Geomechanical Restoration Based Fracture Modelling of Mumbai High Unconventional Basement Reservoir

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Abstract

In recent times unconventional fractured basement reservoir in the Mumbai High field has gained importance due to increasing requirements of hydrocarbon. Exploration and development of fractured basement reservoirs needs assessment of the fracture network as the fractures control the reservoir porosity and permeability. Fracture modelling, based on the geological understanding of the relationship between fracture network and geological evolution of the area has been carried out for entire Mumbai high field in present study. 3D Geomechanical sequential restoration of horizon surfaces was carried out and differential strain was captured between restored and unrestored basement. Discrete Fracture network (DFN) model has been generated by using differential Maximum Principal Strain (e1) as a proxy to input for fracture intensity. Four different fracture sets were modelled by constraining the model by observed fracture parameters from the wells. Susceptibility analysis of fracture sets to failure in present day stress regime show that the fracture set oriented in NNW-SSE direction has very high slip and dilation tendencies, and are optimally oriented and critically stressed to be in slip mode. The validated model can be used for fracture prediction in areas of poor or sparse seismic data for exploring basement sweet spots in new areas.

Introduction

Mumbai High is a prominent basement uplift in the continental shelf off Mumbai. Exploratory drilling initiated in 1974 proved this uplift to be a giant oil and gas field (Fig.1). Maximum production of oil and gas from the field has been from L-II and L-III reservoirs of Miocene age. But in changed scenario attention on hydrocarbon production from fractured basement has gained importance. basement section was tested in 54 wells of which 15 wells produced hydrocarbon to surface. The true potential of the basement is yet to be assessed and no specific development plan could be formulated owing to the fact that accumulation over Mumbai High Basement is sporadic in nature and its inconsistent flow behaviour. So, it becomes pertinent to have a robust fracture model prior to devising an exploration and development plan for fractured basement reservoir. The present study aims to generate a viable and realistic Discrete Fracture Network Model for the basement of Mumbai High.

Geology and Stratigraphy

Mumbai High is a doubly plunging asymmetric anticlinal structure with a gentle western limb. The eastern limb of this structure is affected by a set of major down-to-basin faults. At the basement level, Mumbai High has a vertical closure of 250 m and covers an area of about 1800 sq. km. Structurally Mumbai High field is demarcated by a large displacement, east hading normal fault towards the east extending for about 70 km in NNW-SSE direction with a maximum throw of about 400 m at basement level (Fig.1). In addition the field is marked by the presence of several NE-SW, NNE-SSW and ENE-WSW trending faults across the field (Sinha, et al., 2011). These normal faults are considered to play a very important role in development of fractures in the basement.

In Mumbai High area sedimentary sequence can be broadly grouped into three major units,

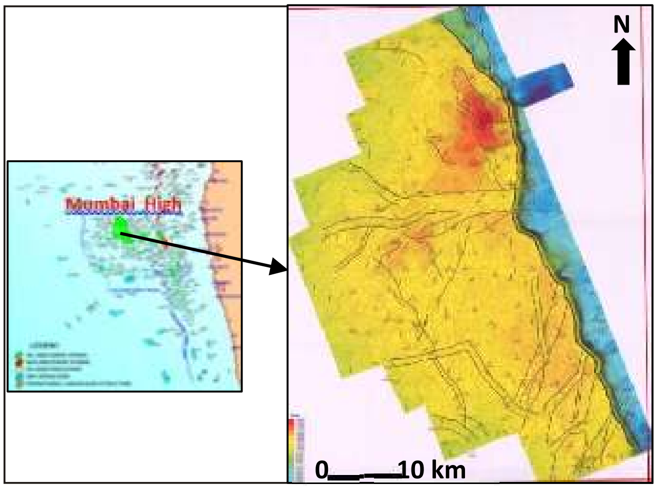

Fig. 1: Structure map of Mumbai High filed on top of Basement

i. Basal unit of clastics consisting of sandstone, siltstone and shales resting over basaltic / granitic / gneissic basement. The basement is granitic / gneissic with occasional basalt in Mumbai High South and mostly basaltic in Mumbai High North,
ii. Limestones and alternation of shales and limestones in the middle, and
iii. Shales and clay / claystone forming the upper part.

2D Structural Modelling

An understanding of geological and structural evolution of an area is a prerequisite for building any fracture model since generation of different fracture sets are primarily effect of different deformation stages associated with structural evolution (Sanders, et al., 2003). Selected seismic line along ENE-WSW direction were interpreted for horizons H5 (Basement), H4, H3A, H3B, LV, H3CGG, LIV, LIII and LII along with all the major faults (Fig.2) and the section was sequentially restored up to H5. Earliest deformation occurred

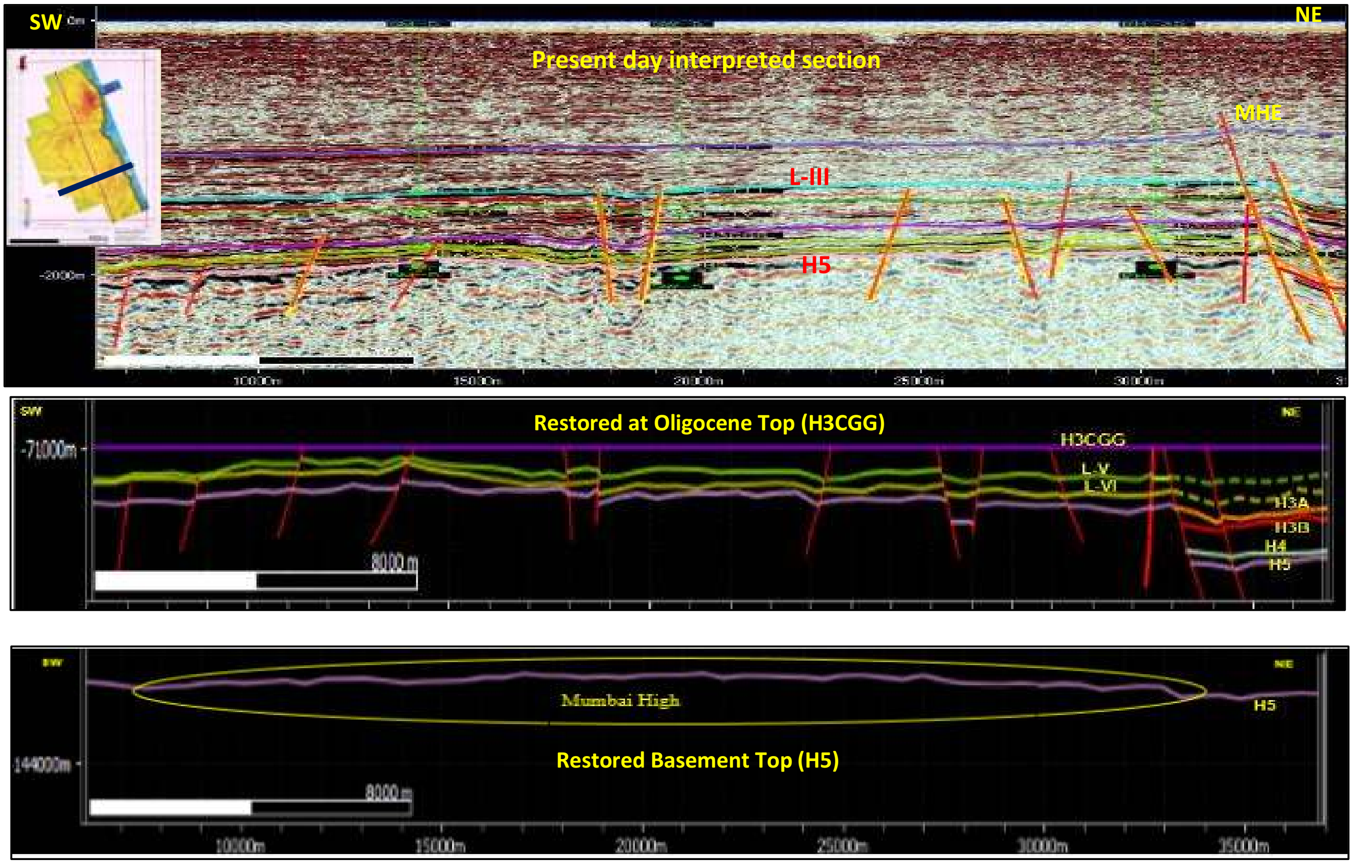

Fig. 2: Interpreted and restored section at Oligocene top and Basement level along the ENE-WSW direction

during Late Cretaceous in the form of extension which resulted in development of normal faults in the basement. During this stage the Mumbai High East fault came into existence and it remained active as a normal fault till Late. Thereafter, occurrence of normal faulting greatly reduced and an inversion along the Mumbai High East fault was initiated during Late Oligocene, which continued up to Late Miocene. Except the MHE fault, rest of the Mumbai field remained structurally passive after early extension. The episodic reactivation of Mumbai high fault suggests that fractures in the basement, genetically related to MHE, were also getting opened up at these stages in geologic past. This might have resulted in accumulation and entrapment of hydrocarbons in the basement.

Geomechanical Restoration

Five interpreted depth surfaces namely H5 (basement top), L-V, L-IV, L-III and L-II along with faults were migrated to Move software platform. Based on dip analysis of the surfaces, anomalously high surface dips were identified and interpreted as fault gap zones and these high dip areas were removed as fault gaps at each horizon for geomechanical restoration.

Each surface was sequentially restored using geomechanical algorithm and the incremental as well as cumulative strains were captured at each restoration stage. Basement surface was restored to datum after decompacting all the sediments overlying it. Incremental strain was captured between the restored undeformed surface and the deformed H5 surface. Strain captured during restoration has brought out well defined and distinct zones of high strain. It is observed that high strain values are confined around the faults and the extent and orientation of high strain zones vary according to the intensity of faulting (Fig.3).

The orientation of the three principal axes show normal faulting stress regime in which e3 (Maximum Compressive Stress) is vertical while e1 (Minimum Compressive Stress) and e2 (Intermediate Compressive Stress) axes are horizontal

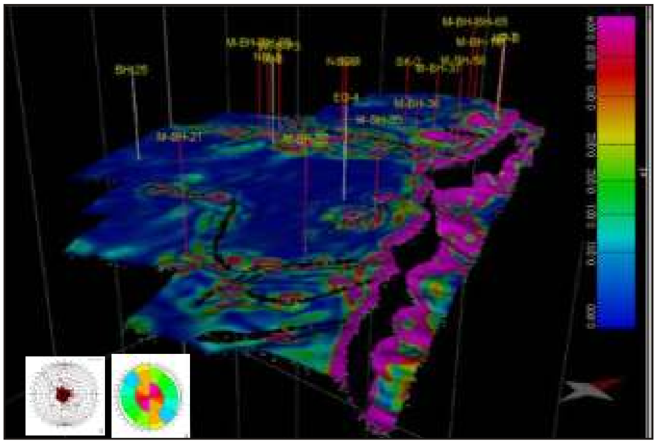

Fig. 3: Incremental strain map for strain captured between restored Basement and deformed Basement state.

as displayed in the stereo plot. The highest magnitude of e1 strain is observed along the MHE fault. Overlay of the well locations which produced hydrocarbon to surface, on the basement strain map, indicated that the wells fall mostly in the areas of high strain around the major faults. It can be inferred that the fracture porosity developed in the basement is genetically related to the major faults and their damage zones. Thus, the strain attribute captured during the restoration, could be used as proxy for fracture intensity in generating a predictive fracture model.

Fracture Modelling

Traditional methods of fracture modelling are geo-statistical in nature and they rely on stochastic realisations requiring large number of evenly distributed wells to allow simple interpolation of fracture statistics between the wells. In the present case there are few wells, where image logs are available for basement section hence a non-deterministic predictive modelling approach can be helpful to address the spatial variability in fracture intensity.In the present study non-deterministic approach was followed to generate a Discrete Fracture Network (DFN). e1 strain map obtained by geomechanical restoration was used as the attribute to model fracture intensity. A preliminary unconstrained, fully predictive model was generated by utilising e1 strain map for fracture density and predicted fracture properties for fracture dip and azimuth. Thereafter, semi predictive constrained models were generated with four different fracture sets oriented in NW-SW dipping NE, NE-SW, E-W and NW-SE dipping SW. The average fracture properties of these fracture sets such as orientation, dip values and Fisher dispersion were obtained from statistical analysis of fractures observed in FMI logs of few of the wells (Fig.4.).

A geocellular volume with cell dimensions of 300x300x300 was created and populated with e1 strain values. Four fracture sets were generated in the geocellular volume having a scenario with an average fracture length of 200 m and average aperture of 0. 5 mm. Mean orientation data for each fracture sets were input from the statistical analysis of observed fractures in the FMI log along with associated Fischer (K-Value) for each set.

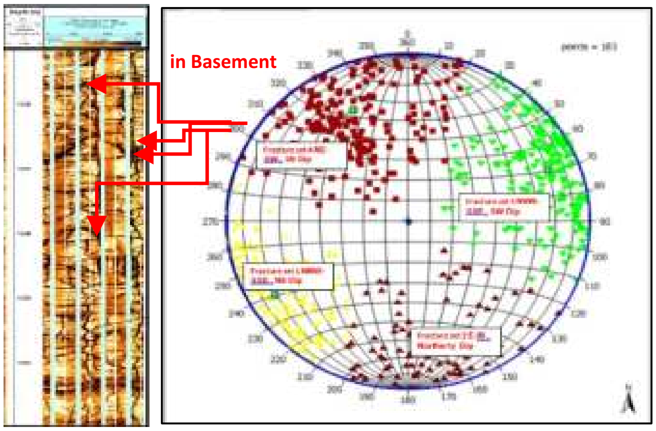

Fig. 4: Stereo plot representing the four sets of fractures measured in some wells of Mumbai High field.

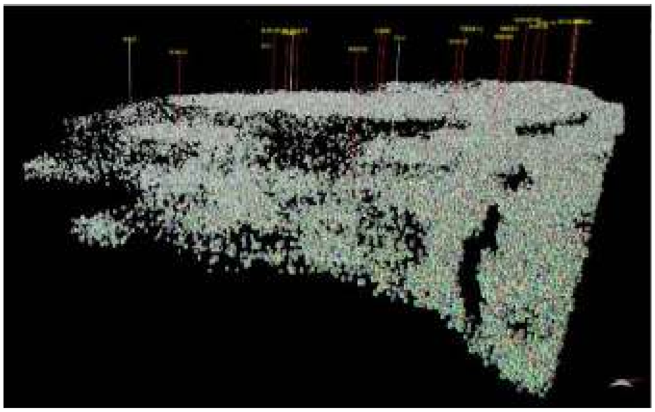

Fig. 5: DFN exhibiting four fracture sets, taking e1 incremental strain captured between geomechanically restored Basement and deformed Basement surface as proxy to fracture intensity.

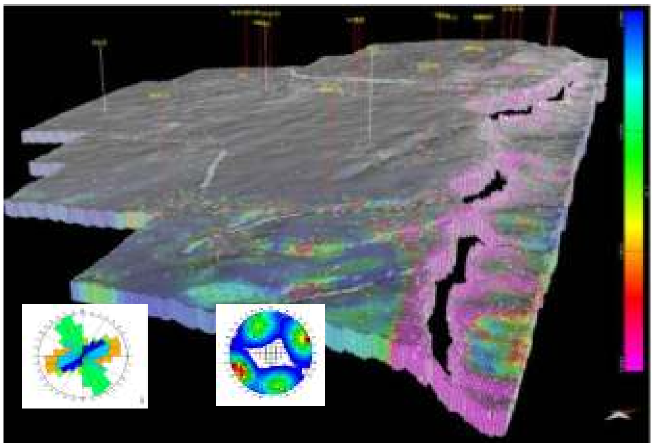

Fig. 6: Geocellular volume populated with e1 incremental strain and modelled fracture sets.

The resultant modelled DFN was utilized for calculating reservoir parameters like P32 fracture density, porosity, and permeability.

Slip susceptibility analysis of fracture

Critically stressed fractures (open mode stress state) are considered to contribute significantly to fluid flow in the reservoir. Geomechanics based technique is applied in this study to assess the likelihood of reactivation or susceptibility of fracture sets to shear failure in present day in situ stress regime. Criticality of fractures to shear failure has been analyzed by computing four geomechanical parameters viz. fracture stability, slip stability, slip tendency and dilation tendency.

Present day geomechanical model of Mumbai field was prepared by determination of orientation and magnitude of three principal stresses, maximum ($\sigma1$), intermediate ($\sigma2$), and minimum ($\sigma3$). Average value of maximum horizontal stress direction is found to be NNW-SSE ($N146^0/326^0 \pm 17^0$) based on analysis of drilling induced tensile fractures observed on FMI logs (Jagdamba Prasad, 2014). Vertical stress (Sv) is calculated by integrating the bulk density of the rocks from the density logs recorded in the wells LOT values collected from 10 wells of Mumbai high field were analyzed and EMW was converted to pressure values, which represent the minimum horizontal stress. Maximum horizontal stress (SHmax) was estimated by the equation S1'/S3'≤ 3.12 where, S1' is effective maximum principal stress and S3' is effective minimum principal stress (Moos, D. and Zoback, M.D., 1991). The compressive principal stresses σ1, σ2 and σ3 at 1900m depth were calculated as 90.3, 49.6 and 29.6 MPa respectively. Orientation of maximum horizontal stress derived from drilling induced fractures within basement in the direction 3260 was incorporated in the model Present day geomechanical model suggests the likelihood of a strike slip stress regime in Mumbai High field at basement level (Fig. 7)

The modelled fracture sets were analysed for their likelihood of reactivation or susceptibility of fracture sets to shear failure in the present day stress regime. Slip stabiility of four fracture sets was calculated in the present day 3D stress regime (Fig. 8). The NNW-SSE modelled fracture sets have very low to zero slip stability values and the poles to these fractures lie above the failure envelope hence most of these fractures are in reactivated state. So this fracture set is optimally oriented and in shear mode so they are likely to be the main contributor to fluid migration and permeability in fractured basement.

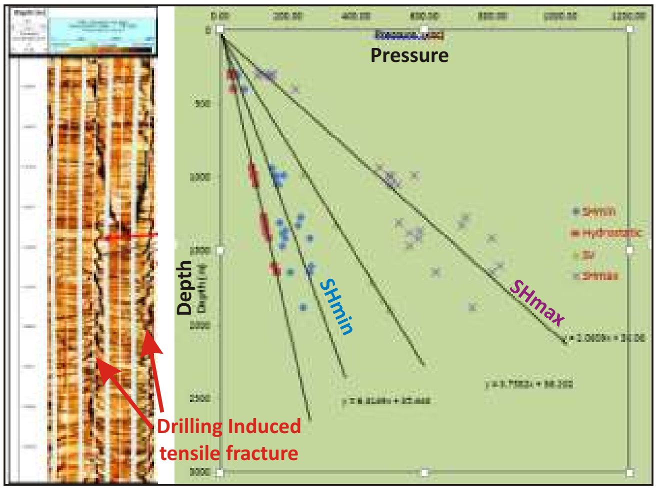

Fig. 7: FMI showing drilling induced tensile fractures depicting maximum horizontal stress direction. Graph showing the trend of Vertical Stress (Sv), Maximum Horizontal Stress (SHmax), Minimum Horizontal Stress (SHmin), with depth in Mumbai High Field.

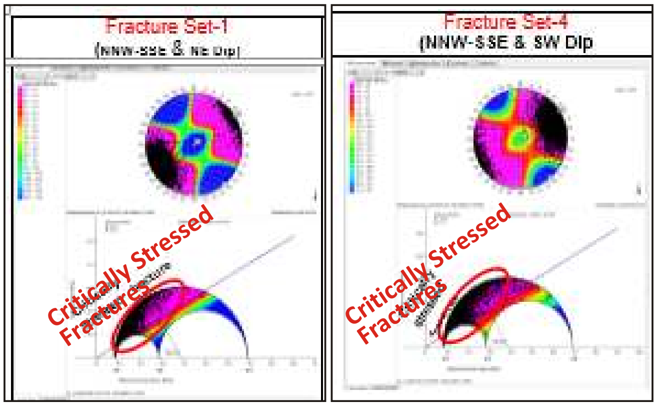

Fig. 8: Fracture Sets oriented in NNW-SSE direction are optimally oriented and they are already in failure state as the poles to these fracture planes are above the failure envelop.

Conclusions

2D structural modelling of Mumbai High field suggests that an early extensional deformation started during Late Cretaceous leading to extension of approximately 475 m along the restored section in ENE-WSW direction at basement level. Inversion along the Mumbai High East fault zone started during Late Oligocene and continued up to Late Miocene. 3D Geomechanical sequential restoration of surfaces has brought out that most of the captured strain was generated during the initial deformation of the basement and confined around the faults fault tips, fault intersections and small structural highs.

Discrete Fracture Network (DFN) model with four fracture sets has been generated by non-deterministic approach by using differential e1 strain as a proxy to input for fracture intensity. Each modelled fracture set was analysed for criticality to slip in the present day stress regime. Fracture sets oriented in NNW-SSE direction have very high slip and dilation tendency and these fracture sets are critically oriented and are prone to remain in opening mode.

Faults optimally oriented in present day stress regime with associated fractures cold be important targets for accumulated hydrocarbon in fractured basement reservoirs. Besides this, the tips of critically oriented faults are also good candidate for development of fracture because of observed high strain values

The workflow adopted in this study can be used for fracture prediction in areas of having poor or sparse seismic data for exploring basement sweet spots in new areas.

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