"Multiscale Determination of Stress Rotation in Baramura Field, Tripura Fold Thrust Belt, Assam and Assam Arakan Basin: Implications for Hydrocarbon Exploration"

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Keywords:

Stress orientation, Stress rotations, Borehole breakouts, 1D MEM, Tectonic stress regimes

Abstract

Understanding the complete in-situ stress state of a petroleum province is becoming increasingly important in petroleum exploration. This acquaintance can be used to reduce the risk in exploration and to improve hydrocarbon production from the operating fields. A broad knowledge of the stress field has critical implications in drilling and completion of well, borehole stability, production field development, etc. The 1D MEM (Mechanical Earth Model) study aids to understand the attributes of subsurface pore pressure and the profile of Earth's principal stresses. Maximum horizontal stress (S_{Hmax}) orientation is usually parallel to the plate movement direction, where tectonic plate force is the dominant contributing factor to the stress field. However, stress perturbation can occur in the transitional tectonic zones.

Among the many natural gas fields in Indian basin, Tripura Fold Thrust Belt, located in the North-East part of India presents significant well drilling and completion engineering challenges for natural gas exploration due to its complex geological history. Major challenges viz. abnormal super-high pressured formation, borehole instability, mud losses, stuck pipe/casing, fishing, shallow gas seepages, etc. are omnipresent across all the structures of Tripura Fold Belt.

In this work, a contemporary stress field of the entire Baramura structure field has been evaluated using the all the relevant dataset from drilled wells. Detailed 1D MEM geomechanical studies were carried for 09 wells across the Baramura structure. Further, stress rotations in the Baramura anticline has been studied with 03 wells by utilizing the acoustic image logs, density image logs and borehole image logs in recently drilled three wells A, B and C. Subsurface stress distribution shows that the present-day stress field in the Baramura structure is normal stress regime in shallower level and changes to strike-slip faulting to reverse faulting stress regime at deeper level.

A cumulative data of borehole breakouts from the recorded logs indicates regional NE-SW / ENE-WSW S_{Hmax} orientation which is parallel to the Indo-Burmese plate convergence direction and represents regional Thrust faults. The S_{Hmax} orientation shows a complete anticlockwise rotation in a well from NE-SW to NW-SE orientation at the associated cross faults. The analysis shows that the Maximum Horizontal Stress (S_{Hmax}) orientation around the faults and natural fractures observed rotated due to geometrics of cross faults.

Introduction

The Baramura anticline, located in the Western Tripura is the second largest structure for the accumulation of hydrocarbons (Fig. 1). The anticline is a doubly plunging asymmetric anticline, trending NNW-SSE with slight convexity to the west. It is appox. 95 km long and 13 km wide. The aerial closure of the structure is around 400 Sq.km. The eastern limb is steep and is affected by a reverse fault which runs almost parallel to the axis of the anticline, while the western limb is comparatively gentler and wider in the central culmination. The structure is affected by number of cross faults. The two sets of NNE-SSW trending cross faults broadly divides the Baramura structure into the Northern Culmination, Central Baramura Bulge and Southern Culmination. Bokabil Formation is exposed at the crestal part of the anticline whereas, Tipam Formation is exposed on the limbs, northern and southern plunge areas (Mitra et al., 1967).

Till date, 37 wells have been drilled in this field. Out of these wells, the studied Well-A was drilled upto 3873m in deeper part of Middle Bhuban formation. Multiple borehole instability issues along with super-high pressured compartment in Middle Bhuban were encountered while drilling the well. Well-B was drilled at the crestal part of Baramura structure with TD 3020m in Middle Bhuban formation. Severe tight pulls, held-ups were observed while drilling the well. Recently drilled Well-C on the western limb of the Baramura anticline reached upto a TD 4529m, a deepest well drilled so far in Baramura field upto the top of Lower Bhuban formation. This well encountered wellbore instability along with severe mud loss complications. This abnormal behavior of mud loss in Well-C without charged formation urged to carry out the detailed geomechanical analysis in the Baramura field.

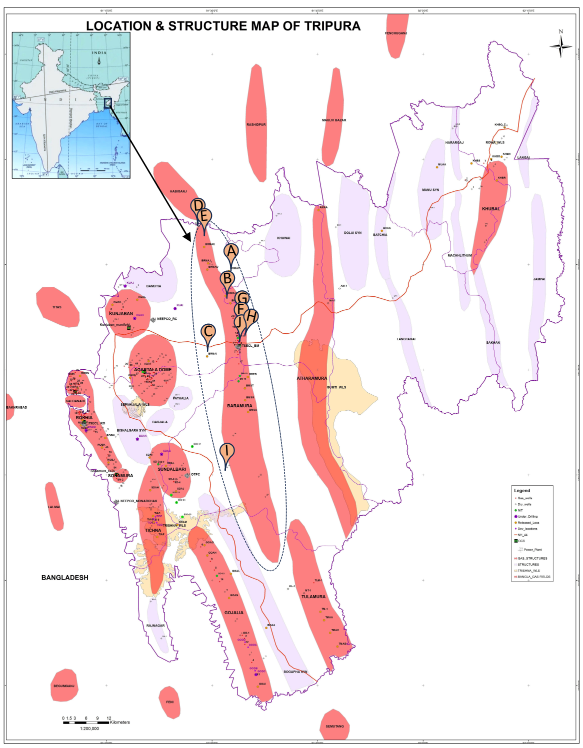

Fig. 1: Represents Location and Structure Map of Tripura. (Source: ONGC Ltd.)

Methodology Adopted, Results & Interpretations:

The study of geomechanics addresses the subsurface distribution of principal stress, its magnitude and orientation of horizontal stresses. (Zoback, 2007; Kundan et al., 2018). However, stress perturbation occurs in the transitional secondary fault zones amongst the large fault planes (Maerten et al., 2002; Morley, 2010). This work investigates 09 wells drilled to the Middle Bhuban formations with a maximum well length of 4335m TVD. The aim of the present study is to 1. Examine the stress pattern using the available well data. 2. Determine the principal stress rotations around the field. To assess this, wireline geophysical logs recorded in all the wells were utilized that include gamma ray, resistivity, porosity, density, shear and compressional sonic slowness data. Various recorded downhole measurements such as in-situ formation pressure, leak off tests (LOT) were used to validate the pore pressure gradients, fracture pressure gradients and provided the most consistent output. An extensive set of acoustic and density image logs was available, which were carefully interpreted to identify wellbore shear failures and validate the maximum principal stress element with stress rotations around the studied wells. An attempt was also made to integrate results with macro-scale interpretation from regional studies of World Stress Map (WSM 2016) in order to get the micro to macro level picture of stress state in this field (Fig. 6). The Brief methodology is discussed in the following sub-sections.

A. Principal horizontal stresses Orientation:

S_{hmin} and S_{Hmax} orientations are important elements of geomechanical modeling for inclined wellbore placement, hydrocarbon production optimization. Wellbore Breakouts (W_{BO}) are stress induced borehole failures and these are important sources for stress azimuth interpretation (Heidbach et al., 2016a, 2018). Image logs provide the best information of borehole failures, where breakouts appear as the two parallel channels (shear failure zones) 180° apart parallel to Shmin azimuth (Heidbach et al., 2016b, 2018).

This work analyzed an extensive set of acoustic and density image log data from Upper and Middle Bhuban formations. Numerous borehole breakouts are found in all the wells and thus studied into number of distinct W_{BO} zones to deduce mean S_{Hmax} stress orientation.

The studied Well-A was drilled on eastern limb of the Baramura anticline. Around 3 different zones of Breakout identified in the length of 40 – 50m intervals. The wellbore breakout shows the mean stress direction of S_{hmin} ~158°N (S_{Hmax} -68°N) respectively; which is consistent with the regional S_{Hmax} (ENE-WSW) reported in regional data. (Fig. 2 and Fig. 3)

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Well-B was drilled at the top of the Baramura anticlinal structure. Image log recorded from 1837-2389m. More than five different zones of breakouts identified in varying length of intervals (6 -16m). The wellbore breakout shows the stress direction of S_{hmin} 138°N (S_{Hmax} - 48°N) respectively. Numerous low to high angle fractures/fault zone have been identified. (Fig. 2 and Fig. 3)

Well-C was drilled in the western side synclinal structure of the Baramura anticline. A recorded LWD density image log from 2565-3087m, shows borehole breakout observed from 5 distinct zones with over a different range in length of 3-10m breakout, oriented in the range 50-70°N (S_{Hmax} ~135°N) with mean breakout azimuth ~49°N. It indicates the breakout rotations associated with faulting. (Fig. 2 and Fig. 3)

To summarize, interpreted mean S_{Hmax} azimuth for Well-A, Well-B and Well-C are interpreted as 68°N, 48°N and 135°N respectively. This study infers a regional NE-SW and NW-SE orientations for S_{Hmax} and S_{hmin} respectively. We looked into the World Stress Map (WSM) database for the published stress indicators from the nearby areas. The majority of the WSM stress data support the findings from this study. The inferred regional horizontal stress orientation supports with the plate movement direction of the Indian plate.

B. Pore pressure (PP) magnitude:

The fluid which is trapped in the pore space of rock exerts pore pressure. The most reliable PP estimates come from the direct downhole formation pressure measurements. There are indirect ways of calculating PP from resistivity / compressional sonic slowness / drilling exponent logs (Zhang et al., 2011) by employing a normal compaction trend (NCT). In this work, PP profile has been established from both the methods and validated with data recorded with direct wireline formation tester tools. An average of 0.45 psi/feet pore pressure gradient is consistent in Upper Bhuban formation. The pressure ramp starts increasing from Middle Bhuban formation with a gradient from 0.54 psi/ft to 0.84 psi/ft in all the studied wells.

C. Vertical stress (S_v) magnitude:

Vertical stress (S_v), also known as overburden stress, is the amount of pressure exerted by the overlying layers of rock column. A density log derived vertical stress modelling in the studied fields provided a confident S_v profile. At the deepest section of wells, analysis captured an average of 1.08 psi/feet S_v gradient in Baramura field.

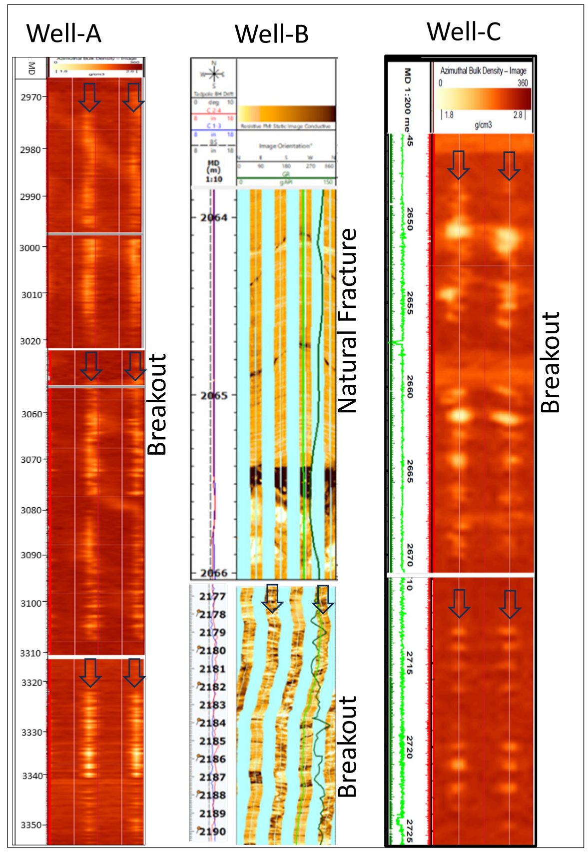

Fig. 2 represents borehole image logs (Well-A, Well-B and Well-C). Interpreted wellbore breakouts have been demarcated as black arrows, displayed as two parallel channels (shear failure zones) at 180°.

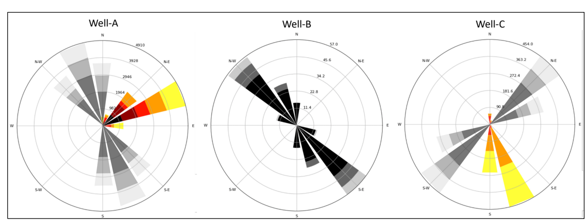

Fig. 3 represents Rose diagram of the interpreted S_{Hmax} orientations (Red Color) from Image log derived wellbore breakouts. (Well-A, B and C). Well-A =mean azimuth 68°N. Well-B = mean azimuth 48°N. Well-C = mean azimuth 135°N.

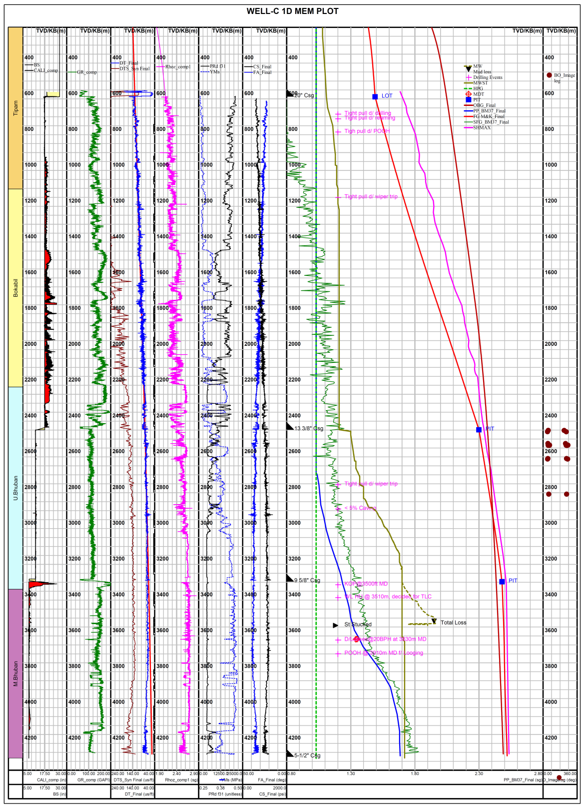

Fig. 4 represents 1D MEM model of Well-C

D. Minimum horizontal stress (S_{hmin}) magnitude:

S_{hmin} is an important parameter geomechanical modelling. It indicates the lower limit of the pressure required to fracture a formation. Leak off tests (LOT) / extended leak off test (XLOT) provide the best direct estimation of S_{hmin} (Kundan et al. 2017). The poro-elastic model is used in this work to determine the S_{hmin} magnitude throughout structure. Static elastic properties were available from core-based measurements which were used for calibration. Numerous available LOT test data fields were utilized for calibration. All the measured data distribution provided a very narrow range of 0.84-1.11 psi/feet gradient for S_{hmin}.

E. Maximum horizontal stress (S_{Hmax}) magnitude:

The most difficult parameter in geomechanical modelling is the quantification of S_{Hmax} since there are no direct measurement methods. Wellbore breakout widths from image logs are utilized to constrain the S_{Hmax} magnitude (Zoback, 2007; Lai et al., 2018). As borehole breakouts depends on the distribution of hoop stress magnitudes surrounding the wellbore, S_{Hmax} magnitude can be derived from borehole compressive failures. (Barton et al., 1988).

In this work, acoustic image logs have been investigated for breakout widths and utilized to estimate the S_{Hmax} magnitude.

F. Current stress state of the field:

1D MEM depicts the principal stress gradients. The mechanical earth modeling examples with rock properties and continuous stress profiles are presented in Fig. 4, estimated from geophysical logs after calibration with core data of the offset field. It is to note that Subsurface stress distribution clearly shows that the present-day stress field in the Baramura structure is normal faulting stress regime ($S_v > S_{Hmax} > S_{hmin}$) upto the middle part of the Upper Bhuban formation and changes to strike-slip faulting ($S_{Hmax} > S_v > S_{hmin}$) to reverse faulting stress regime ($S_{Hmax} > S_{hmin} > S_v$) at deeper level inside bottom part the Middle Bhuban formation.

Discussion:

There is no data available on stress orientations and stress rotation from literature including world stress map at Baramura field. A regional mean S_{Hmax} azimuth of 58° N±10° is thus concluded in the A&AA basin from this study. The interpreted maximum horizontal stress field orientation is parallel to the present direction of convergence of the Indo and West Burma plates (NE-SW to NNW-SSE). This suggests that the tectonic force is the principal contributor to the Baramura field. S_{Hmax} rotation observed is mainly due to presence of cross faults and due to deviation in cross fault geometries.

This work has multifaceted applications in drilling, hydrocarbon field development and well production stimulation in the Baramura field. The pore pressure and S_{hmin} magnitudes provide the drilling window for drilling in the deeper part of the Middle Bhuban formation. A roughly 15-20% rise in pore pressure is required for fault reactivation and this information will be critically useful to design optimum injection

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pressure in hydraulic fracturing job. Being in a strike-slip to reverse tectonic regime, vertical wells are prone to borehole shear failures, as can be seen in the acoustic image logs in the studied wells. A deviated or horizontal well parallel to regional S_{hmin} direction (NE-SW) will offer more formation stability and also this wellbore placement will enhance transverse hydraulic fracture network parallel to S_{Hmax} direction at deeper level of Middle Bhuban formation and below.

Fig. 5: Wells plotted on Baramura Structure geological map showing surface fault pattern.

Analysis from the three Well Image logs shows wellbore stresses from Well-A & Well-B is oriented towards 48°N-68°N (S_{Hmax}), which is consistent with the regional S_{Hmax} (NNE-SSW) reported in regional stress data, Where the Well-C shows the S_{Hmax} from Breakout direction is 135°N It's a clear indication of Stress rotation observed around the Baramura North Culmination. Two different types & directions of Faults (Thrust & Strike-Slip cross faults). From the three wellbore stresses concluded that two different of Fault sets plays role in the Baramura Field.

Here, it was attempted to integrate the interpreted Stress orientation from the three well logs data along with incorporated with ONGC's inhouse seismic interpretation compiled with the World Stress Map database (Zoback et al., 2016) and geological map of Baramura field (Fig. 5). It helps to understand the faulting pattern, stress distribution and structural deformation in and around the study area. The color coding for three stresses is clearly defined in the WSM - Red for Normal Fault Regime, Green for Strike-Slip Fault Regime and Blue for Thrust fault regime (Fig. 6)

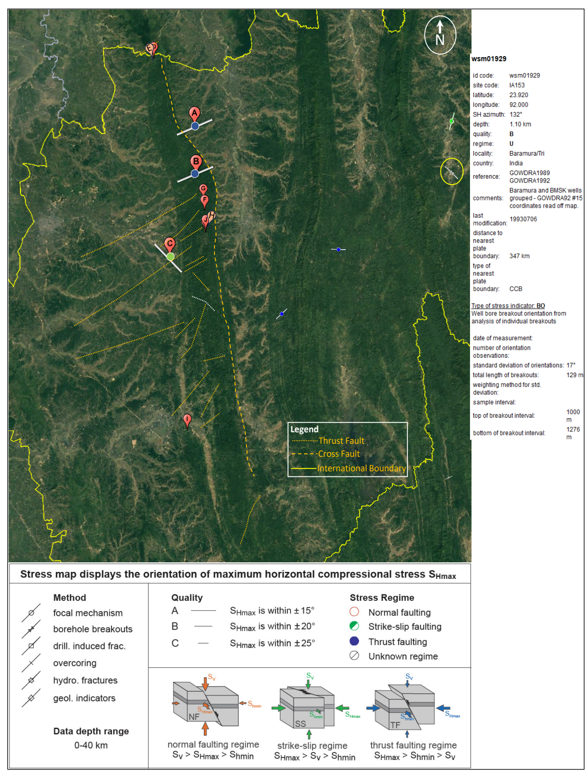

Fig. 6: Represents comparisons of wellbore stress with world stress map.

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Conclusions:

A complete geomechanical approach has been carried out to ascertain pore pressure, in-situ stress magnitudes and horizontal stress orientations in the entire Baramura structure of A&AA Basin. All the interpreted pressure gradients are calibrated and validated with direct measurements, which provides greater confidence in the outputs. A new stress orientation database is provided from the wellbore failure interpretations. These will enrich the regional stress database in the World Stress Map and will be helpful for the geoscience community working in and around this area. The present study would enable understanding in optimizing exploratory and development locations with respect to the role of fault orientation, pressure compartmentalization, complications of naturally fractured formations (ballooning and loss circulation), effective well design & its placement, fracture permeability and hydro-fracture design for production enhancement.

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Acknowledgments:

The authors express their heartfelt thanks to Ms. Shusma Rawat madam, Director (Exploration) and ONGC management for giving permission to present & publish this paper. The authors express sincere gratitude to Shri. Vishal Shastri, ED– Basin Manager, A&AA Basin for his constant encouragement and support. The authors also express their sincere thanks to Shri. D. P. Manke, Head Forward Base-Tripura for his guidance and providing facilities for the study.