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Critically Stressed Fracture- the key to optimal production from Basement- A case study from Pundi Field of Cauvery Basin

Abstract:

Hydrocarbon have been under production from basement rocks round the world for many decades. Since late 20th Century, there has been a growing interest in exploration & exploitation from these formations where matrix porosity is negligible and storage and production are dominated by fracture system. In basement reservoirs, natural fractures and faults are the primary pathways for fluid production. Natural fractures & earth stresses currently acting on them control the apertures of the fractures & hence the permeability. Sets of fractures favourably oriented to fail in shear under the present-day stress field are said to be critically stressed (CSF).

In this work Geomechanical work flow for identification of CSF for granitic basement of Pundi Field has been discussed considering four wells of Pundi field depending on the availability of image data & other logs. The production behaviour of key wells were found to be in line with our findings.

Introduction:

Pundi field, located in the northern part of Tanjore sub-basin (Fig. 1), lies on the rising flank of Kumbakonam Madanam horst. . Cauvery Basin is an intra-cratonic rift basin, divided into a number of sub-parallel horsts and grabens, trending in a general NE-SW direction. Tanjore Sub basin is a major tectonic feature in Cauvery Basin. It is one of the rift related features of NE-SW trending features which make the framework of the basin. This Sub basin is a host to a thick pile of sedimentary succession (Fig. 2) ranging in age from Albian to recent. Thick shales belonging to Andimadam formation are the source facies.

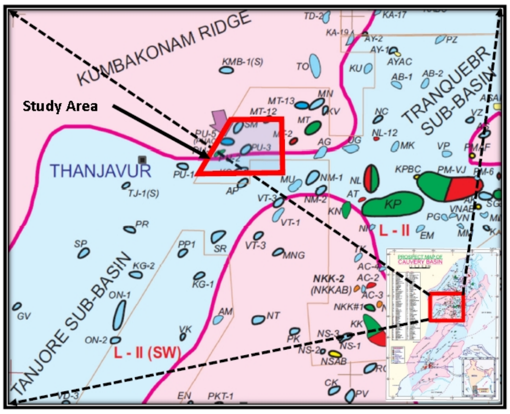


Fig.1: Location Map of the Study Area

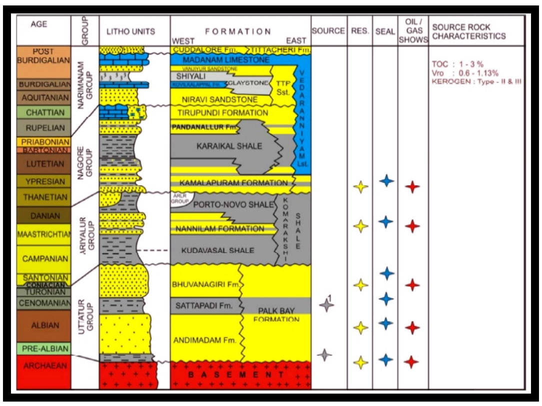


Fig. 2: Generalized stratigraphy of Cauvery basin

Seven wells have been drilled in the field. Out of these seven, 4 wells have been proved to be hydrocarbon bearing in the basement section. In basement reservoirs, natural fractures and faults are the primary pathways for fluid production. Natural fractures (i.e. those induced by paleo geostresses) and the geostresses currently acting on them control the apertures of the fractures and hence control their permeability. It is believed that critically stressed fractures (CSF) tend to slide and dilate and thus they can serve as highly efficient pathways for fluid migration. The stress regime acting in the reservoir and the orientations of fracture sets in relation to these stresses have a major control on the productivity of the fractured reservoirs. We can therefore argue that identification of CSF's becomes all the more important in a fractured basement to forecast a sustained production and additionally the direction of these CSF's may give further lead during the placement of future wells.

In this paper we focus on developing a workflow that integrates geomechanics, geology, and petrophysics to identify critically stressed and open fractures. High-resolution resistivity images integrated with the Stoneley response have been used to identify the natural open fractures and faults and their orientation. A mechanical earth model (MEM) is then constructed to estimate the prevailing stress state. The fracture and fault planes are finally subjected to the prevailing stress state to see if they are likely to slip. If yes, they are flagged as critically stressed.

Critically Stressed Fracture Methodology:

The critically stressed fracture analysis consist of following steps (Fig. 3):

1. Characterization and identification of the orientation of natural fractures from image logs.
2. Estimation of magnitude & direction of the three principal in-situ stresses acting in the reservoir.
3. The far filed in-situ stress tensor is projected onto the fracture plane to give the normal and shear stress acting on the plane.
4. Comparison of the stresses, plotted on a normalized Mohr-Coulomb diagram, and compared to the fracture shear failure envelope.
5. Classification of the fractures as critically stressed if the ratio of shear to normal stress exceeds the shear failure fracture envelope.

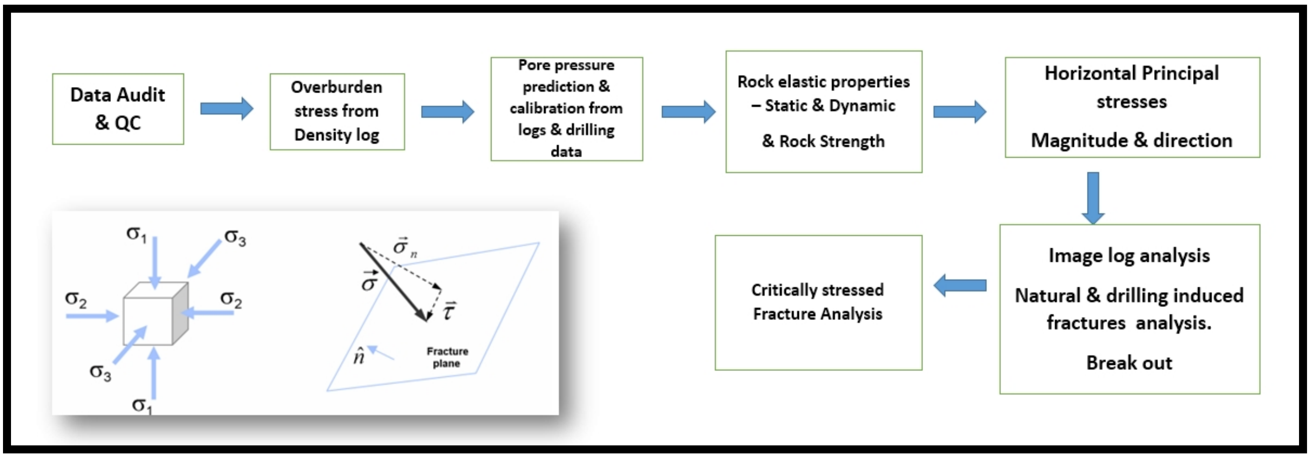


Fig.3 Work flow for Critically Stressed Fractures

Critically stressed fracture identification has several important implications on fluid flow behaviour through naturally fractured porous media. Barton et al, verified that fluid flow in fractured rocks is largely controlled by critically stressed fractures; therefore, this analysis may help to identify producing fractures.

In situ stress Estimation:

The in-situ stress tensor in a reservoir is a 3-dimensional second order tensor with three principal stresses (σ_1, σ_2 and σ_3).

Overburden Stress:

The overburden stress at any point below the surface is the weight of overlying sediments and can be estimated by integrating the density log for the above formations. Overburden stress is computed by integrating formation density using the equation below.

$$Sv= 0z\rho dzg$$

As the density log were not available up to the surface, the densities of the shallow formations were estimated from acoustic velocities, while the density log was used in the deep formations to integrate the overburden stress. The vertical stress gradient obtained in well- A, B, C & D was about .9 psi/ft.

Horizontal stresses:

The magnitude of minimum horizontal stress is normally estimated from the overburden (σ_{v}), Poissions's ratio, pore pressure (P_p) & Biot's poroelastic parameter (α) . Poro-Elastic Horizontal Strain Model discussed by Bratton (1999), takes the tectonic strains into account and therefore accommodates the anisotropic horizontal stresses.

Assuming flat-layered poro-elastic deformation in the formation rock, a pair of particular constant strains, $\in Sh$ and $\in SH$ are applied to the formation in the directions of minimum and maximum stress respectively. By adjusting these strains, we can calibrate the calculated stresses with the measured horizontal stresses at depth.

For a fluid saturated porous material that is assumed to be linear elastic and isotropic, considering anisotropic tectonic strain, the horizontal stresses (σh and σH) are equal to:

$$\sigma h = \nu 1\text{-}\nu \sigma V\text{-}\nu 1\text{-}\nu \alpha\ Pp + \alpha\ Pp\ +\ E 1\text{-}\nu 2\ \epsilon h + \nu E 1\text{-}\nu 2\ \epsilon H$$

$$\sigma H = \quad \nu 1\text{-}\nu \sigma V\text{-}\nu 1\text{-}\nu \alpha \quad Pp + \quad \alpha \quad Pp + \quad \nu E 1\text{-}\nu 2 \quad \epsilon h + \quad \nu E 1\text{-}\nu 2 \quad \epsilon H$$

Where: ϵh is the minimum principal horizontal strain, ϵH is the maximum principal horizontal strain, E is the Static Young's modulus, v- Poisson ratio, α: Biot's constant, σV overburden stress, and Pp is pore pressure.

The magnitude of this theoretical horizontal stress needs to be calibrated with field data. When mini-frac or micro frac data are not available, the magnitude of the horizontal stresses could be back calculated from borehole breakouts and induced fractures observed on image logs.

The direction of horizontal stress can be estimated from resistivity image logs (FMI / STAR/XRMI) by looking at the orientations of drilling breakouts or drilling induced fractures. Similar inference can also be drawn from a 4-arm calliper by identifying breakouts and their orientation. Tools like DSI, XMAC or Sonic Scanner respond to stress anisotropy if recorded in cross-dipole mode.

Results

Four wells PU-A, PU-B, PU-C & PU-D have been considered for the present study depending upon the availability of image log data. The basic 1D MEM (consisting of Pore pressure, Fracture pressure, Overburden & Horizontal stresses) of these wells were prepared in Techlog. The image log for all the four wells were processed & dip and azimuth of naturally occurring fractures were picked and analysed. All these information were loaded in Geolog's Geomechanics module to get CSF's in these wells.

The image log of well PU-B shows borehole failure in the form of break out (Fig. 4) and drilling induced tensile fracture (Fig. 6). From the image log the direction of SH_{max} is taken as NW-SE (Fig. 5)

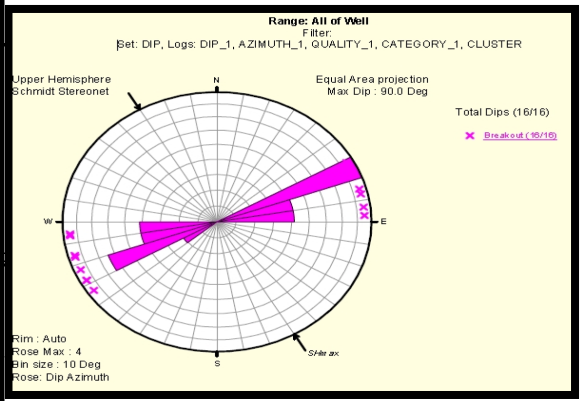
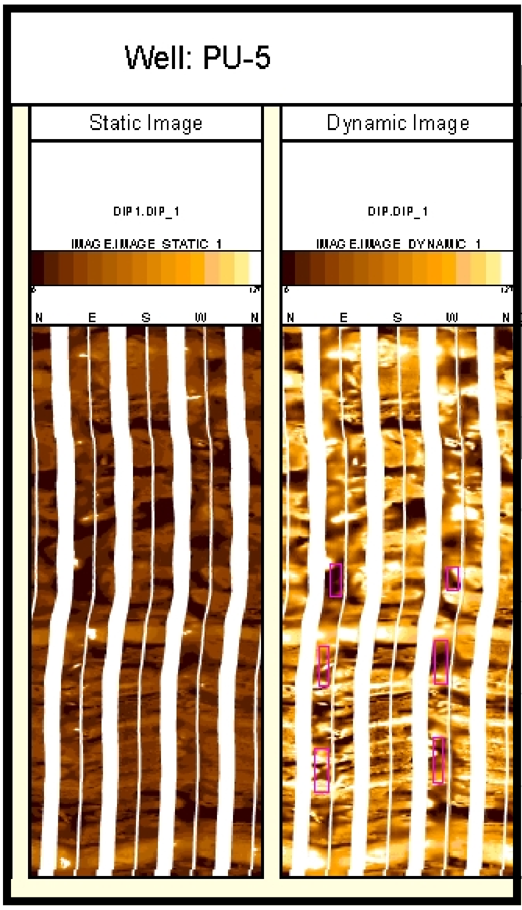


Fig.4 Rose diagram showing Breakout in well PU-B



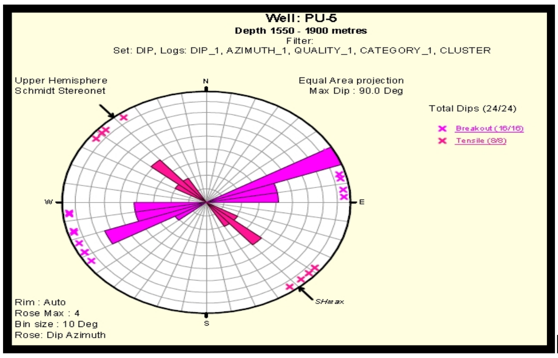


Fig.5 Bore hole breakout seen in PU-B

Fig.6 Rose diagram showing DITF in well PU-B

1D MEM of four wells has been modelled. In well PU-A, 109 m of weathered basement is encountered. A good number of critically stressed fractures are seen in the direction NW (Fig 7). This is in line with the production behaviour of well PU-A which flowed oil @ 3.3 m^3/day through 6 mm bean.

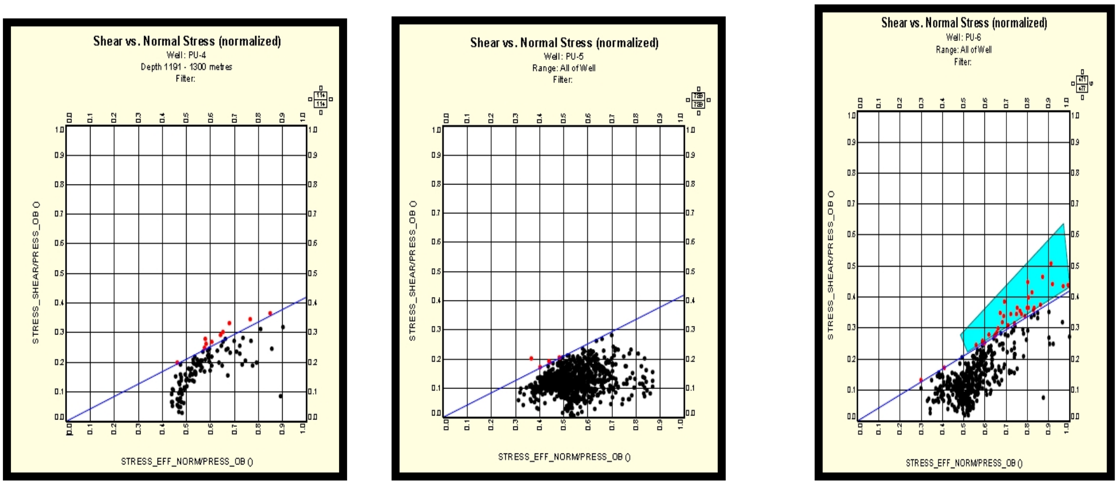


Fig. 7 Normalized Mohr's diagram of Wells PU-A,B &C respectively

Well PU-B lies in a different fault block. A good number of natural fractures are seen on the image log in the basement section, which is not supplemented by Sonic scanner/ DSI logs. CSF analysis (refer to Fig .7) shows that the natural fractures are not critically stressed in the present day stress and this is also validated by the fact that the well PU-B did not show any sign of hydrocarbon shows and was declared as dry and abandoned. Inspite of presence of good fracture aperture and density (Fig.8), the well did not produce any hydrocarbon.

In Well PU-C during the drilling, hydrocarbon shows PYF and faint cut were observed in both Bhuvanagiri and basement sections. The object-I in the interval 1187.5-1330 m (basement) was tested with slotted casing. On activation, well flowed oil@ 40m3/day thru 6 mm bean. Basement section at the top is weathered. Fractures are observed throughout the section. The major fracture strike direction is observed to be almost in EW direction. The DSI log has been processed for energy and time shear anisotropy. The energy anisotropy at the top of the basement may be due to the open fractures. The pore pressure from sonic log shows a normal gradient. The CSF are mostly oriented in NW-SE direction and they are in good number. This is in line with the fact that the basement has produced good quantity of oil.

In Well PU-D hydrocarbon shows in the form of specky PYF and faint cut were observed during drilling of basement in the interval 1248-1285 m. Basement on testing flowed oil with poor influx. Cumulative oil of 32 m3 was collected during testing. With SRP the basement produced oil @27 m3/day & gas @2150 m3/day. The major fracture strike direction in Pundi filed is observed to be almost in EW direction from the image logs recorded in wells PU-A, PU-C & PU-D. CSF analysis on Mohr-Coulomb plot shows that large number of fracture points cross the failure line. The well is on production from basement with SRP. This corroborates our finding from this study that presence of CSF enhances the production from basement section.

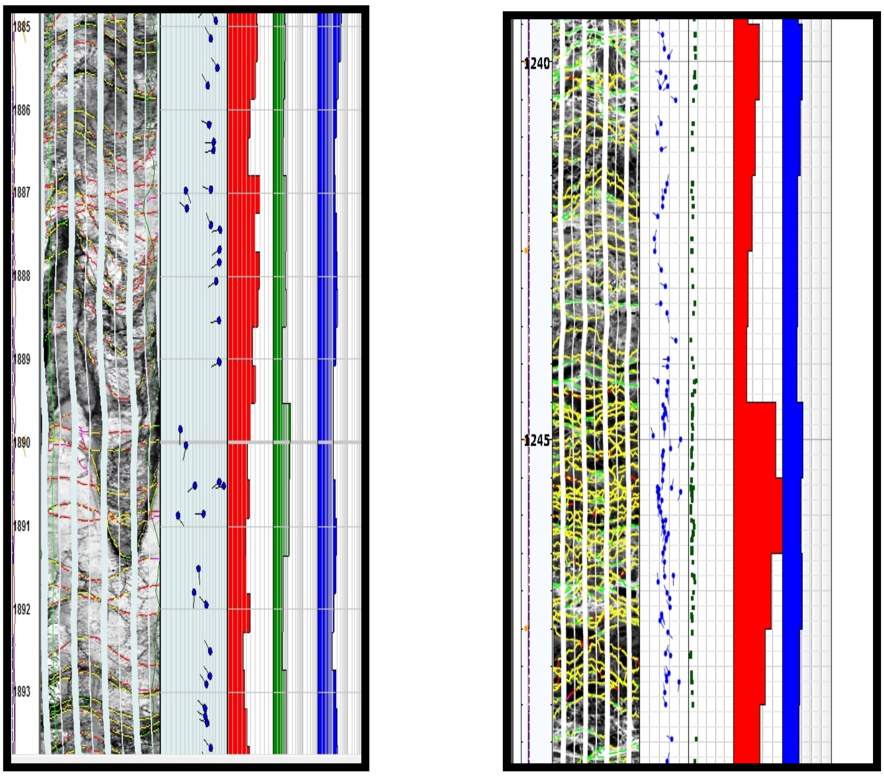


Fig.8 Fracture aperture and density of PU-B & C respectively.

Conclusions

The CSF analysis was performed on 4 wells where detailed image log analysis and natural fracture characterization was available. Analysis suggest that the NE-SW direction corresponds to the minimum horizontal stress orientation, is the preferred trajectory of horizontal wells in terms of mud weight requirement.

1D MEM of all the wells indicate that the pore pressure in the basement section is hydrostatic. Based on the borehole breakout seen in well PU-B, and DITF in PU-C the present day maximum horizontal stress direction can be approximately taken as NW-SE. Occurrences of DITF in basement even while drilling with a mud-weight of 1.14 sg indicate towards high stress regime.Consequently, the stress regime in the basement section has been considered as strike-slip for estimation of the magnitude of maximum horizontal stress.

The critically stressed fractures are broadly aligned in the direction of maximum horizontal stress (i.e. NW-SE). Hence wells drilled in the orthogonal direction are likely to cut across maximum number of CSF's.

Good number of the natural fractures are seen in Wells PU-A, PU-C & PU-D. Maximum no. of fractures are critically stressed in PU-C and PU-D as compared to PU-B. These are the fractures which are potentially productive. This is in agreement with the observed production trend from these wells.

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