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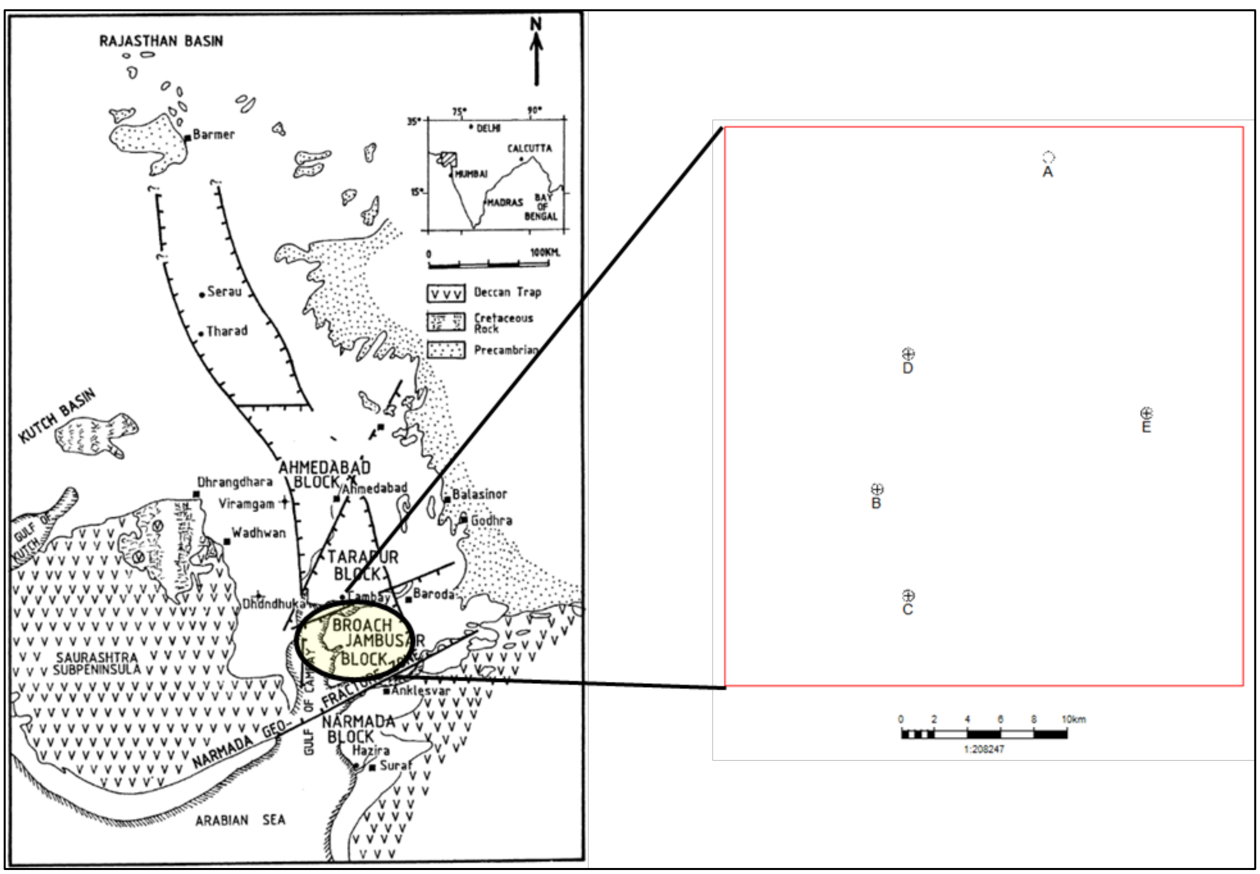
Geo-mechanics in Shale Exploration: South Cambay Basin a case study

Abstract: Role of Geo-mechanics in Shale exploration and exploitation is of utmost importance. The current study involves Geo-mechanical characterization of Cambay shale and its applied aspects for effective Shale exploration and development. Five wells in South Cambay Basin were studied and 1D Mechanical Earth Model for each well was prepared. The process of building a 1D Mechanical Earth Model involves evaluation of rock mechanical properties, pore pressure, magnitude of the principal stresses and their direction. This 1D Mechanical Earth Model is used as an input in different stages of shale exploration. It is used for construction of well bore stability plots to know the optimum mud weight required for drilling. Horizontal Well trajectory determination is also dependent upon the magnitude and direction of the stresses. Hydraulic fracturing which is an indispensable process of shale exploration can be optimized by using the inputs from the 1D Mechanical Earth Models. The study indicates that Cambay Shale in the area lies within Normal Fault to Strike Slip Fault regime. The maximum horizontal stress direction from this study for the five wells is ENE-WSW to NE-SW. Wellbore stability plots for drilling horizontal wells were constructed in this study. The most optimum horizontal well drilling direction is also suggested.

Introduction

Cambay Shale is the main target for shale hydrocarbon exploration in Cambay Basin as it is the established source rock for the basin. Cambay Shale is present throughout the Cambay basin with



varying thickness depending upon paleogeography at the time of deposition. In depo-centers its thickness is more than 1000m which gradually becomes less as we move towards Basin margin.

Figure-1:Cambay Basin Map (after Banerjee et al, 2002) with the study area and distribution of wells.

Shale hydrocarbon exploration involves looking for sweet spots in the extensive shale sequences both laterally and vertically. These sweet spots are the locales of favorable geo-chemical, petrophysical and geo-mechanical properties. The current study involves the geo-mechanical characterization of Cambay Shale in South Cambay Basin. Shale gas/oil exploration and exploitation requires use of two vital technologies viz. hydraulic fracturing and horizontal drilling. These two technologies have made the extraction of hydrocarbons from shales possible. Effective hydraulic fracturing and horizontal drilling is dependent upon the geo-mechanical properties and knowledge of insitu stresses along with their orientation. Therefore this study was aimed at geo-mechanical characterization of Cambay Shale for effective shale exploration and exploitation.

Five wells in South Cambay Basin were chosen for present study. These wells had penetrated a considerable thickness of Cambay Shale in the area. Extensive logging data was available in these wells making them the most suitable candidates for study.

Methodology

Mechanical Earth Model

The utilization of Mechanical Earth Models have become indispensable in modern oil and gas industry especially in reference to shale reservoirs for drilling and hydraulic fracturing optimization. Mechanical earth model is the modeling of the mechanical properties of the rock in conjunction with the regional earth effective stresses (Barton et.al. 1998). The well logs that are recorded in a well for physical properties are directly influenced by the elastic and mechanical properties of the formation. These relations are well known and are extensively applied in lieu of continuous core derived properties. These estimations of the rock mechanical properties, pore pressure and horizontal & vertical stress with their orientation are used to construct a 1D Mechanical Earth Model.

Rock mechanical properties

Different rock mechanical properties are needed as an input in making a 1D Mechanical Earth Model viz. Unconfined Compressive Strength, Young's Modulus, Poisson's Ratio, Tensile Strength, Coefficient of internal friction etc.. These properties were determined using the empirical relations from the log data. The values of the elastic moduli was converted to static values using the established correlations. Shales having Young's Modulus above 20 GPa and Poisson's ratio less than 0.25 are considered to be brittle (Sondergeld, 2010). The values of the Young's Modulus was < 20GPa and Poisson's ratio > 0.25 for the studied shales. Therefore these shales are ductile in nature.

Pore Pressure Modelling

The pore pressure was calculated using the Eaton's (1975) equation for computing pore pressure from sonic data.

$$P = S - S - P_{hyd} \Delta t_n \Delta t_{log} n \qquad \textbf{Eq- 1}$$

Where P and S are pore pressure and overburden stress, P_{hyd} is hydrostatic pressure, Δt_n is sonic transit time in normal pressured shales and Δt_{log} is the observed sonic transit time in the formation respectively. There was absence of direct pore pressure data as direct pore pressure data in shales is rarely available because of ultra-low permeability. Therefore the modelled pore pressure data was validated using the drilling events. The pore pressure gradient values obtained for the studied shales varies from 0.5-0.7 psi/ft.

Insitu stress Computation

Vertical stress: The vertical stress (S_v) at any depth is the stress which results from the combined weight of the rock matrix and the fluids in the pore spaces above a particular depth (McGarr and Gay, 1978). Mathematically it can be expressed as

$$Sv = 0zg\rho zdz \qquad \textbf{Eq- 2}$$

where ρz is the bulk density at depth z, g is acceleration due to gravity.

Horizontal stresses determination: The horizontal stresses in sedimentary rocks can be estimated by poroelastic horizontal strain model equations. The equations for computing horizontal stresses $SHmax$ and $Shmin$ which were based on the assumption of uniform anisotropic tectonic strain and isotropic material (Thiercelin & Plumb, 1994) are

$$Shmin = PR1\text{-}PR\,(S_V - \alpha PP) + \alpha PP + YMS1\text{-}PR2\epsilon Hmax + YMS\,PR1\text{-}PR2\epsilon Hmin \qquad \textbf{Eq- 3}$$

$$SHmax = PR1\text{-}PR\,(S_V - \alpha PP) + \alpha PP + YMS1\text{-}PR2\epsilon Hmin + YMS\,PR1\text{-}PR2\epsilon Hmax \qquad \textbf{Eq- 4}$$

where PR is the Poisson's ratio, S_V is the vertical stress or the overburden stress, α is Biot's coefficient, PP is formation pore pressure, YM_S is the static Young's Modulus, $\epsilon Hmin$ and $\epsilon Hmax$ are the minimum and maximum horizontal strain and represent the tectonic contributions to closure pressure.

Stress direction determination

Borehole breakouts and Drilling induced tensile fractures (DITF), if visible on an image log, aid in constraining the horizontal stresses direction. The presence of any one of the two on an image log alone is sufficient. These image logs could be acoustic image log or resistivity image logs. The direction of the stresses was ascertained using the resistivity image log (FMI) recorded in the study. Borehole breakout occurs when the circumferential stresses around the well bore exceed that required to cause compressive failure of the borehole wall (Zoback et al 1985). DITFs occurs when the minimum circumferential stress around the wellbore is less than the tensile strength of the rock (Peska, Zoback 1995). The wellbore breakouts and the drilling induced tensile fractures (DITFs) tend to form in the direction of S_{hmin} and S_{Hmax} respectively. Figure 2 (left image) shown below DITF direction in Well A is 80-90^0 which is the S_{hmax} direction. In the same figure (right image) shows breakouts oriented in 120-130^0 which is the azimuth for S_{hmin} in Well C. As the principal stresses are orthogonal to each other, the azimuth of S_{Hmax} in Well C is 30-40^0. In similar manner the horizontal stresses direction for the other three well was determined.

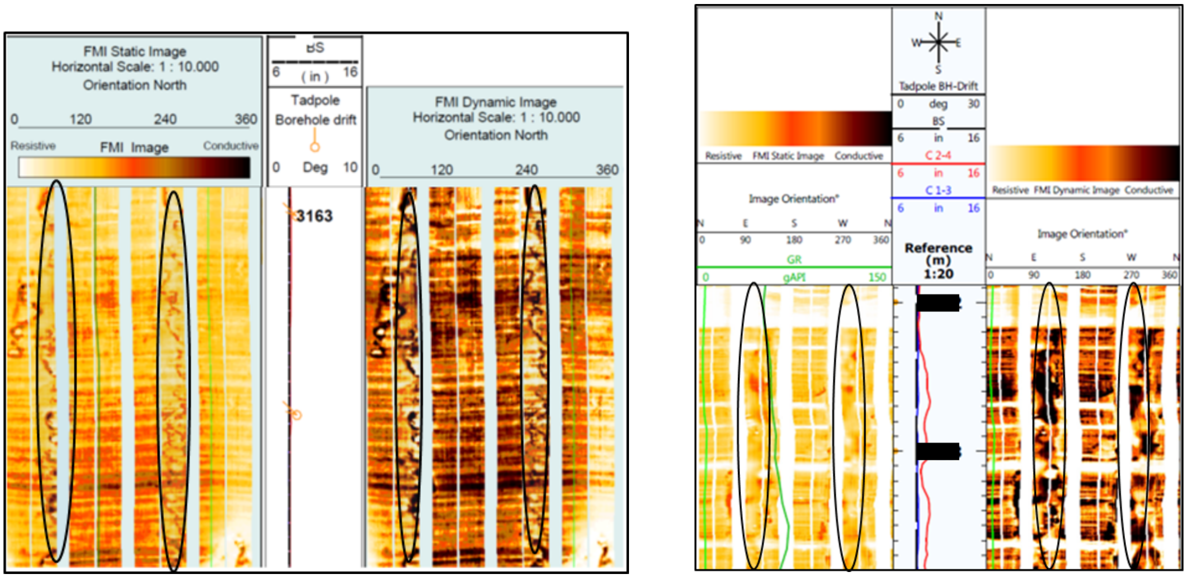


Figure-2: DITFs in Well A oriented 80-90^0 shown in Image to the left, Breakout in Well C oriented 120-130^0 shown image to the right.

Results and Discussions

The magnitude of the three principal stresses were compared w.r.t. each other to arrive at the fault regime in the area after using the classification given by Anderson (1951). The classification is mentioned below.

Normal Fault Regime	Strike Slip Fault Regime	Reverse Fault Regime
$S_v > S_{Hmax} > S_{hmin}$	$S_{Hmax} > S_v > S_{hmin}$	$S_{Hmax} > S_{hmin} > S_v$

It is seen from the results of magnitude comparison that Cambay Shale in the area lies within Normal to Strike Slip fault regime. Stress direction was also ascertained as discussed previously. The direction of the Maximum Horizontal Stress (S_{hmax}) for the five wells is shown in the Figure 3. It is observed that the Maximum Horizontal Stress (S_{hmax}) is oriented in ENE to NE direction.

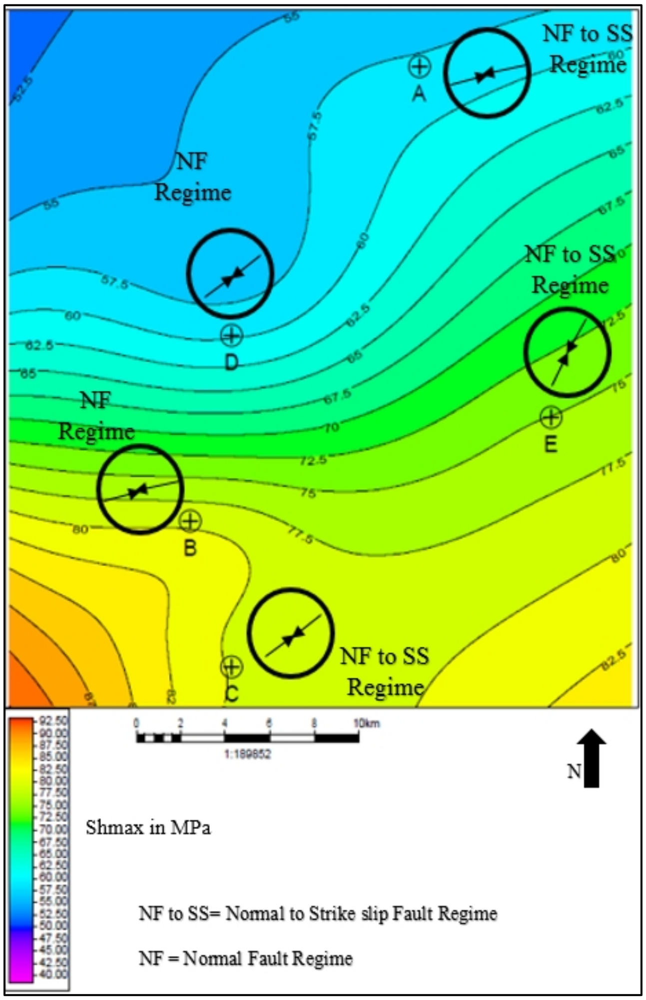


Figure-3: Contour Map of Maximum Horizontal Stress Magnitude and its direction at each well.

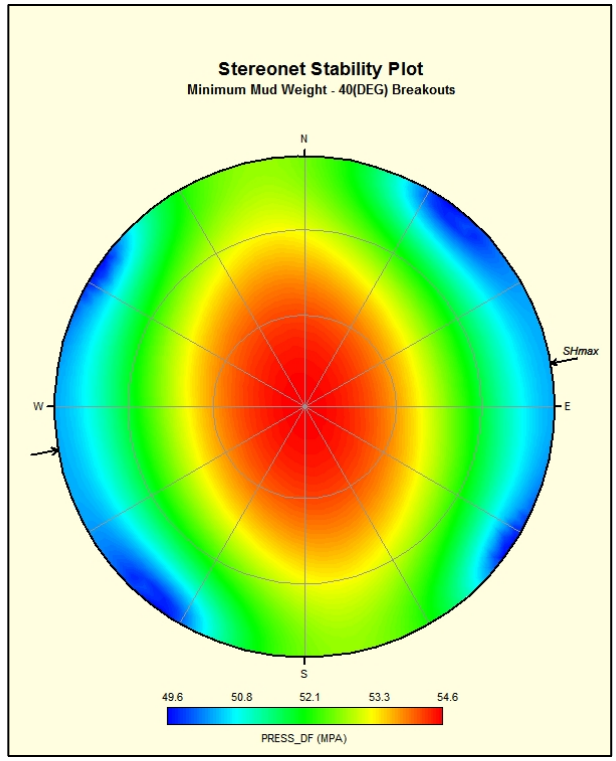


Figure-4: Wellbore Stability plot for a given depth in Well E

The stress magnitudes, directions, rock mechanical properties and pore pressure are used as an input for making wellbore stability plots. These wellbore stability plots suggest the optimum mud weight required to drill the wells in any direction at different angles. As seen from wellbore stability plot (Figure 4) the optimum direction of drilling horizontal well from Well E would be NE-SW where least mud weight will be required to drill the well in a stable manner.

Shale exploration and exploitation requires hydro fracturing therefore objective is not only drilling a stable well but also placing well in the direction of optimal production results. Development drilling of shale plays needs placing horizontal wells in the direction of the minimum horizontal stress so that the hydraulic fractures propagate perpendicular to the wellbore thereby maximizing the reservoir contact area and better production results. Therefore if a horizontal well is drilled from Well position E, placing it in S_{hmin} direction at that point which is NW-SE will give better production results. The wellbore stability concern in the horizontal well can be overcome by maintaining the mud weight in that direction as illustrated in Figure 4. The direction of the stresses do not vary much in studied wells as can be seen from figure-3 therefore the horizontal wells for optimal production results may be placed in the NW-SE to NNW-SSE direction which is the S_{hmin} direction for the study area.

The horizontal stress is an input in hydraulic fracturing design. Incorrect horizontal stress profile prediction results in undependable vertical fracture growth estimation thereby jeopardizing the vertical fracture containment. The vertical fracture propagation is controlled by the net pressure imposed during fracture propagation and constrained by the stress contrast between the stratigraphic layers (Ahmed 1988). In Figure 5 the hydraulic fracture geometry along with the horizontal stress for one of the objects in Well C is shown. It is clearly evident from the figure that the vertical growth of the hydraulic fracture is limited by the stress barriers. Therefore the closest estimates of the magnitude of the stresses is required for better fracturing design.

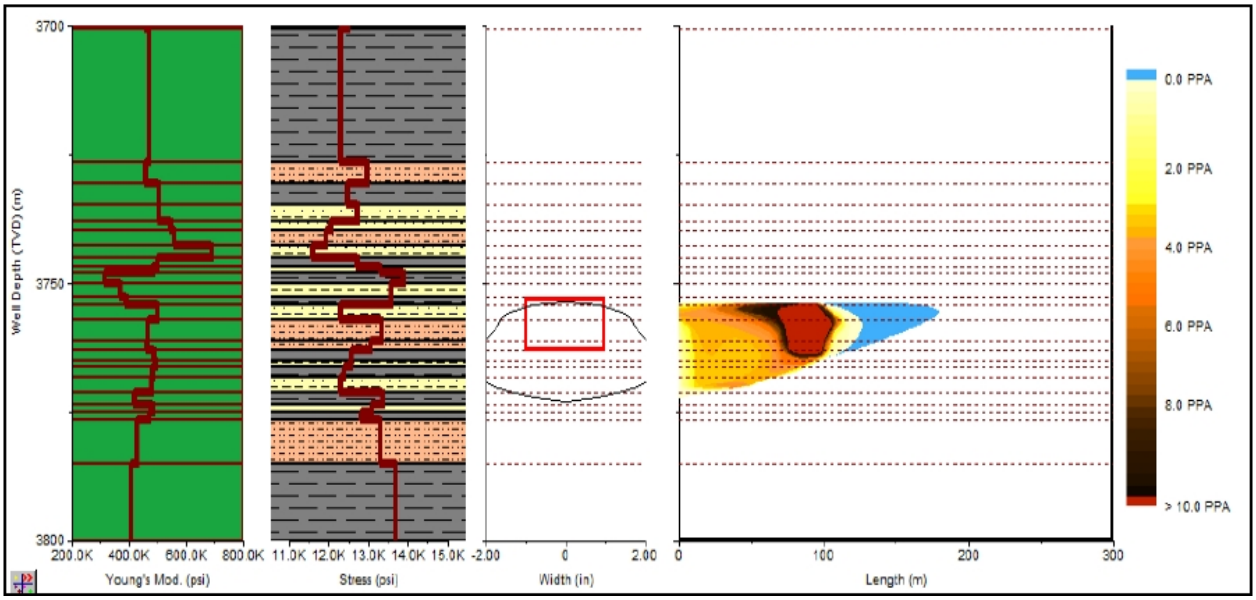


Figure-5: Hydraulic Fracture geometry along with horizontal stress magnitude (source: Schlumberger Post HF report for Well C)

Conclusions

The outcomes of study suggests that the insitu stress regime in the South Cambay Basin is Normal to Strike Slip Fault regime. The Maximum Horizontal Stress direction as seen from the five wells for the area is ENE-WSW to NE-SW. The most optimum direction for drilling horizontal wells in the area for effective hydraulic fracturing and maximum production would be NW-SE. The wellbore stability concern can be addressed by using the wellbore stability plots for optimum mud weight with help of inputs from the Mechanical Earth Model. The computed values of the Young's Modulus are less than 20 GPa. The Poisson's ratio values are greater than 0.25. These values suggests that the shales are relatively ductile therefore will be less responsive to hydraulic fracturing.

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