Seismic driven 3D Geomechanical Modeling in Tight Reservoirs-A Case Study from Cambay Basin India

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Abstract

Exploration and Development of tight reservoirs is deemed to be challenging. One of the key challenges is how to ably place wells in the zones with better reservoir quality and how to fracture these wells efficiently to produce these reservoirs economically.

3D Mechanical Earth Model (MEM) attempts to address the above challenge. 3D-MEM is representative of the Earth's stresses and rock's mechanical properties, formation temperatures and pressures acting on rocks at depth. It helps to comprehend the behavior of the rocks, their deformation and failure criteria when subject to drilling, completion and production operations. Wellbore stability analysis can be carried out using 3D-MEM for determining the well orientation, casing design and properties of drilling mud. Interval selection for hydraulic fracturing (HF) can also be carried out on the basis of stress profile for improving reservoir contact and ensuring fracture containment. Therefore, 3D-MEM will help in better well design and HF planning.

Introduction

The study aims at devising an optimal 3D reservoir geomechanics workflow with a case study from a field in Cambay basin. The reservoir (Member of C Formation) is having a depth of (up to 1700 m) and the production rates from most of the wells are very low. Hydraulic fracturing has to be carried out in all the wells and it is the only way to make the reservoirs produce. The main goal of building a 3D geomechanical model for the study area is to predict in-situ stress conditions for optimal well and HF planning as the reservoirs are very fine-grained tight, silty and shaly.

The study area of nearly 110 SKM lies in the Ahmedabad block of North Cambay Basin (Fig. 1). The main producing reservoirs in the area are Pay-II and Pay-III sands of C formation. Additionally, Pay-I sand is developed sporadically in the study area.

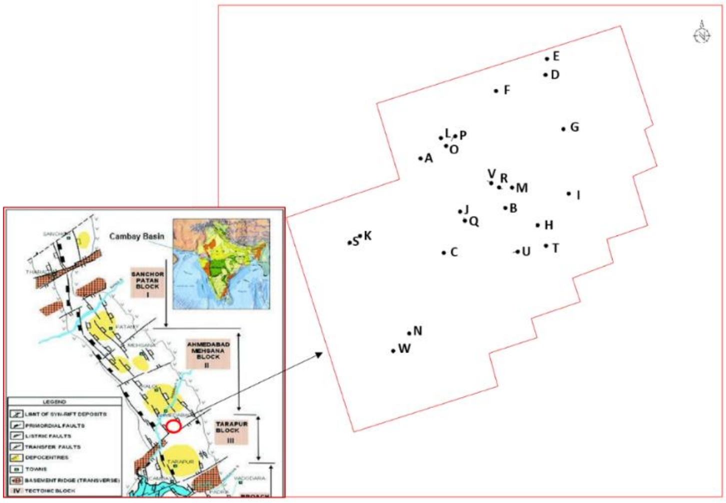

Figure 1: Tectonic Map of Cambay Basin (Kundu et al. 1993) and Study Area

Only oil shale contact is observed in all the drilled wells and reservoirs operate under depletion drive. The hydrocarbon entrapment is controlled by facies development rather than structural configuration. Pay-**II** payzone is broadly distributed in the area and is the main oil-bearing reservoir. Pay-**III** is developed around wells H, M, N, Q & T while Pay-**I** is developed around wells H & I.

Fine to very fine sand and siltstone of Pays-**I**, **II** & **III** with intervening shales in low energy, tidally influenced distributary channels, levees or interdistributary bay fills might have deposited in prograding lower-delta plain to prodelta setup.

The reservoir comprises of thin, tight and silty facies. Mapping the spatial distribution of better reservoir facies poses a significant challenge. Well design and better hydro-fracturing planning are very much essential for better exploitation of reserve. Thus, seismic driven MEM has been attempted to address the challenge and assist further development of field.

Methodology

Geomechanics involves the study of mechanics of rocks. A 3D geomechanical model can explain the mechanical behavior of the reservoir. The main goal of building a 3D geomechanical model for the study area is to predict in-situ stress conditions for optimal well and HF planning as the reservoirs are very fine-grained tight, silty and shaly. The study aims at devising an optimal seismic driven workflow for 3D-Geomechanical Modeling. The workflow adopted is shown in Fig. 2.

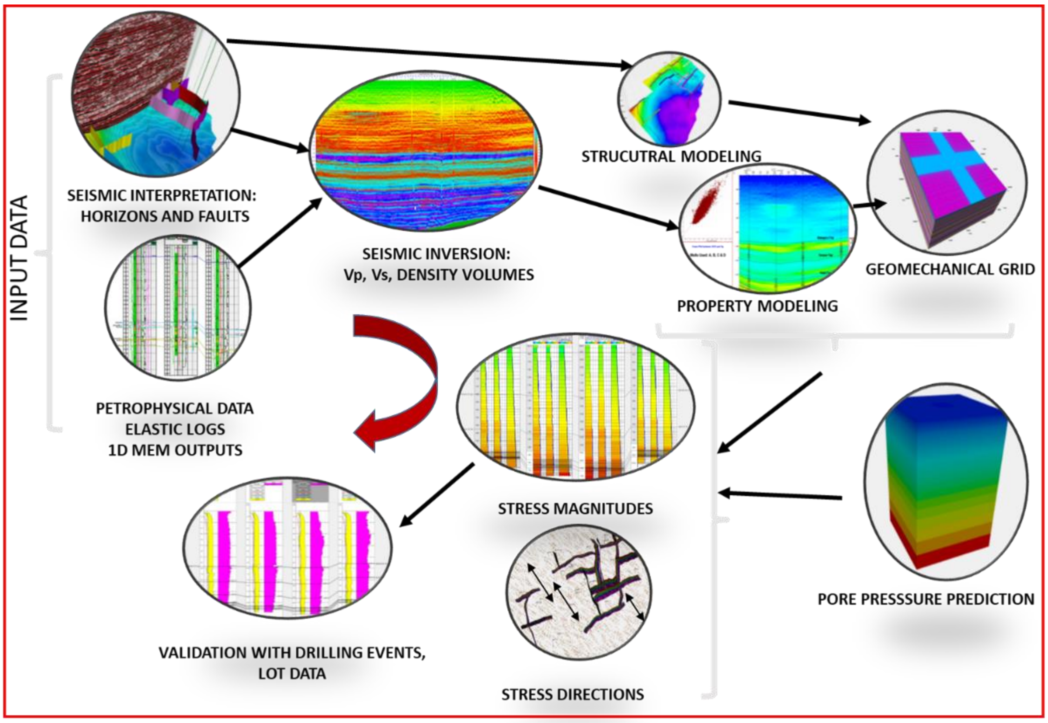

Figure 2: 3D MEM Workflow

1D MEM

The 1 D MEM logs of four wells viz. A, B, C, D was carried out. MEM data provides elastic properties such as Young’s Modulus, Poisson’s Ratio etc.; yield criteria such as Unconfined Compressive Strength (UCS), friction angle etc.; overburden, pore pressure and principal stresses. Overburden (Sv) is more than two horizontal stresses viz. SHmax and Shmin

(Sv>SHmax>Shmin) indicating the extensional regime in the study area.

Fast Shear Azimuth (FSA) from sonic scanner data provides the SHmax direction. FSA direction for the A, B, C & D is NNW, NW, NE & NE respectively.

Pre-Stack Inversion

Model based Pre-Stack Inversion was carried out from t=0 to reservoir zone plus ~100ms after optimizing the inversion parameters to generate rock-physical properties i.e. Vp (P-wave velocity), Vs (S-wave velocity) and Density which are vital inputs to a 3D geomechanical model. QC of the inversion result was performed by comparing inverted properties and well logs in seismic bandwidth. Significant correlation between the two validated the quality of the output.

Building the Structural Framework

The initial step is to build a structural framework for the 3D Geo-Mechanical model incorporating well and seismic data. Seismically mapped horizons close to Formation-D, Pay-III, Pay-II, Formation-C, Formation-B and Formation-A tops were depth converted and used as an input to generate simple 3-D grid with a resolution of 50x50m. The grid was constrained at the top by the topography of the area and bottom by a flat surface at 1850 m depth in SSTVD. Zones corresponding to Pays-III, II and I reservoirs were created by zone modelling. Layering was done to capture the finest possible information (close to seismic resolution) in the 3-D grid (up to 5m at the thickest part of II and III reservoir).

Property Modeling

The Pre-Stack inversion outputs viz. Vp, Vs, Vp/Vs and density were brought in to the grid through seismic resampling. Dynamic elastic properties such as Young's modulus (E), Poisson Ratio (σ) were then generated from Vp, Vs and density (ρ) volumes.

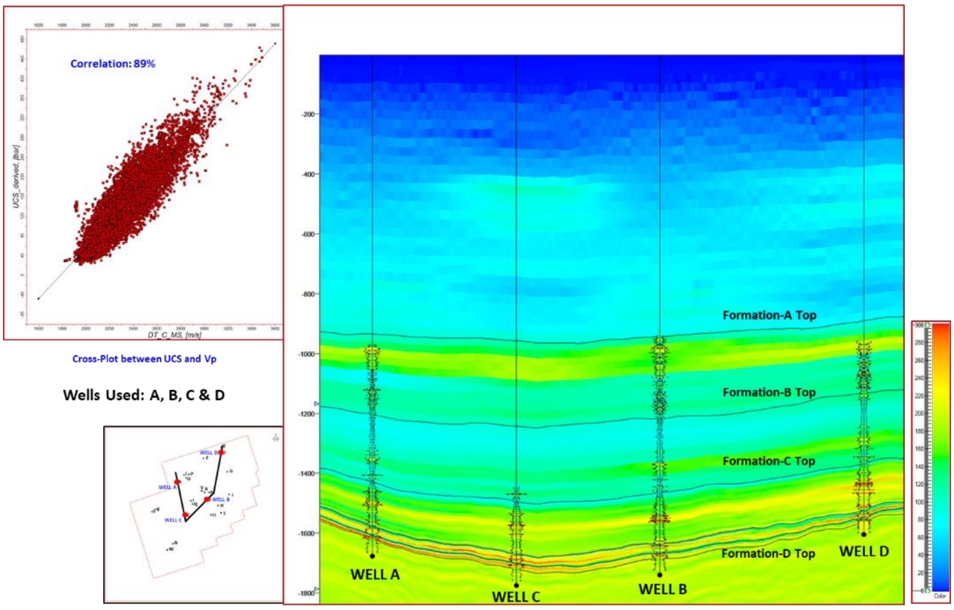

Figure 3: Properties for 3D MEM: UCS from Vp

1D MEM logs were used to generate functional relationships between elastic properties & strength parameters obtained from conditioned sonic scanner data and MEM logs. Functional relationships were also derived between static elastic properties (Young's modulus and Poisson's ratio) from 1D MEM data and dynamic elastic properties. The generated functions were used to generate elastic properties and strength parameters such as UCS, Friction angle, Tensile strength etc. in the 3D grid. These functions also converted dynamic properties i.e. Young's modulus and Poisson's ratio to static ones. The generated properties were further refined by populating the 1D MEM logs using 3D trend of derived volumes. A representative cross-plot between UCS and Vp to derive the functional relationship along with the generated UCS section overlain with 1D-MEM logs is shown in Fig. 3.

Pore Pressure Prediction

A number of cross plots were generated between various properties (Vertical Effective Stress (VES), density, P-velocity, NPHI, effective & total porosity and overburden) vs pore pressure from the 1D MEM data. An excellent correlation (99%) was obtained between overburden (OBG) and pore pressure from 1D MEM logs. Overburden was calculated from the density volume obtained from the inversion output. The functional relationship between the overburden and pore pressure was thus used to generate 3D pore pressure volume.

3D Geomechanical Grid

Creating a geomechanical grid involves adding overburden, underburden and sideburden grid cells to an existing reservoir grid. The under burden is attached to the base of the models to ensure appropriate transfer of stresses from the model boundaries to the reservoir and overburden in the simulations. Side burden is also added to avoid localized boundary effects. An extra layer of cells (Plate) is added around sideburden to ensure that the load is applied uniformly to the embedded grid.

In the present work, no overburden was added as reservoir modelling was done from the topography of the area itself. Parameters used to create sideburden and underburden are as follows:

Sideburden: It is extended on both sides of the reservoir by 30 Kms in the X direction and 30 Kms in the Y direction. It is divided into 20 cells in X direction & 20 cells in Y direction, with a geometric variation of 1.25 away from the reservoir.

Underburden: It is extended 27 Km below the reservoir. It is divided into 40 cells in Z (depth) direction with a geometric variation of 1.15 away from the reservoir.

Plate: A stiff plate of 50 m thickness was added to reduce stress concentrations at the model boundaries

The total number of cells in the geomechanical grid were 22556160.

Property Modeling in Geomechanical Grid

Once the embedded geomechanical grid was ready, all the rock-mechanical properties were extrapolated in sideburden using minimum curvature algorithm. Functional relationships representing the variation of rock-mechanical properties with depth were generated and used to extend the properties in the underburden area. Properties extended in the underburden area were quality checked to eliminate any anomalous values at greater depth.

Material Modeling and Property Population

Material modeling was carried out to create materials that describe different types of rocks (or geomechanical materials) and assign their associated parameters such as Young's modulus, Poisson's ratio, bulk density, etc. A very stiff material has been created for plates to reduce stress concentrations at the model boundaries. The mechanical behavior of rock is highly dependent on the material and location of discontinuities in the vicinity. Therefore, to model the detailed behavior of stress at these places, faults were modelled into the grid as equivalent material, with properties weaker in strength and lower in elastic stiffness than surrounding rocks. This material was assigned to all the faults in discontinuity modeling.

In property population, the different geomechanical properties that describe the characteristics of different rocks were populated in each cell of the geomechanical grid. One region was defined for the plate and other for the reservoir grid, sideburden and underburden. The property modelling process was able to capture the complex distribution of geomechanical properties within the area.

Stress Initialization

After property population, the modeled fault framework was incorporated in the geomechanical grid and simulation under discontinuity modeling. The pressure condition was defined using generated pore pressure volume for simulation. Finally boundary conditions i.e. Shmin gradient, SHmax/Shmin and Shmin azimuth were estimated from 1D-MEM logs and thus incorporated in final geomechanical simulation.

To initialize the stress tensor, 3D finite element method (FEM) is used (Qui. K et al., 2013). In each cell of the grid, both magnitude and direction of three stress tensors i.e. vertical stress (Sv), minimum & maximum horizontal stresses (Shmin & SHmax) were stimulated using the geomechanical properties, pore pressure, boundary conditions and discontinuity data.

A set of equations relating forces, mechanical properties, and deformation is solved at each point in the grid to calculate stresses in a FEM (Qui. K et al., 2013).

A number of iterations were run updating the various input parameters and boundary conditions to achieve satisfactory calibration with 1D MEM outputs.

Results & Validation

The generated results were loaded from the final simulation case and validated with available 1D MEM, well data and drilling events. Well correlation panel in Fig. 4 shows good match for the magnitude of Shmin, SHmax and Sv with the 1D MEM data.

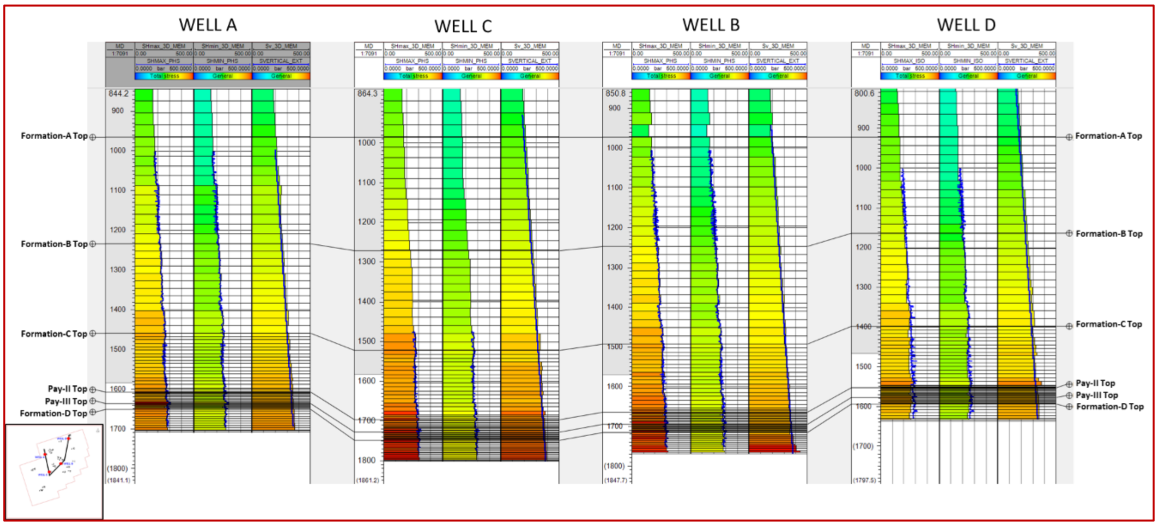

Figure 4: 3D MEM Output: QC: SHmax, Shmin and Sv validated with 1D MEM logs

Further, Wellbore stability analysis was carried out to define the mud weight window for efficient drilling. Directions generated for Shmin and SHmax were validated with Fast Shear Azimuth (FSA) of the sonic scanner data close to formation top (Fig. 5). SHmax direction for the wells C and D is NE-SW which matches with the direction of Fast Shear Azimuth. In the well B, SHmax direction is NW-SE which is also validating with FSA direction as obtained from sonic scanner data. It appears that stress tensors have rotated close to well B due to presence of faults. The FSA direction in the well A is NNW-SSE. However, the SHmax direction obtained at the well A from MEM model is NE-SW which may attribute to presence of a discontinuity beyond the seismic resolution which might have realigned the stress tensors.

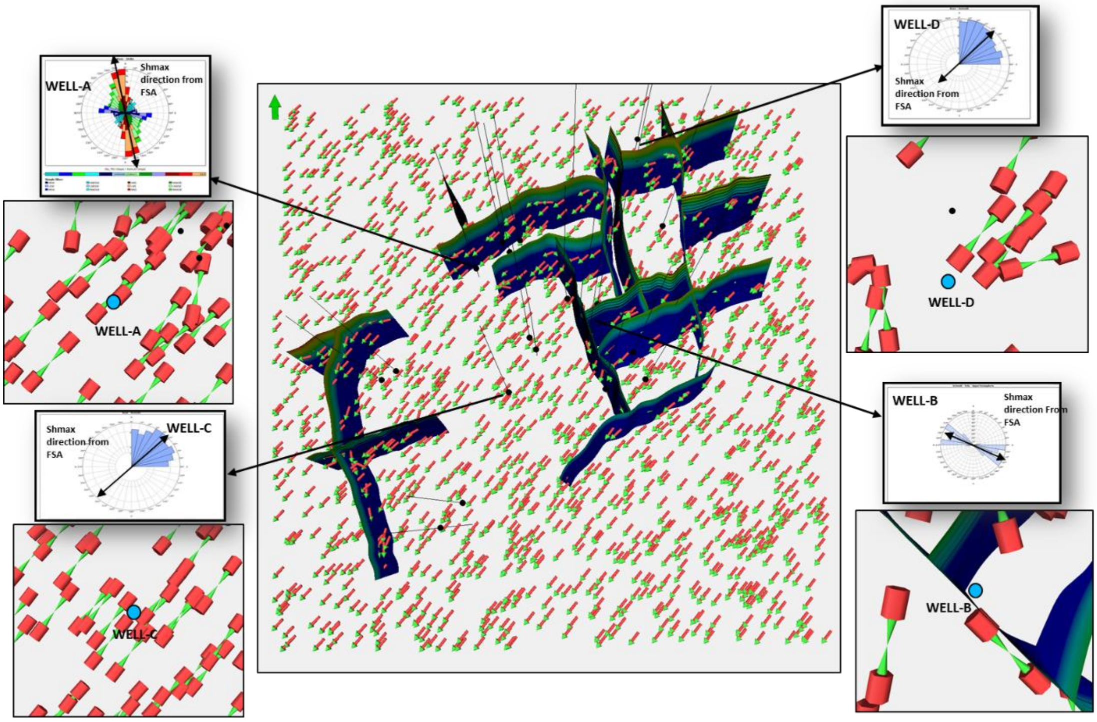

Figure 5: Direction of maximum horizontal stress (NE-SW) with redistributed stress close to faults: Validation with Wells

Conclusion

Now once we have in-situ stress magnitudes and directions, horizontal wells in the areas with good reservoir facies can be planned in the direction of minimum horizontal stress. Hydro-fracturing can be carried out in the direction of maximum horizontal stress for efficient exploitation of the reserves.

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