3D Basement Fracture Characterization using Geomechanical and DFN analysis in Mumbai High Field

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Keywords

Critically Stressed Fractures, MEM, Basement, Discrete Fracture Network (DFN)

Summary

Exploitation of hydrocarbon pools in Basement reservoirs has always been a challenge. Capturing the lateral variation of the reservoirs in conjunction with locating the possible conduits is critical. This work uses the principles of critically stressed fractures (CSF), acoustics and geology to a prepare a pseudo 3D sweet-spot map for basement reservoirs of Mumbai High Area in Western Offshore Basin. This paper discusses the adopted integrated workflow and how it assisted in taking decisions over suitable trajectory, wellbore placement and simulation strategy for the planned wells.

Analysis begins at 1D scale, where geophysical logs, drilling parameters and geological information is integrated to construct a Mechanical Earth Model (Plumb et.al, 2000) at 16 well locations across the area. Mechanical Earth Models (MEMs) are then calibrated with available rock mechanics core test results, leak-off pressure (LOT) and formation pressure measurements. These 1D-MEMs are corroborated by doing history match of predicted failures with caliper log and drilling events. Further validation is supported by the results of integrated fracture evaluation in drilled wells, where Critically Stressed Fractures predicted intervals match with the production logging and testing results. A 3D MEM is constructed incorporating structural model, seismic velocity and 1D MEM outputs. Elastic and strength properties are populated using co-kriging technique whereas, stresses are initialized using finite element analysis. Estimated 3D stress field is then decomposed over fracture planes of Discrete Fracture Network (DFN) model to identify critically stressed fractures using a slip criterion. It involves estimation of parameters (slip tolerance and critically stressed pore pressure) to understand the proneness of fracture/fault planes to shear dilation (Barton et.al 1995). 3D sweet-spot maps have been generated to evaluate the planned locations and suggest modifications to encounter potential conduits. Estimation of critical pore pressure change has enabled to take decisions on suitable stimulation technique.

An attempt has been made to perform lateral mapping of potential hydrocarbon pools based on advance petrophysical logs and production history of the field.

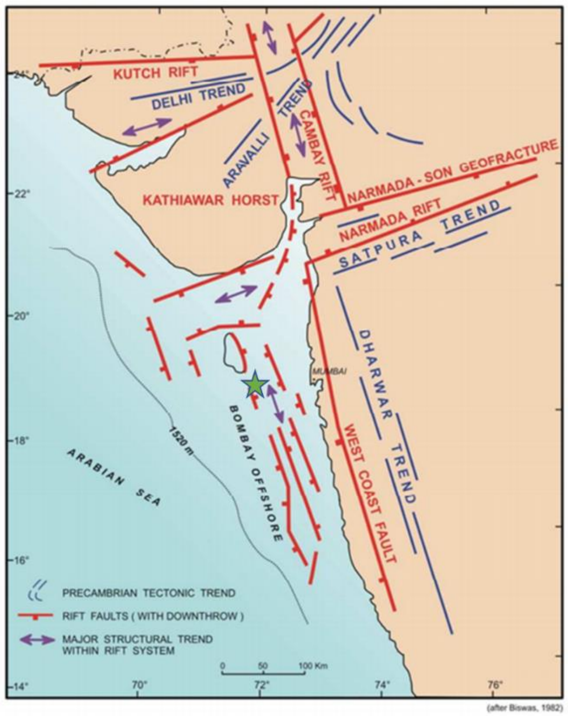
Robust geomechanical model establishes elastic and strength properties of the basement. Youngs modulus and Poisson’s ratio lies in the range of 11.6 Mpsi-8.1Mpsi and 0.18-0.21 respectively. As expected, rock is strong with uniaxial compressive strength (UCS) above 15kpsi to a maximum of 30kpsi. Reservoir pressure is hydrostatic with gradient range between 0.45psi/ft to 0.49psi/ft. Initialized stresses captures the variation of stresses due to lithology and structural changes in the study area. It is found that stress regime varies from normal to strike-slip regime. Fast shear azimuth and near-wellbore failure analysis based on wellbore image logs establish the regional orientation of maximum horizontal stress as NNE-SSW to NE-SW.

Analysis resulted in preparation of pseudo 3D sweet-spot maps governed by slip tolerance parameter indicating openness of fractures. It suggests that, most of the high dipping fractures located in the proximity of intersection of faults are critically stressed. Fractures aligned to current day maximum horizontal stress within 20deg-30deg deviation have higher slip tolerance. However, few are also at 90deg to maximum horizontal stress azimuth depending on dip. Critical stressed fractures are present at varying depth: 50m to 250m from Basement top in the field as seen in Offset wells.

The discussed multidisciplinary approach of fracture analysis has also been successfully used to predict and validated the contributing intervals in near-by fields

Introduction

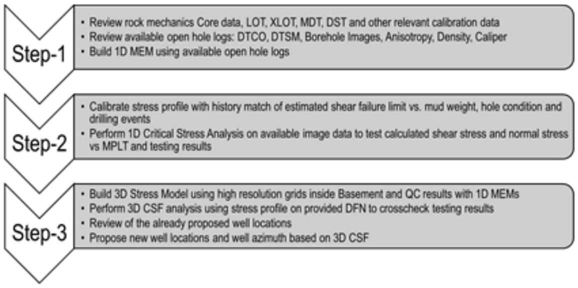
In the quest to explore the potential hydrocarbon reserves in Basements of Mumbai High South Area, multiple wells are required to be drilled in the study area as seen in **Figure 1**.



(after Biswas, 1982)

Figure 1: Western offshore Tectonics with study area

To optimize locations, well trajectory and stimulation design for better cost-effective production in basement, an integrated approach involving 3D Critically stressed fracture evaluation has been performed using constructed 1D Mechanical Earth Models (MEMs) of offset wells, static model of the area, DFN model and seismic data. Fracture sets which are critically stressed in provided DFN model has been identified at different well locations. Slip tolerance and critical pore pressure change have been evaluated which indicates proximity of the fractures to failure line and to provide details about expected stimulation design. Key steps involved in the workflow are summarized in **Figure 2.**


Step-1
- Review rock mechanics Core data, LOT, XLOT, MDT, DST and other relevant calibration data
- Review available open hole logs: DTCO, DTSM, Borehole Images, Anisotropy, Density, Caliper
- Build 1D MEM using available open hole logs

Step-2
- Calibrate stress profile with history match of estimated shear failure limit vs. mud weight, hole condition and drilling events
- Perform 1D Critical Stress Analysis on available image data to test calculated shear stress and normal stress vs MPLT and testing results

Step-3
- Build 3D Stress Model using high resolution grids inside Basement and QC results with 1D MEMs
- Perform 3D CSF analysis using stress profile on provided DFN to crosscheck testing results
- Review of the already proposed well locations
- Propose new well locations and well azimuth based on 3D CSF

Figure 2: Key steps involved in the study

Understanding the stress state acting on faults and fractures is required to characterize their mechanical behavior during field development which may also impact their hydraulic behavior. A pre-existing discontinuity, i.e. fault or fracture, will re-activate when the shear strength on the fault/fracture plane is exceeded i.e. slippage occurs along the discontinuity. The discontinuity is then referred to as unstable. If the shear strength on the discontinuity plane is not exceeded, the discontinuity is referred to as stable under the current stress state.

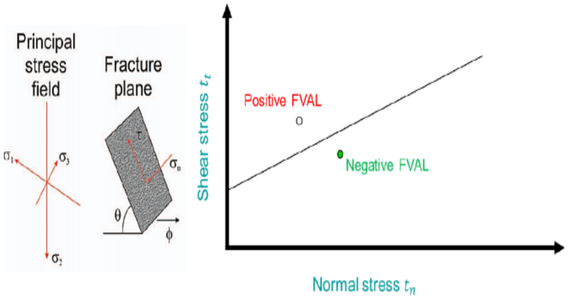


Figure 3: Evaluation of stresses acting on fractures

- Evaluate if the stresses acting on a fracture lie above or below the failure line
$$FVAL = \tau - (c_0 + \tan\phi\,\sigma_n)$$
- Positive FVAL value means fractures are critically stressed (un-stable) and negative FVAL implies fractures are not critically stressed (stable) as seen in **Figure 3**

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- Features experiencing high shear stress to normal stress ratios are expected to be more conductive. Moreover, high shear stress to normal stress scenarios are likely to be more prevalent in regions experiencing stress relaxation due to structural uplift or removal of the overburden

1D Critically Stressed Fracture Evaluation

Available open hole logs including sonic, density, caliper, borehole images, anisotropy analysis, extended leak-off pressure (XLOT), leak-off pressure (LOT) and formation pressure measurements (MDT, DST, RFT) have been used to estimate rock mechanical properties and stress profile for different formations across field. Fast Shear azimuth (**Figure 4**) from acoustic measurement and drilling induced features observed on image logs (**Figure 5**) have been used to estimate the direction of horizontal stresses. Based on fast shear azimuth and DIFs, maximum horizontal stress azimuth is to vary between NNE-SSW/NE-SW direction.

Drilling events related to formation damage have been reviewed and history matched with the predictions of geomechanical model incorporating mud weight used while drilling. **Figure 6** shows an example from the field.

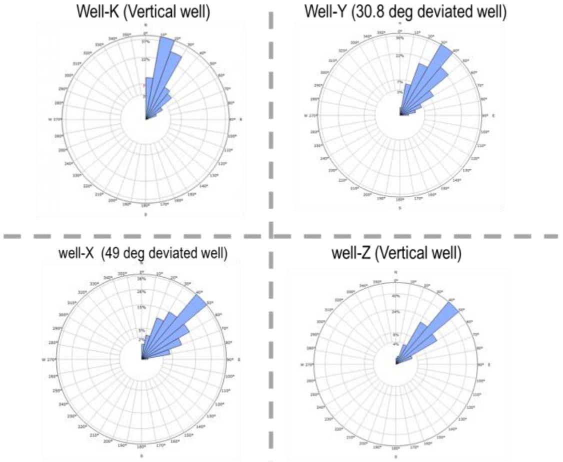

Figure 4: Stress Orientation Based on processed Fast Shear Azimuth data available in offset wells

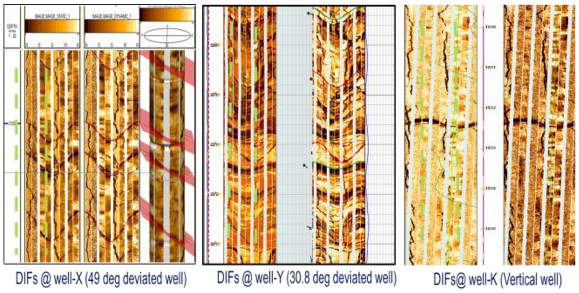

Figure 5: Stress Orientation Based on drilling induced fractures (DIFs) observed on image logs in offset wells

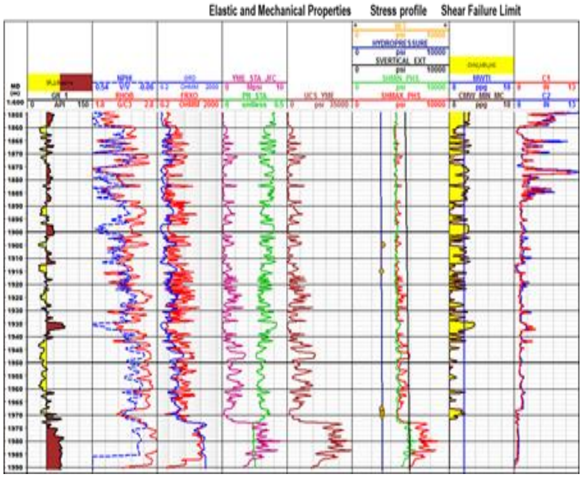

Figure 6: Mechanical Earth Model and Borehole Failure Analysis for an offset well

Critical stressed fracture analysis using 1D MEM outputs and dips dataset has been performed at well scale to history match production logging and testing results. Two examples from 1D-CSF analysis have been discussed in the section below.

Example-Well X

Stability of image based interpreted fractures were analyzed using Mohr Coulomb failure criterion assuming no cohesion and 10deg friction angle. Fractures in the interval ~2080m to 2100m and ~2125m to 2155m showed presence of critically stressed fractures. Temperature data suggested possible minor entries in these intervals, establishing good history between the 1D analysis and production logging results. Results of the analysis is shown in **Figure 7**.

Example-Well Y

Similar workflow was followed in other wells, which validated the 1D models and build high confidence in the parameters used. **Figure 8** shows results of 1D-CSF analysis and temperature logs for well-Y. Deflection in temperature curve indicated fluid entry in the zone corresponding to critically stressed fractures.

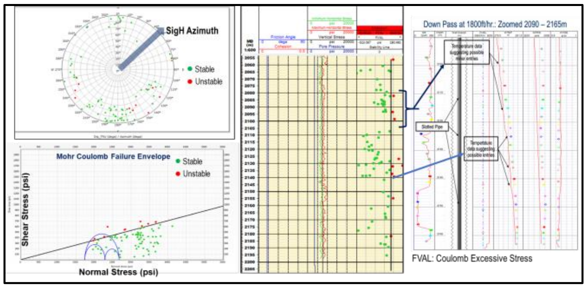

Figure 7: History match between estimated critical stressed fractures with testing results and production logging in well-X

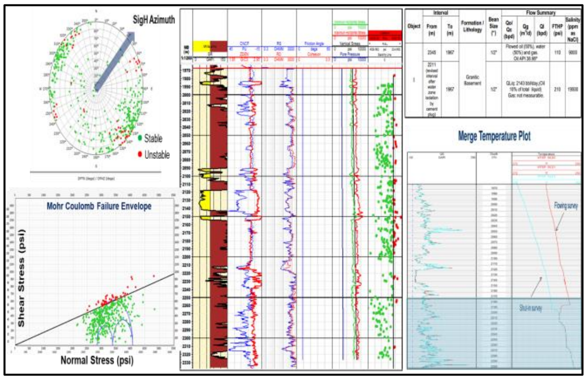

Figure 8: History match between estimated critical stressed fractures with testing results and production logging in well-Y

Estimation of Stresses in 3D

Determination of accurate horizontal stress magnitudes is one of the most difficult stages in the construction of 3D-MEM since this data cannot be directly measured or deduced from log measurements without some modelling. Lack of calibration points can be a significant limitation since the in-situ stresses are strongly influenced by geological setting and events that may not be fully captured through the modelling. In this study, stresses were initialized in the 3D model using a finite element-based stress simulator. It takes input of the estimated 3D property cube of elastic properties (Young's Modulus and Poisson's ratio) and pore pressure along with boundary conditions. These boundary condition were altered to obtain a reasonable match between resultant stresses extracted along the offset wells, and 1D stress model with other calibration factors (Talreja et.al, 2019). **Figure 9** shows the QC of minimum horizontal stress estimated from 3D workflow (black curve with shaded region) and 1D workflow (in blue) and **Figure 10** shows the variation of magnitude of maximum horizontal stress gradient in the 3D space.

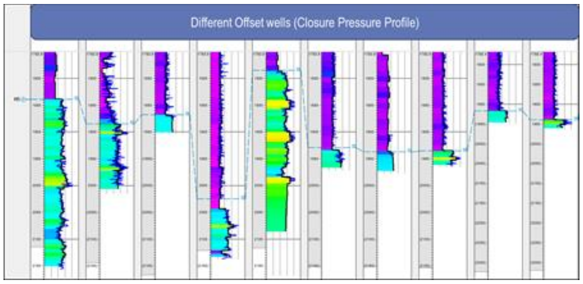

Figure 9: QC of minimum horizontal stress estimated from 3D workflow (black curve with shaded region) and 1D workflow (in blue)

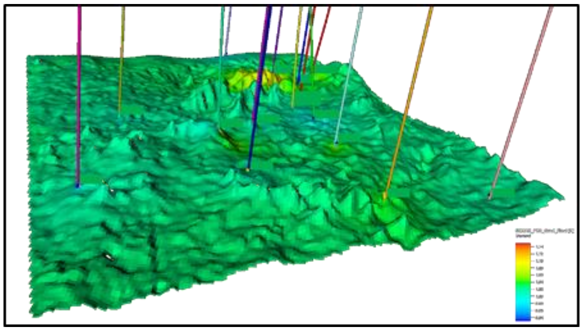

Figure 10: 3D-spatial variation of maximum horizontal stress gradient in target basement zone

Study shows that the stress regime is primarily normal fault in shallower formations and Basement interval tends to show strike-slip (mainly) to reverse fault regime with lithological variations.

3D Critically Stressed Fracture (CSF) Evaluation

In this part of the workflow, analysis of the stability of faults and fractures based on 3D and time-lapse geomechanical inputs is performed. Fault and fracture stability are calculated based on the Mohr-Coulomb criterion taking into consideration the friction angle and cohesion of the discontinuity, its dip angle and dip azimuth, and the 3D stress field as show in the **Figure-11** below. Discontinuity stability analysis thus accounts for the relative orientation between the 3D in-situ stresses and the orientation of the fault or fracture. In the plots, slip tolerance is plotted. It is a quantity describing the ‘distance’ to fault/fracture failure on a scale from 0 to 1, with 0 being stable and 1 being failure. It is estimated based on following equation

$$ST = \frac{\tau}{\sigma_n \mu + c_0}$$

Based on similar inputs, additional analysis is performed which are used during stimulation like critical ones include Critical Pore Pressure (CPP) and Critical Pore Pressure Change (CPPC) which are defined below:

CPP is the pore pressure at the point of failure, i.e. the reservoir pressure when the fault or fracture is failing under the imposed stress state.

$$CPP = \sigma_n \left(\frac{\tau - c_0}{\mu}\right) + PP$$

CPPN is the difference between the actual reservoir pore pressure and the CPP, i.e. the amount of pore pressure increases to reach the Critical Pore Pressure - and thus failure (positive values), or the amount the pore pressure already exceeds the Critical Pore Pressure (negative values).

$$CPPC = CPP - PP$$

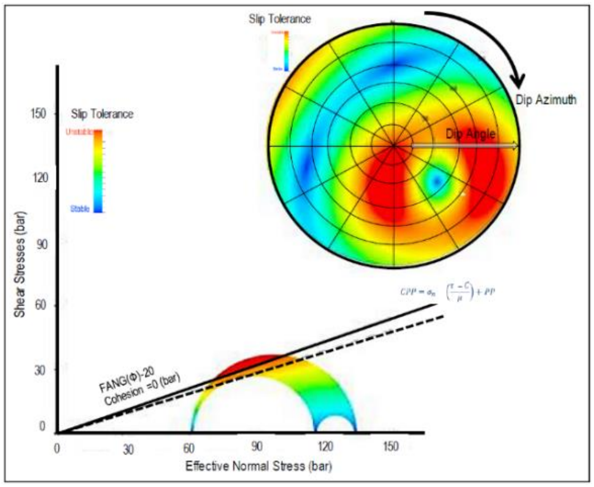

Figure 11: Results of discontinuity stability analysis showing the slip tolerance for all possible fault/fracture orientations in 3D under a given stress state.

Results of 3D CSF analysis is shown in the **Figures 12 to 15** which shows that:

- There exist critically stressed fractures aligned both in the direction of maximum and minimum horizontal stress depending on shear stress and normal stress components. However, majority of them lies in vicinity of 20deg-30deg of maximum horizontal stress azimuth.
- Fractures at 90deg to maximum horizontal stress direction require higher injection pressure to slide
- Presence of unstable fractures along with Hydrocarbon zone in the area has resulted in positive well/production testing.
- Most of critical stressed fractures are located in proximity to multiple fault sets.

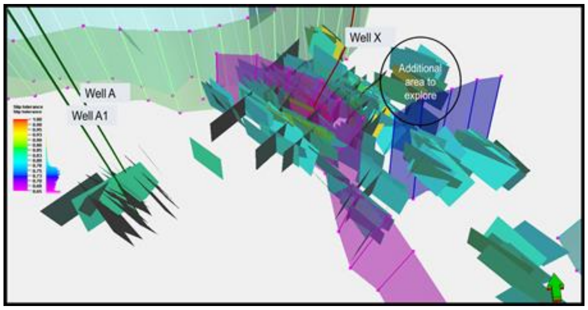

Figure 12: 3D CSF Results vs well history around well-X discussed under Example-A. Slip tolerance is plotted on the

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fractures suggesting presence of unstable/critically stressed fractures near well-X.

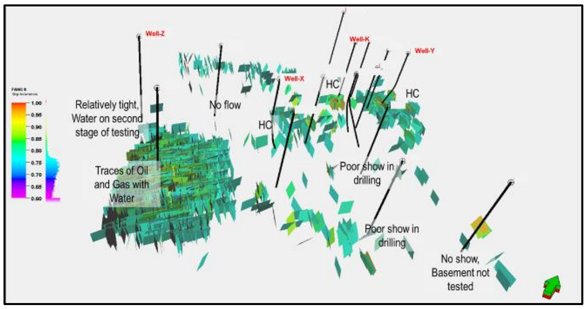


Figure 13: 3D CSF Results vs well history in the area. Areas containing critically stressed fractures have high probability of encountering flow

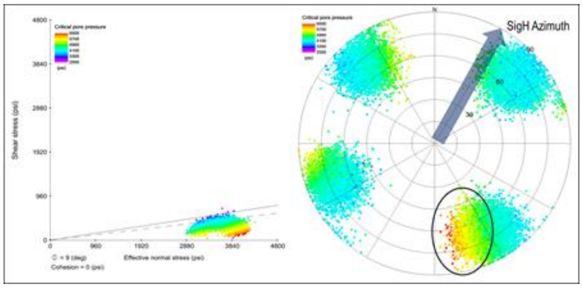
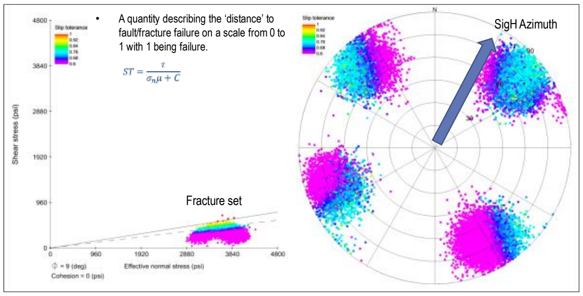


Figure 14: Critical Pore Pressure (CPP) variation on fractures plotted on Mohr-Coulomb failure criterion and a rose plot.



- A quantity describing the ‘distance’ to fault/fracture failure on a scale from 0 to 1 with 1 being failure.

$$ST = \frac{\tau}{\sigma_n \mu + C}$$

Figure 15: Slip Tolerance variation on fractures plotted on Mohr-Coulomb failure criterion and a rose plot.

Conclusions:

- 3D CSF results show good match with production and testing results at 16 wells in the field. It also provides sweet spots for next locations with anticipated depth intervals ranging 30m-200m at various locations.
- On 1D scale Horizontal stress profile has been estimated using poro-elastic horizontal strain method. Method is constrained with available LOT and by doing history match of model predicted borehole failures and actual failures seen on caliper log.
- Stresses at 3D scale are based on Finite element method validated against the 1D calibration results.
- Typical stress regime is Normal to strike slip faulting regime in the area.
- Maximum horizontal stress azimuth has been identified as NNE-SSW to NE-SW based on fast shear azimuth and borehole image feature analysis.
- Each of four fracture sets as part of DFN has contribution to critical stressed fracture sets with NE one having higher slip tolerance and lower critical pore pressure change.
- Typical slip tolerance for critically stressed fracture sets ranges 0.6-1.0.
- Critical pore pressure changes for critical stressed fracture sets range: -750psi to 3100psi. Few fracture sets will be slippage prone even with depletion up to 750psi while others will require stimulation or clean up job.

Recommendations

- Most of the CSF are located at proximity to multiple faults close to each other. Typical areas have been identified to evaluate the planned locations in the field.
- Study recommends drilling of vertical wells in proximity to identified CSF areas or deviated wells perpendicular to strike of identified CSF areas set as identified in analysis.

Nomenclature

c_0 - Cohesion
t_t - Shear Stress
t_n - Normal Stress
μ - Coefficient of Internal Friction
ϕ - Friction Angle for fractured surface
PP - Pore pressure
CPP- Critical Pore Pressure
CPPC-Critical Pore Pressure Change
ST – Slip Tolerance

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Acknowledgments

The authors thank ONGC for their support and permission to publish the paper. The authors wish to thank all the members of project and Schlumberger management who provided support during this study.