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Tight Synrift Reservoirs : Relevance of Geomechanical Modelling to enhance hydrocarbon productivity

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Abstract

Significant discoveries of oil and gas within tight reservoirs of Synrift Plays, is being pursued vigorously through focused exploration. Considering the tightness and low permeabilities of reservoir sequence encountered, hydrofracturing and specific stimulation jobs are required to establish commerciality. Hence, to aid HF designing, geomechanical modelling SRI and Malleshwaram area was taken up. Development of deep tight oil and gas reservoirs offers numerous challenges, including production and recovery rate estimations. Generation of a comprehensive geo-mechanical model for Synrift sequence will lead to improve production potential and formulation of Appraisal & Development Plan at a later stage.

Geomechanical model has been generated through integrating basic petrophysical logs, dipole sonic data, rock mechanical tests on core, processed image log data, seismic, regional tectonic history and drilling data. Petrophysical and rock mechanical studies were carried out on 22 plugs from 8 cores of Nizampatnam and Malleshwaram areas to calculate parameters such as porosity, permeability, grain density and bulk density. These were used for calibrating electrologs of SR, MS and BN wells, thus providing a better geological and geophysical understanding of synrift sequence. Pore pressure, fracture gradient, overburden gradient and minimum and maximum stress magnitudes were generated & calibrated.

Stress directions identified from FMI data indicate SH_{min} 20°-40° N and 200°-220° N and SH_{max} 110°-130° N and 290°-310° N. Study suggests normal pressure regime in Nizampatnam area with pore pressure values 6500psi - 7500psi within Synrift sequence. Mohr-Coulomb plots for wells indicate failure zones parallel to SH_{max} (ESE-WNW). Average fracture pressure value ranges between 0.62-0.64 psi/ft. Findings provide required inputs for HF designing and planning for lead perusal of the pays encountered in tight synrift reservoirs.

1. INTRODUCTION

Petroleum geomechanics is defined as the interaction between the evolving earth stresses and the overburden and reservoir rock mechanical properties.(Jaeger & Cook, 1979). A comprehensive understanding of rock mechanical behaviour is key to successful field appraisal and development.(Fjaer et al, 1992). About 70% of the world's oil and gas reserves are contained in reservoirs where rock failure and sand production becomes a problem at some point. A reliable and robust predictive geomechanical model can address these issues. (Barton et al, 2009).

A significant oil discovery in a synrift reservoir was made in KG onland and shallow water block in Nizampatnam Bay. A considerable net pay thickness was encountered, but is tight and also having High Temperature conditions. For lead perusal and appraisal, HF was planned, followed by subsequent development plan. As HF is a highly cost intensive procedure, especially in the offshore, it requires meticulous planning. It was envisaged that Geo-mechanical studies would provide the necessary inputs for proper planning of HF jobs. Oil discovery from synrift sediments in Malleswaram area in Bantumili graben and promising lead (gaseous presence on logs) in Kottalanka area has provided significant impetus to the exploration of hydrocarbon within syn-rift sequence not only in Nizampatnam and Bantumili graben, but also entire basin.

In Krishna-Godavari Basin, commercial accumulation of hydrocarbons is observed in reservoirs of Triassic to Pleistocene age in sediments ranging from late Permian to Recent overlying Pre-Cambrian crystalline basement (Fig.1.).

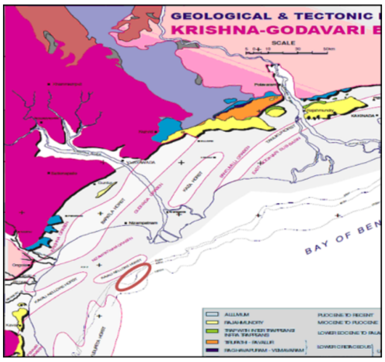

Fig.1: Geological map Krishna Godavari Basin

Optimal use of conventional and unconventional HC reservoirs depends, amongst other things, on local tectonic stress field. Wellbore stability, orientation of hydraulically induced fractures and – especially in fractured reservoirs – permeability anisotropies are controlled by present-day in situ stresses. Faults & lithological changes lead to stress perturbations and produce local stresses that can significantly deviate from the regional stress field. Geomechanical reservoir models aim for a robust, ideally "pre-drilling" prediction of local variations in stress magnitude and orientation. Numerical modelling approach is capable to incorporate specific geometry & mechanical properties of subsurface reservoir. Workflow incorporated can be used to build 3-D geomechanical models based on finite element (FE) method and ranging from field-scale models to smaller, detailed sub-models of individual fault blocks.In situ stresses predicted by geomechanical FE model were calibrated against stress data actually observed, e.g. Borehole Breakouts & LOTs. Such validated models provide insights into the stress perturbations in inter-well space and undrilled parts of the reservoir. In addition, tendency of the existing fault network to slip or dilate in the present-day stress regime can be addressed.

2. TECTONICS AND SEDIMENTATION

KG Basin has a series of rift axis parallel highs and lows trending broadly NE-SW in an en- echelon pattern (Fig.2.). Further, the structural disposition of the basin elucidates presence of Pithapuram, Chintalapudi, Avanigada and Ongole cross-trends from northeast to southwest. In the onland part, the basin is characterized by Krishna, West Godavari and East Godavari sub-basins, which are separated by Bapatla and Bhimavaram-Tanuku Highs (Fig.2). The major tectonic high and low trends extend further in the offshore part. It is envisaged that the earliest marine transgression occurred during Berriasian age (lower part of Early Cretaceous). The Synrift sediments were deposited during early tectonic subsidence of initial rifting and further accentuated by basement rifted fault systems.

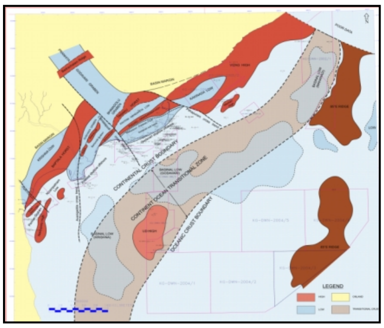

Fig.2: Tectonic map of Krishna Godavari Basin

3. STRATIGRAPHY

The stratigraphy of Krishna Godavari Basin ranges from Permian to Recent and on basinal scale there is a wide vertico-lateral litho variation. The prevailing lithostratigraphy includes a large number of litho units on regional / sub-regional scale. In the north-western and western margins of the basin, outcrops of Pre-Cambrian crystalline and sediments ranging in age from late Permian to Pliocene are present. The offshore sequences are not well correlatable with the onland / shelfal part due to lateral change of facies and growth related tectonics in shelf and slope areas (Fig.4). Onland sedimentary sequence starting with the Gondwana (Kommugudem and Mandapeta Formation) sediments of Permo-Triassic age, followed by late Jurassic to early Cretaceous Golapalli, Kanukollu, Nandigama, Krishna and Gajulapadu shale and late Cretaceous Raghavapuram and Tirupati / Chintalapalli formations. Tertiary sequence starts with Razole volcanics of Paleocene age followed by Palakollu Shale of early to late Paleocene age and Pasarlapudi Formation of early Eocene age which is overlain by Bhimanapalli limestone / Vadaparru shale of middle Eocene age. Matsyapuri sandstone and Narsapur Formations of Oligo-Miocene age, Ravva and Rajahmundry sandstone Formation of Miocene age and Godavari Clay of Pliocene-Pleistocene age show lateral facies variations towards offshore. The envisaged petroleum system constitutes the Synrift petroleum system, having established both Liquid and Gaseous hydrocarbons. In addition, Pre-Rift petroleum system is also envisaged. Hydrocarbon migration is envisaged to be through fault conduits and carrier beds.

Reservoir characterization of synrift : Gross lithology of syn-rift reservoir constitutes thick massive sandstone, off-white, hard, compact, coarse to pebbly, poorly sorted, feldspar rich matrix, occ. feebly calcareous. Claystone clasts and asphalt are impregnated at places. Visual porosity is moderate to poor. Two cycles of deposition i) fining up channel sandstone ii) amalgamated sandstone is observed. Sedimentary features include planar cross bedding, sub parallel bedding, abrupt bedding contacts at places micro faulting is evident and poor sorting collectively indicate fluvial briaded channel sand.
Petrographic evaluation showed extreme grain size variation, angular to sub rounded, poor sorting, matrix rich. Texturally immature wacke type reservoir facies

SEM analyses depicts micro porosity, resulting in tight packing of framework grains. Sporadic micro pores are discernable. Pore lining rosette chlorite is noticeable, and abundance of fibrous illite in association with smectite; extensive altered feldspar and clay authigenesis is observed.
Pore bridging filamentous illite and water absorbent smectite are detrimental to the quality of reservoir, thus affecting fluid mobility.

4. Geomechanical Modeling

Methodology

Integrated interpretation of Well log, additional well data, and Petrophysical Laboratory core data is undertaken in the present study to bring out an geomechanical model Nizampatnam-Pennar area of Krishna Godavari Basin. (Fig.3).

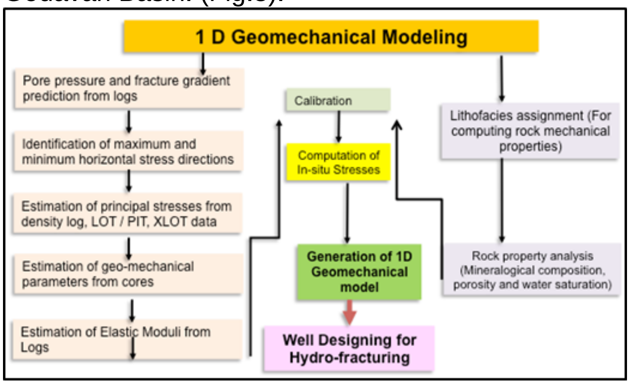

Fig. 3. Work-Flow adopted for Geomechanical Modelling

The inputs for Geomechanical 1D modeling included (a) Core plugs for Petro-physical studies, b) Facies and Quality of reservoir / non-reservoir (c) Faults, its vertical extension, (d) structural configuration, e) electro-logs and drilled well data. (Ljunggren et al, 2003).

Well Log Studies

Well data of 3 wells is selected for geomechanical study of KG-OSN-2009/2 block. The data included mud weight maintained during drilling, casing details, MDT record, production testing record, LOT/PIT record, lithological information collected from the well bore along with density, porosity, velocity information. The data set were utilized to generate 1D geomechanical models for these wells through Predict module of Drillworks software.

Pore pressure gradient, fracture gradient, over burden gradient, minimum and maximum stress magnitudes were estimated and the Stress directions are identified from FMI data. (Perumalla et al, 2009). In this method shale is chosen as the reliable compaction trend indicator and it was discriminated out of the sand. The methodologies for calculation of different geomechanical parameters are described below.

Overburden Gradient : Over Burden Gradient (OBG) is calculated by integrating density log from top to bottom of the well. Well sections with missing density log synthetic RHOB was generated using DT or VSP data by using Gardner's method and Miller's method (for shallow depth). The OBG is used for pore pressure and fracture gradient calculations.

Normal Compaction trend : Development of normal compaction trend was determined through selection of shale point on lithology curve. Based on shale intervals selected on lithology curve corresponding values in shale intervals of porosity-indicating dataset (i.e. Resistivity and/or DT) were integrated to generate normal compaction trend by drawing line on the track based on resistivity data or from Sonic data using Miller or Bower's sonic equation.

Pore Pressure Gradient: Pore pressure gradient is generated using all the above inputs by Eaton's sonic or Bower's sonic methods.

Fracture Gradient: Finally fracture gradient is calculated using pore pressure gradient and OBG as inputs.

Stress Magnitudes: Fracture gradient is taken as minimum stress magnitude, as it gets validated by LOT/PIT data. The maximum stress magnitude is generated from OBG and Minimum stress magnitude.

Near-wellbore stress analysis: The near well bore stresses, effective tangential stress, effective radiean stress and effective axial stress is calculated using the OBG, PP and FG as an input.

5. Results

Stress direction analysis
The FMI data of SRA and SRB is used to get the stress orientation in the wells. The breakouts indicate the minimum stress direction to be in the range 20^0-40^0 North and 200^0-220^0 North (i.e. NNE-SSW direction). The maximum stress direction will be around 110^0-130^0 North and 290^0-310^0 North (i.e. ESE-WNW direction) (Fig.5 & 6.).

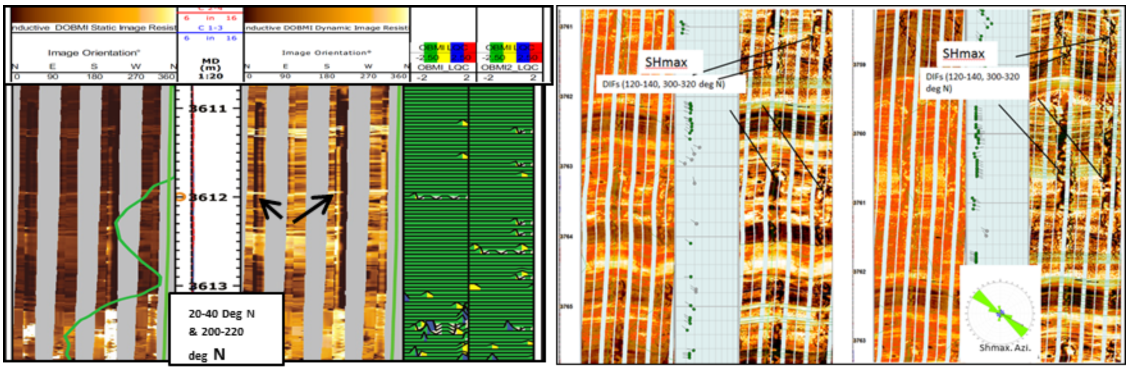

Fig-5: Minimum stress direction from SRA and MS well

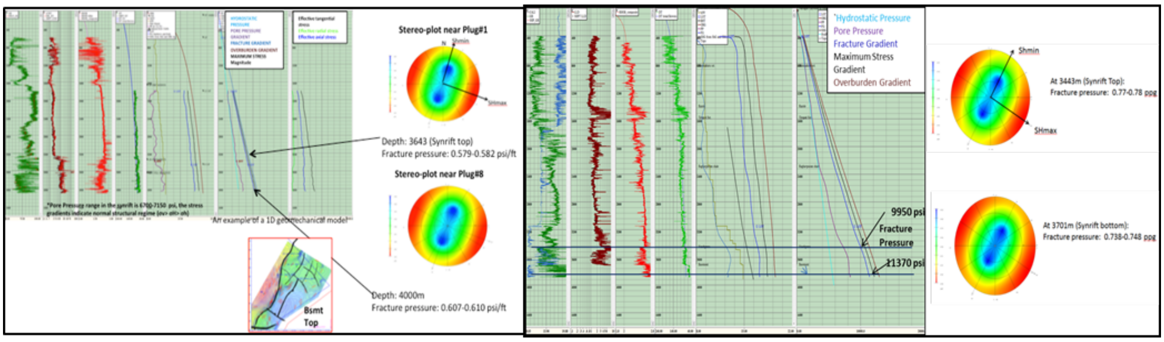

Fig.6. Mohr-Coulomb Stereo plots displaying mud weight requirements at SR and Malleshwaram can used in pre-drill UBD feasibility assessment.

Petrophysical & rock mechanical studies of core

Rock mechanical properties viz. Elastic Moduli and Poisson's ratio are estimated from core plugs of the SRI wells at at varying pressures (500-4500 psi). The porosity, permeability, grain density and bulk density of 8 plugs were measured with "Automated multi-sample **porosimeter-permeamert** (KEYPHI) equipment at 1000 psi confining pressure. Results are tabulated in Fig. 7 and were used for other calculations and calibration.

S.NO	Plug no.	Depth of the core plug (m)	K(he) (mD)	Liquid permeability	Φ (%)	Grain density (gm/cc)	Bulk density (gm/cc)
1.	SR-1	***3680.57***	0.442	0.113	11.36	2.617	2.320
2.	SR-2	***3684.14***			Plug damaged		
3.	SR-3	***3685.71***	0.496	0.150	12.64	2.549	2.227
4.	SR-4	3793.27	0.911	0.314	14.24	2.508	2.151
5.	SR-5	3797.18	0.768	0.254	11.65	2.536	2.241
6.	SR-6	3797.98	0.296	0.061	12.99	2.551	2.220
7.	SR-7	3799.96	0.745	0.267	11.52	2.549	2.255
8.	SR-8	**3913.94**	0.441	0.116	10.50	2.574	2.304

Fig. 7. Rock mechanical parameters were measured at varying pressures (500-4500 psi)

Pore Pressure Gradient

The study provides a continuous record of pore pressure, fracture and over burden gradient for the reservoir section. The mud weight that is used in a well during drilling should be in between Pore Pressure Gradient (PPG) and Fracture Gradient (FG) to avoid drilling complications. If the specific gravity of drilling fluid used is higher than FG, there will be mud loss and if the specific gravity of drilling fluid is less than the pore pressure, we may encounter kicks, washouts and blowouts.

Model calibration

Before any conclusions can be drawn from the geomechani- cal model, it has to be calibrated, i.e. the modelling outcome has to be compared to stress data actually observed. Subse- quently, the fit is improved by iteratively adjusting poorly constrained parameters, such as the friction coefficient of the faults and the magnitude of the maximum horizontal stress, within geologically reasonable limits. (Fig.8).

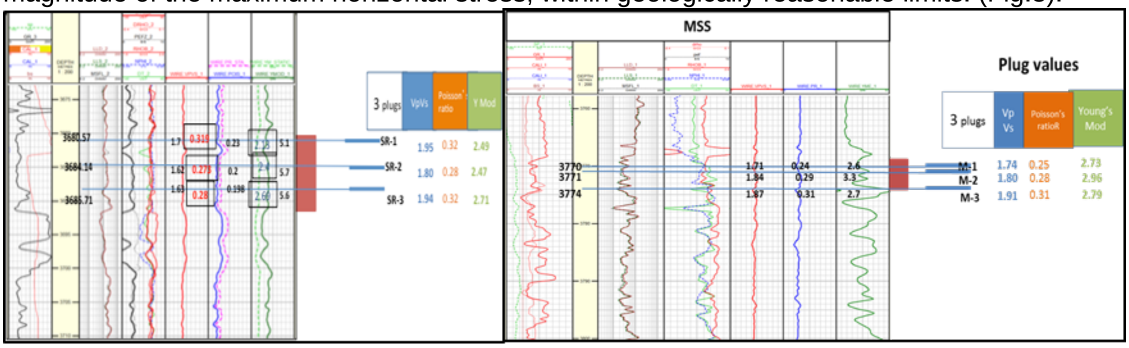

Fig. 8. : Calibration of well-log studies with Core plug analysis from SR and Malleshwaram

The model was validated by all reliable calibration data reproduced within the assumed ranges of measurement errors. Following this calibration process, the validated geomechanical model was then used for stress and strain analysis of the drilled section.

6. Discussions

The geomechanical model suggests a normal stress regime (Sv>SH>Sh) for the wells SRA, SRB & SRC. Maximum horizontal stress is oriented in N110^0-N130^0 and N290^0-N310^0. The Synrift sequence in these wells is analyzed for well bore stability and it is sensitive to borehole inclination and azimuth in the present day stress regime determined by geomechanical model.

The vertical wells and well inclined up 45^0 deviated in N30^0 – N210^0 require minimum pressure gradient to prevent shear failure. The horizontal wells oriented parallel to the Hmax would require maximum pressure/M.Wt. to prevent failure zones within the well making them most unstable well orientation (Fig. 8).
GeoMechanical model for SR and Malleshwaram area also suggests that vertical Hydraulic Fractures oriented parallel to maximum stress direction will form and boreholes deviated parallel to Hmax direction (N110°±20°) will require minimum fracture initiation pressure to generate hydraulic fractures. Average fracture pressure value ranges between 0.62-0.64 psi/ft within synrift sequence for SRA and 0.58-0.61 psi/ft for SRB.

7. Conclusions

The results of geomechanical model can be used to build and validate geomechanical models of reservoirs at field-scale or specific fault blocks. The workflow is applicable to all kinds of stress-sensitive reservoirs including conventional and unconventional hydrocarbon as well as geothermal reservoirs. (Shah et al, 2010). Pore pressure values within Synrift sequence lies between 6500psi to 7500psi. The magnitudes of vertical stress, minimum horizontal stress and maximum horizontal stress calculated from geomechanical model indicate a normal stress regime in the area.
The FMI image log data of wells SR and Malleshwaram indicate maximum horizontal stress direction is oriented in N110° - 130° and N290° - 310° (i.e. ESE-WNW direction).The minimum stress magnitude in the well SRA over the Synrift interval (3740-4000m+) varies from 6645.4- 7151.2 psi while the minimum stress magnitude within the Synrift interval (3650-4080m+) in the well SRB varies from 6361- 7102 psi. Vertical Hydraulic Fractures oriented parallel to maximum stress direction will form since a normal to Strike –slip faulting stress regime exists in KG basin.
The geomechanical model suggests that borehole deviated parallel to Hmax direction (N130^0) will require less fracture initiation pressure to generate hydraulic fractures.

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