locations in 3D seismic driven Geomechanical modelling in the study area. The present study will also ensure safe and cost effective drilling during upcoming development phase of the Kutch offshore area.

1. Introduction

Kutch offshore basin forms northern most part of western offshore basin of India and is located in a divergent margin setup. Hydrocarbons have been established from multiple pay horizons from Miocene to Jurassic age (Sandstone, siltstone and limestone). The study area has been presented in Fig-1. The studied boreholes are at depths ranging from 1500 m to 2000 m and drilled through tertiary sediments. In the present study, an attempt was made to build a robust 1D MEM (Mechanical Earth Model) and application of it in 3-D seismic driven Geomechanical modelling of tertiary sediments of Kutch-Saurashtra area. 1-D MEM comprises of pore pressure, over-burden gradient, elastic properties, rock strength parameter and magnitude and direction of stress has been carried out for Kandla, Chhasra, Godhra, Narayan Sarovar, Tuna, Fulra, Jakhau and Nakhtrana formations of tertiary age in the nine key wells viz. well-A, B, C, D, E, F, H, I & J in the area of GK-28/42 area.

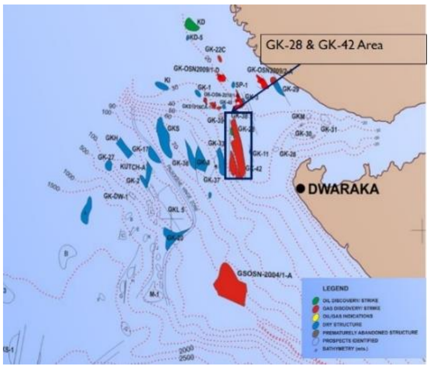

Fig-1 Location map of study area

The quality of shear wave velocity is very important in 1D MEM study and good quality shear log have been predicted through rock physics modelling (RPM) in those wells where it was not recorded or affected by bad borehole or rugosity. The interpretation of high-tech logs FMI and sonic scanner log were also integrated in the study. The static/dynamic resistivity image from processing of formation micro imager (FMI) and fast/slow shear waveform generated through processing of sonic scanner data has been analysed and interpreted for estimation of stress direction. The results of 1-D MEM has been validated with used mud weight, MDT, LOT and drilling events. The used mud weight in these studied wells has been found in the range of 8-11 ppg.

2. Data audit, preparation and conditioning of log data for MEM

Good quality of log data is essentially required to build robust 1-D MEM. The log data of the 9 key wells were depth matched, spliced and conditioned. In few of wells, where density or other log data affected due to bad bore hole condition and has been replaced by synthetic logs generated through multi-regression/MRGC technique. Basic log data likewise gamma ray (GR), bulk density (RHOB), neutron porosity (NPHI), sonic and resistivity logs have been used for petrophysical evaluation. The density and compressional / shear sonic logs (DT/DTS) have been not recorded in shallow sections from sea bottom. The RHOB & DT logs have been estimated in shallow sections based on multi linear regression generated in formations viz. Kandla, Chhasra and Godhra. Relation between compressional & shear sonic log has been established from RPM and predicted shear log up to sea bottom. These data of RHOB, DT & DTS up to sea bottom is the pre requisite for carrying out pre stack inversion in the present study.

3. Petrophysics & Rock physics modelling

The log data processing have been carried out in the different formations viz for Kandla, Chhasra, Godhra, Narayan Sarovar, Tuna, Fulra, Jakhau and Nakhtrana of tertiary age in the key wells. The comprehensive multi-mineral model consisting of quart, clay, calcite, coal has been developed for the estimation of petrophysical outputs like effective & total porosity, water saturation, clay volume & mineralogical volumes. The processed output porosity has been used as input for pore pressure prediction. The processed petrophysical outputs have been used as inputs in RPM study to predict elastic logs Vp, Vs and density which is required in MEM. RPM helped for prediction of shear wave velocity in the well: C where recorded shear was not available.

4. Methodology and work flow for 1-D MEM

The methodology and workflow adopted in the current study to build 1-D MEM model is shown in Fig-2.

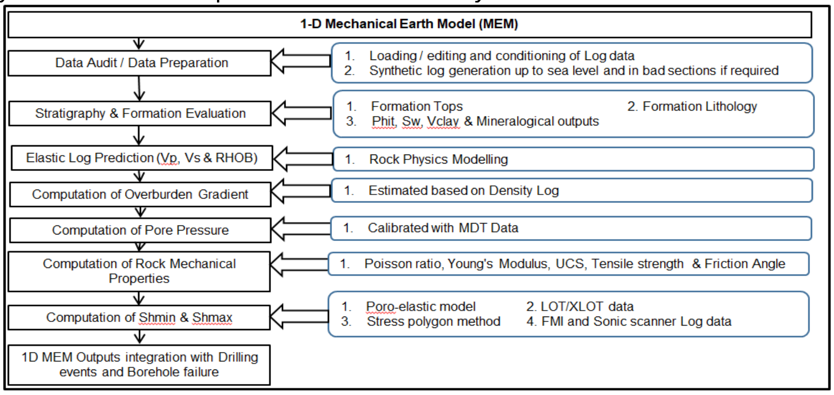

Fig-2 Workflow to build 1D MEM

5. 1-D Mechanical Earth Modelling (MEM)

1-D MEM have been carried out in the 9 key wells for computation of OBG, pore pressure, elastic properties and strength parameters and magnitude and direction of in situ stress.

5.1Overburden/Vertical stress (Sv)

Overburden stress was calculated through integrating the bulk density along true vertical depth (TVD), using following equation (1).

$$Sv = \int_0^z \rho g dz \qquad (1)$$

Where, Sv=vertical/overburden stress (Pa)

ρ=Formation bulk density (kg/m3), g=gravitational acceleration (m/s2) and z=depth (m)

The computed values of OBG are found in the range of 7-19 ppg in the studied wells.

5.2 Pore Pressure Prediction

In the present study, a porosity based approach (Zhang, 2011) has been adopted to predict pore pressure using eq(2). Two compaction trends has been used one from water bottom to Jakhau top and other Jakhau top to well bottom. It has been observed that predicted pore pressure values has excellent match with the MDT measured pressure in the entire drilled section. Porosity has been computed through a comprehensive petro-physical evaluation using multi-mineral probabilistic model.

$Ppg = OBG - (OBG - P)*(\ln\Phi_0 - \ln\Phi)/cZ$ (2)

Where, $\boldsymbol{\Phi}_n$ is porosity in the normally compacted formation at depth Z; $\boldsymbol{\Phi}_0$ is the porosity in the mud line (sea bed); Z is the true vertical depth below the mud line; c is the compaction constant in 1/m or 1/ft, P is hydrostatic pressure and OBG is overburden gradient

5.3 Observations on 1D MEM in the key wells

1-D MEM was carried out in the key wells. Results of MEM studies in the key wells was discussed here.

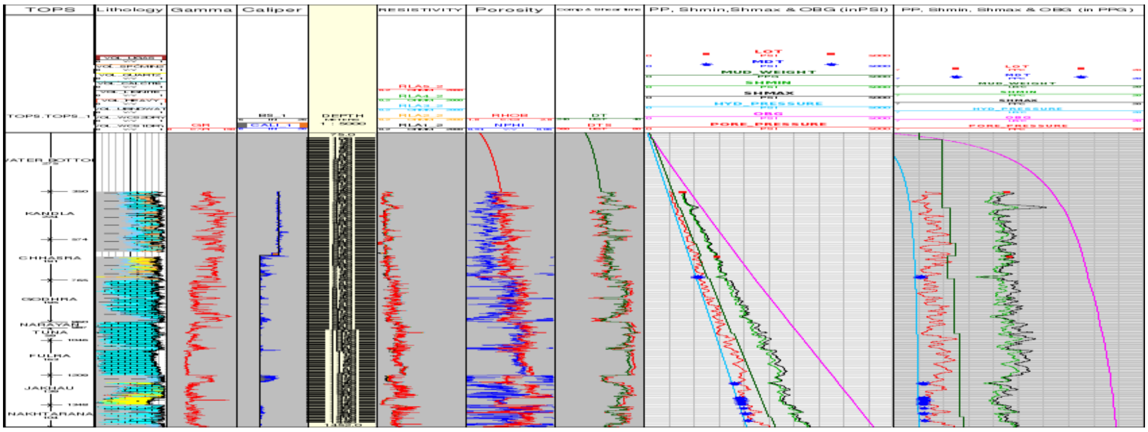

Fig-3 Well-A; Basic conditioned logs, interpreted lithology and 1-D MEM Outputs (Overburden gradient, Pore Pressure & Stresses calibrated with formation pressure data & Leak off test)

(1) Well: A

The basic logs (caliper, gamma ray, resistivity, bulk density, neutron & compressional, shear sonic log) and processed lithology along with estimated pore pressure, overburden gradient, Shmin & Shmax, used drilling mud weight, MDT pressure data and leak of test data of well: A is shown in Fig-3. The estimated pore pressure and stresses has been displayed in psi unit in track-9 and in gradient form in track-10 in ppg unit. The borehole condition is good in this well except caving has seen a few places. Pore pressure is found in the range of 8 to 10 ppg. Estimated pore pressure has very good match with MDT data in the formation of Chasra, Jakhau, Nakhtarana and are shown in track-9 & 10. The computed Shmin is found in the range of 12 to 13.5 ppg and calibrated with LOT data at two places. The computed Shmax is found in the range of 12 to 14 ppg.

(2) Well: B

Pore pressure, over burden gradient, Shmin & Shmax along with open hole log data, MDT, LOT data and mud weight used for well: B have been presented in Fig.-4. It is observed that pore pressure is increase from surface to Fulra in the range 8 to 10 ppg then it decrease and found 8-9 ppg in Jakhau and Nakhtarana. The pore pressure predicted has excellent match with MDT data. In chasra formation, break out has been observed at some places which is also reflecting in pore pressure that is slightly more than or equal to used mud weight. The increasing trend in Shmin has been observed from 12 to 14 ppg from surface to Tuna formation and then values are 12 to 13 ppg in Jakhau and Nakhtarana. The estimated Shmin is calibrated with LOT data. The values of Shmax have been found in the range of 12 to 15 ppg.

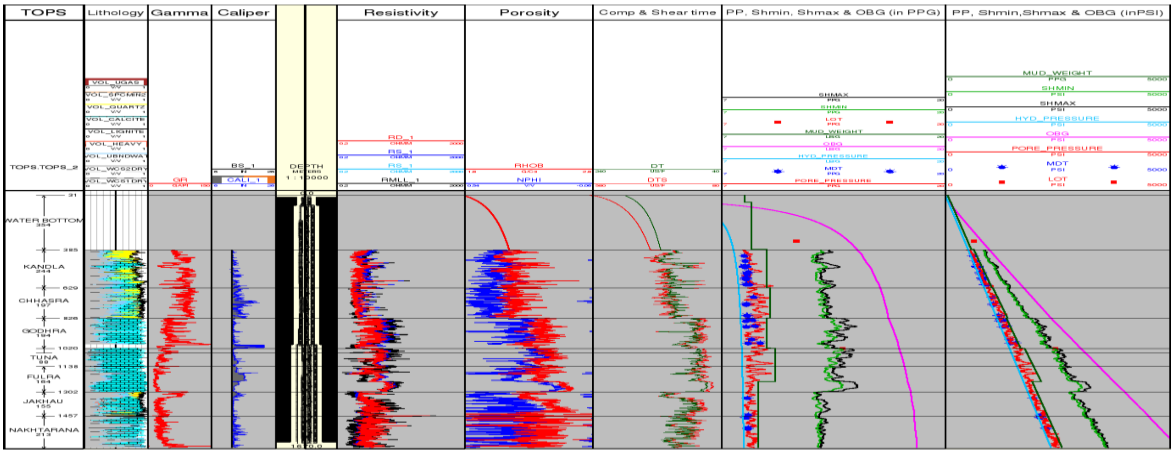

Fig-4 Well-B; Basic conditioned logs, interpreted lithology and 1-D MEM Outputs (Overburden gradient, Pore Pressure & Stresses calibrated with formation pressure data & Leak off test)

5.4 Elastic properties & rock strength parameters

Rock elastic properties were computed using modelled bulk density, compressional and Shear slowness data estimated from rock physics modelling. Young's modulus (E) and Poisson ratio using the following equation(3) and (4)

$$E = \frac{\rho V_p^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} \qquad (3)$$

$$\textit{Poisson Ratio}(\sigma) = \left[\frac{0.5\left(\frac{V_p}{V_s}\right)^2 - 1}{\left(\frac{V_p}{V_s}\right)^2 - 1}\right] \qquad (4)$$

In absence of core studies, two empirical correlations, one by Onyia(1988) for carbonate and Lal(1999) for shale/clastics.

UCS estimated from equation (5) given by Onyia (1988); and equation (6) given by Lal (1999) ;

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UCS = (1 / (8.07E-6 * (DT - 23.87)^2)) + 0.014
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(5)

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UCS  =  10*(304.8/DT  -  1)
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(6)

and angle of friction from following equation (7);

Angle of Friction= $\sin^{-1}$[(Vp-1000)/(Vp+1000)]

The estimation of elastic properties and rock strength parameters for all the 9 key wells was carried out in the study. For example well-A have been presented in Fig-5. The values of Vp/Vs (track-5), UCS(track-6), Poisson ratio(track-7), YMOD(track-8) & coefficient of internal friction (track-9) are 1.6-3.0, 1000-16000 psi, 0.24-0.42, 0.55-8.3 MPsi, and 0.22-0.95 respectively (Fig-5). The dynamic values of these properties have been calibrated with core measured values.

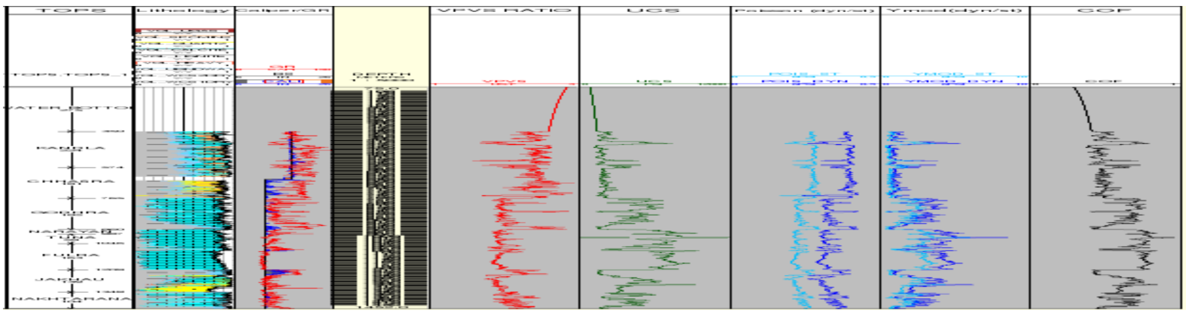

Fig-5 Well-A; Elastic properties (Vp/Vs, UCS, YMOD (Static/Dynamic), Poisson ratio (Static/Dynamic) & coefficient of internal friction)

5.5 Laboratory studies on core samples

Nineteen no's of the core samples (Fig-6) have been studied and computed bulk density, compressional velocity(Vp) and shear velocity (Vs) and have been tabulated in table-1.It is observed that log values of these elastic properties are matching with core derived values.

Sl No.	Well Name	Sample No	Depth (M)	Bulk Density		Vp(m/s)		Vs(m/s)	
				Lab	Log	Lab	Log	Lab	Log
1	Well-A	1	746.5	2.41	2.45	3037	3172	1516	1586
2		2	745.75	2.21	2.37	2547	2681	1552	1183
3		7	1240	2.28	2.21	2718	2349	1622	1048
4		8	1246.8	2.15	2.13	2199	2714	1210	1528
5		8A	1246.9	2.1	2.14	3903	2725	2163	1529
6		9	1247.2	2.17	2.163	2107	2781	1142	1541
7	Well-H	10	1177.5	2.91	2.22	2485	2256	1148	847
8		12	1294.5	2.1	2.59	2918	4140	1592	2003
9		13	1295.5	2.41	2.45	4802	4196	2264	2030
10	Well-L	20	854.5	2.12	2.47	2425	3561	1470	1815
11		21	851.5	2.15	2.36	2709	3392	1587	1637
12	Well-M	26	744.2	2.66	2.42	2644	3811	1598	1889
13	Well-F	14	1334	2.13	2.37	1958	2867	1215	1220
14	Well-G	15	1217.5	2.17	2.4	3293	3690	1735	1932
15		16	1219.5	2.31	2.45	2899	3931	1434	2090
16		17	1220	2.5	2.44	4702	3780	2385	2055
17		18	1222	2.56	2.48	4063	3274	2267	1753
18	Well-I	19	1174.25	2.38	2.25	2469	3083	1481	1413
19	Well-K	28	658.97	2.45	2.46	4469	3752	2532	1917

Table-1 Comparison of Laboratory measured and log derived elastic properties

Fig-6 Studied Core plugs samples for acoustics laboratory measurements

5.6 Estimation of magnitude of Stresses

The magnitudes of minimum horizontal stress and maximum horizontal stress have been computed using poro-elastic model (eq-8). The estimated Shmin have been validated with LOT/XLOT data in the key wells and are presented along with Shmax in last track of in Fig-3 & Fig-4.

$$SHmax = \frac{POIS \times (PRESS_{OB} - BIOT \times PRESS_{FM})}{1 - POIS} + BIOT \times PRESS_{FM} + \frac{YMOD \times STRAIN_{MAX}}{1 - POIS^2} + \frac{POIS \times YMOD \times STRAIN_{MIN}}{1 - POIS^2} \tag{8}$$

$$Shmin = \frac{POIS \times (PRESS_{OB} - BIOT \times PRESS_{FM})}{1 - POIS} + BIOT \times PRESS_{FM} + \frac{YMOD \times STRAIN_{MIN}}{1 - POIS^2} + \frac{POIS \times YMOD \times STRAIN_{MAX}}{1 - POIS^2}$$

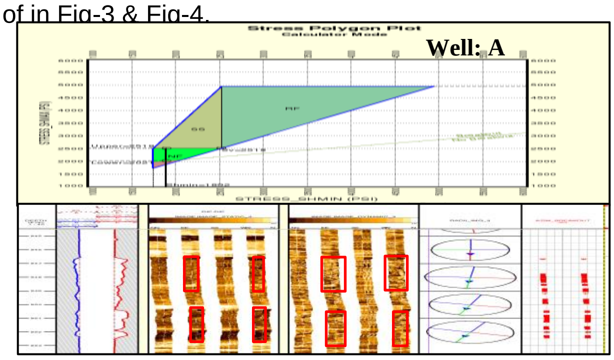

Fig-7 Well-A, Estimation of Shmax from stress polygon method (depths: 847.5m & 851m) integration with FMI

The static and dynamic resistivity images have been generated from processing of FMI data. The breakouts have been identified from oval shape of borehole from callipers log C1 and C2 as well as on resistivity image in FMI log. The magnitude of Shmax has been computed from stress polygon method in the wells A & E and used these values for validating the Shmax estimated in poro-elastic model (Fig-7 & 8)

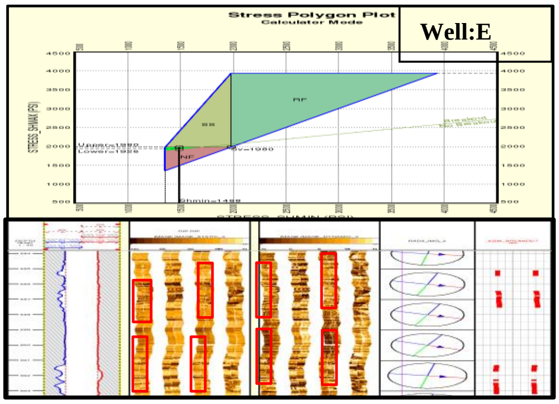

Fig-8 Well-E, Estimation of Shmax from stress polygon method (depths 686.7m and 692m) integration with FMI log

Well Name	Depth Interval	Shmin direction	Shmax direction	Av. Shmin direction	Av. Shmax direction
Well-E	685.5-687.2	105	15	100-115	10-25
	688.7-691	105	15		
	845.5-847.2	108	18		
	804-804.5	100	10		
	724.2-727	95	5		
	703.6-706.5	110	20		
	688.8-690.5	110	20		
Well-A	700.5-701.7	105	15	100-110	10-20
	691.4-693.5	105	15		
Well-G	566.5-568.2	100-105	10-15	95-105	5-15
	532-534	85 95	5		
	875.5-878.5	100-110	10-20		
	585-588.5	105	15		
	666-669	95	5		
	1301-1302	105	15		
	1406-1409	95	5		
	860.5-861	106	16		
	1260-1380	95	5		
	520-631	105	15		
Well-F	693-695	96- 102	6-12	95-105	5-15
	547-549.5	101	11		
	1338-1341	95	5		

Table-2 Summary of Stress direction from breakout analysis using FMI log

5.7 Estimation of direction of principal stresses:

A. Breakout analysis from FMI log

The direction of horizontal stress can be estimated from an image log by looking at the orientations of drilling breakouts or drilling induced fractures. FMI logs were processed in the wells A, E, F and G and breakouts have been identified by oval borehole shape in calipers (C1 and C2) in track-2 Figs-7 & 8 in static/dynamic image. The breakout direction is the direction of minimum stress and found the values are 95-115 degree in these four wells (Table-2).

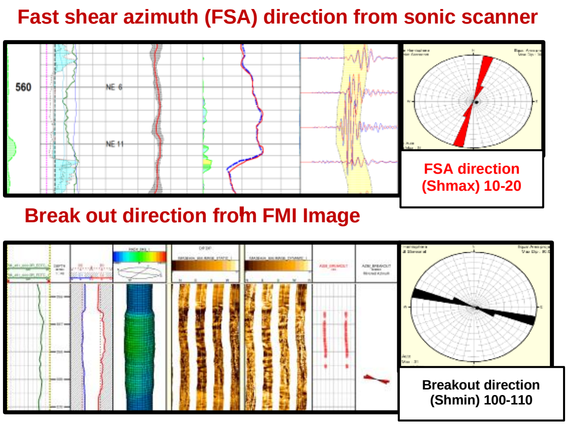

Fig-9 Well-G, Estimation of stress direction from FMI and Sonic scanner data

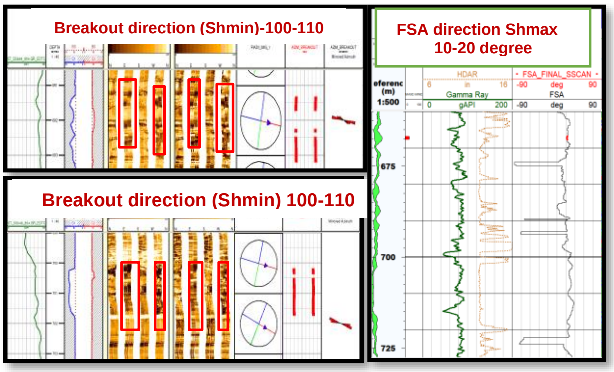

Fig-10 Well-A Estimation of stress direction from FMI and Sonic scanner data

B. Discussion of Fast shear azimuth (FSA) from Sonic data

Sonic scanner data were processed to generate fast and slow shear waveform and estimated fast shear azimuth in the wells A & G. FSA direction is 10-20 degree indicative of maximum stress direction which is perpendicular to breakouts direction 100-110 degree in well: A (Fig-10). In another well-G, FSA is 10-20 degree and perpendicular to direction of breakouts 100-110 degree (Fig-9). Hence, estimated stress direction from both methods validates each other and same direction has also been found in world stress map of Kutch-Saurashtra area.

6. Use of 1D MEM in 3D Geomechanical Modelling

Pre-stack inversion was carried out for P-Impedance, S-Impedance & density volumes in 3-D space. The density volume generated through pre-stack inversion shows a very good correlation with density logs at well locations as shown in seismic section. This density volume has further been used for estimation of overburden pressure in 3-D space (Fig.-11). Similarly other 1D MEM outputs were also used for the calibration of 3D Geomechanical model results at well locations in the study area.

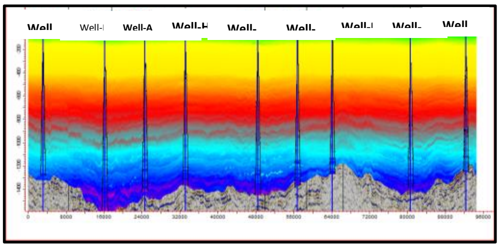

Fig.11- Section of 3-D density volume from pre-stack inversion calibrated with conditioned density at wells

7. Conclusions

- The present study has brought out an integrated methodology and work flow for building 1D MEM model based upon comprehensive petro-physical evaluation, rock physics modelling, interpretation of resistivity image log, fast/slow shear sonic waveform and pre-stack inversion of seismic data for prediction of pore pressure, elastic properties and strength parameters and in situ stress magnitude and direction in the nine key wells of GK-28/42 area. The methodology may be applied in nearby area to build 1D MEM model.

- The estimated pore pressure has been found hydrostatic though out depth in different formations and has good match with formation pressure data. The magnitude of stress was computed using poro-elastic model. The values of estimated Shmin are 12-14 ppg and calibrated with LOT/XLOT data. The Shmax was also validated using stress polygon method.

- The stress direction has been estimated through advance interpretation of sonic scanner log & FMI image. The estimated values of fast shear azimuth (FSA) indicative of maximum stress direction from sonic scanner tool are 5-25 degree are perpendicular to the breakout direction 95-115 degree (minimum stress direction) validating each other. The same direction has also been observed in world stress map of Kutch-Saurashtra area.

- The 1D MEM outputs have been successfully used for calibration of 3D pore pressure, stresses, elastic properties and strength parameters at well locations in 3D seismic driven Geomechanical modelling in the study area. The present study will be helpful for safe drilling and reduction in non-productive time during up-coming field development of GK-28/42 area in Kutch offshore.

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NB. The views expressed in this paper are solely of the authors and do not necessarily reflect the view of ONGC.

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