PaperID **AU251**

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Determination of Regional Stress Magnitudes and Directions: A case study on Offshore Exploratory wells of Tertiary Sequence in Kutch-Saurashtra Basin.

Abstract

Excessive wellbore breakouts, wellbore washouts (uncontrolled borehole enlargement) frequent tight pull & held up, undesirable log quality in drilled wells, necessitates understanding the subsurface behavior of the wells & basic cause of the problems. Rocks at depths are subjected to stresses resulting mainly from the weight of the overlying strata and the locked in stresses of tectonic origin. In-situ stress magnitudes and orientations play a very significant role in understanding the subsurface behavior during drilling, reservoir modeling, well stimulation and production optimization. The in-situ principal stresses are characterized as vertical stress (σ_v) minimum horizontal stress (σ_h) and maximum horizontal (σ_H). Altogether 35 vertical boreholes were studied of which 14 vertical borehole were considered to measure in-situ-stress magnitude and orientation. These selected boreholes are at depths ranging from 1500m to 2000m and drilled through Tertiary sediments. The variation of the in-situ stress components with depth was analyzed. The analysis shows that the Horizontal stress magnitude (SH_{max} or σ_H) is larger than the vertical stress (S_v or σ_v) within most of the measurement depth ranges. This indicates that the regional stress field is dominated by tectonic horizontal stress rather than by the overburden stress (S_v or σ_v). The study also indicates that $\sigma_H > \sigma_v > \sigma_h$ which validates Strike –Slip fault regimes. The maximum horizontal stress dominantly oriented in N10°E to N20°E direction also corroborates with the World Stress Map predictions for the study area.

Introduction:

Exploration activity in the Kutch-Saurashtra area (would be 8th producing basin of India) has drawn major attention and recent hydrocarbon discoveries from shallow offshore have been significant in India's E&P energyscape contributing to domestic energy demand. Understanding of stress state (both magnitude and direction) is important for any field development program. Vertical and lateral distribution of pore pressure and in-situ stress components, i.e. overburden (S_v), minimum and maximum horizontal stresses (Shmin and SHMax respectively) are preliminary input parameters for Geo-mechanical modeling which provides in-depth insights into variation of local stress field contributing to proper drilling fluid and casing design. Inclined wells drilled in the direction of minimum horizontal stress tend to be more stable in normal faulted basin compared to those drilled in any other directions (Kundan et al., 2015). Further, they also have the advantage of cutting through the natural fractures as these fractures tend to align themselves with the direction of maximum horizontal stress. On the contrary, inclined and horizontal wells drilled in the direction of maximum horizontal stress are likely to be more stable in a strike-slip fault regime or thrust fault regime. Well stimulation jobs like hydro- fracturing (HF) are preferred in the direction of maximum horizontal stress as all the induced fractures eventually tend to align themselves in this direction and fracturing in other directions will unnecessarily increase the tortuosity. In this paper, we focus on i) estimating magnitudes of pore pressure and principal in-situ stress components, ii) estimation of horizontal stress directions, iii) providing inputs for regional stress map, iv) validation of interpreted stress direction with World Stress Map.

Geology and Tectonics of the Study area:

Kutch-Saurashtra basin is a typical craton margin rift basin located in the North Western margin of the Indian continent and north of commercially proven Mumbai offshore. The basin stretches over an area of 43,000 sq.km onland and 28,000 sq.km offshore up to 200m isobath. The Kutch rift was initiated during the Late Triassic breakup of the Gondwanaland by the reactivation of primordial faults in the Precambrian Delhi fold belt (Biswas, 1982). The basin evolved through three tectonic phases: (1) Rift phase, (2) Late rift divergent wrench phase, and (3) post rift convergent wrench phase. These three phases correspond respectively to break up, drifting and collision of Indian plate. The rifting was aborted during Late Cretaceous pre-collision stage of the Indian plate. During post-collision compressive regime of the Indian plate, the Kutch rift basin became a shear zone with strike-slip movements along sub-parallel rift faults (Biswas, 2005). Oil and Natural Gas Corporation (ONGC) has been drilling shallow offshore wells to explore the hydrocarbon potential of Kutch-Saurashtra area. The study area has been presented in Figure 1. Hydrocarbons have been established from multiple pay horizons from Miocene to Jurassic age (Sandstone, siltstone and limestone)

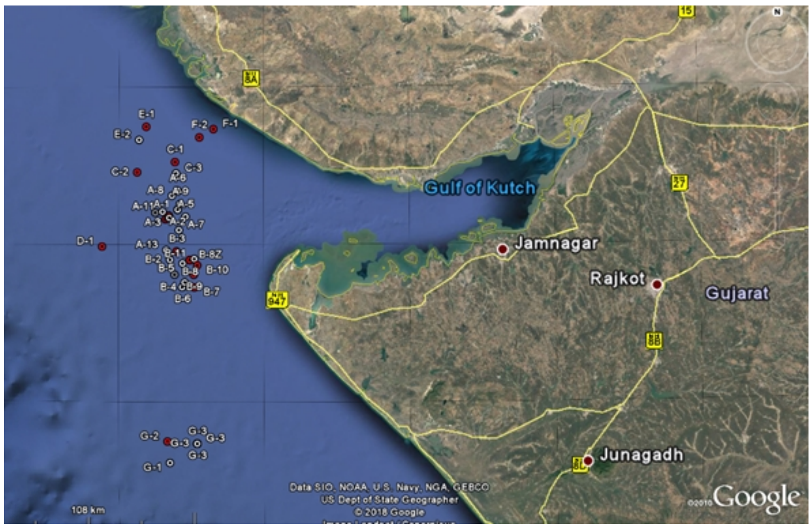

Fig 1. Map showing the studied well locations in offshore Kutch-Saurashtra Basin (wells marked with red color are main contributor of prominent wellbore breakouts, Stress Anisotropy and Borehole breakout on Image Logs.

Approach:

High resolution wireline logs (Gamma-Resistivity-Sonic-Density) have been the primary tool for calculating pressure (OBP- PP- FP) magnitudes and gradients. Vertical/Overburden stress gradient (Sv) has been estimated from density logs (Plumb et al., 1991). Pore pressure has been estimated from resistivity and sonic logs using Eaton's method (Eaton, 1975), Here, it was very challenging to use NCT and therefore PP calculations relied mainly on direct formation pressure measurements (MDT) (Sen et al., 2017). Eaton' and Mathews & Kelly equation (Mathews and Kelly, 1967) have been applied to restrict the upper and lower bounds of fracture pressure and calibrated with XLOT / LOT data. Minimum horizontal stress (Sh_{min}) has been estimated with effective stress ratio (ESR) of 0.75. Maximum horizontal stress (SH_{Max}) has been estimated from Minimum horizontal stress (Sh_{min}) and Pore Pressure (PP) (Zoback, 2007). Borehole breakouts have been studied thoroughly from four-arm caliper (Sonic Scanner) and image logs, along with stress anisotropy analysis which helped to determine minimum and maximum horizontal stress orientation. Only clean borehole breakouts having caliper magnitude > 10-20% of borehole size were considered for determination of stress direction.

Analysis of Stress Magnitude:

Altogether 35 vertical boreholes were studied of which 14 vertical boreholes (Study wells; A-10, A-12, B-3, B-7, B-8Z, B-9,B-10, E-1, F-1, F-2, C-1, C-2, D-1, G-2) were considered to measure in-situ-stress magnitude and orientation. The selected boreholes, at depths ranging from 1500m to 2000m, were drilled through Tertiary sediments. Study reveals that in Kutch Saurashtra area, the vertical stress (S_v) has an average gradient of 22 MPa/km. Pore pressure, shows nearly hydrostatic behavior throughout the well ranging between 8.5-9.0ppg. Availability of extensive downhole formation pressure measurements has guided in finalizing the pore pressure profile. Fracture pressure gradient varies in the range of 16.74-18.6 MPa/km (Eaton's method and Mathews & Kelly method respectively; yellow shaded region in Fig 2). LOT-XLOT data available from all the drilled wells have been instrumental for Sh_{min} calibration. SH_{Max} shows an average gradient of 24.5 MPa/km in the study area.

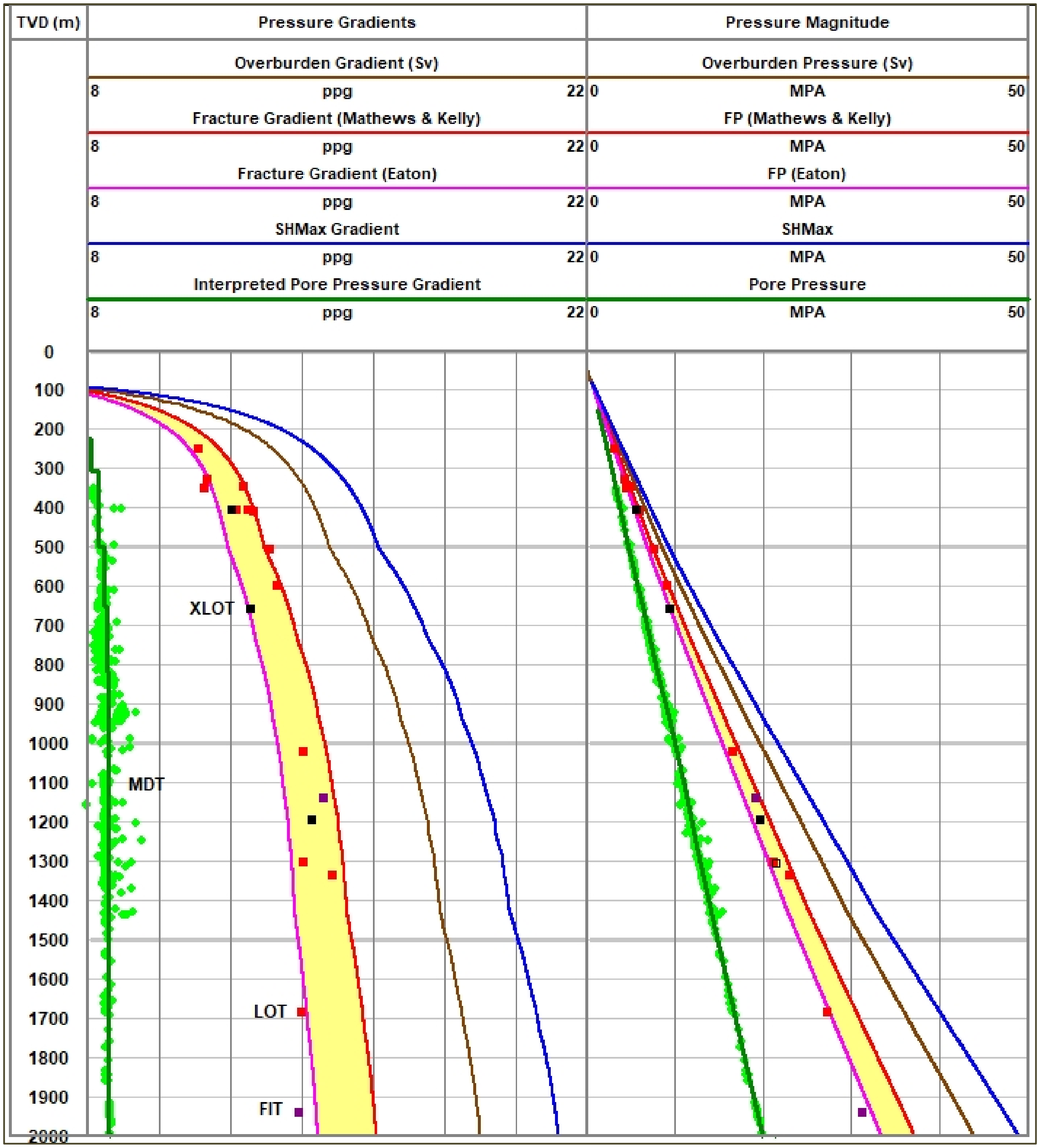

Fig 2. Pore pressure (PP), Overburden (Sv), Fracture gradient (Sh_{min}) and SH_{Max} gradients (ppg) and Pressure magnitudes (MPa) from Kutch-Saurashtra area, along with downhole calibration measurements (MDT, LOT/XLOT/FIT)

Analysis of Stress Direction:

Stress Direction from Breakouts;

Borehole breakouts and stress anisotropy have been the source to interpret the horizontal stress directions. Breakouts were studied from four arm caliper dataset (Sonic Scanner) and image logs available for the studied wells. Prominent wellbore breakouts have been identified **(Fig 3**) and used for determining regional stress field orientation. The interpreted maximum horizontal stress is predominantly oriented in N10°E to N20°E direction (Fig 4a).

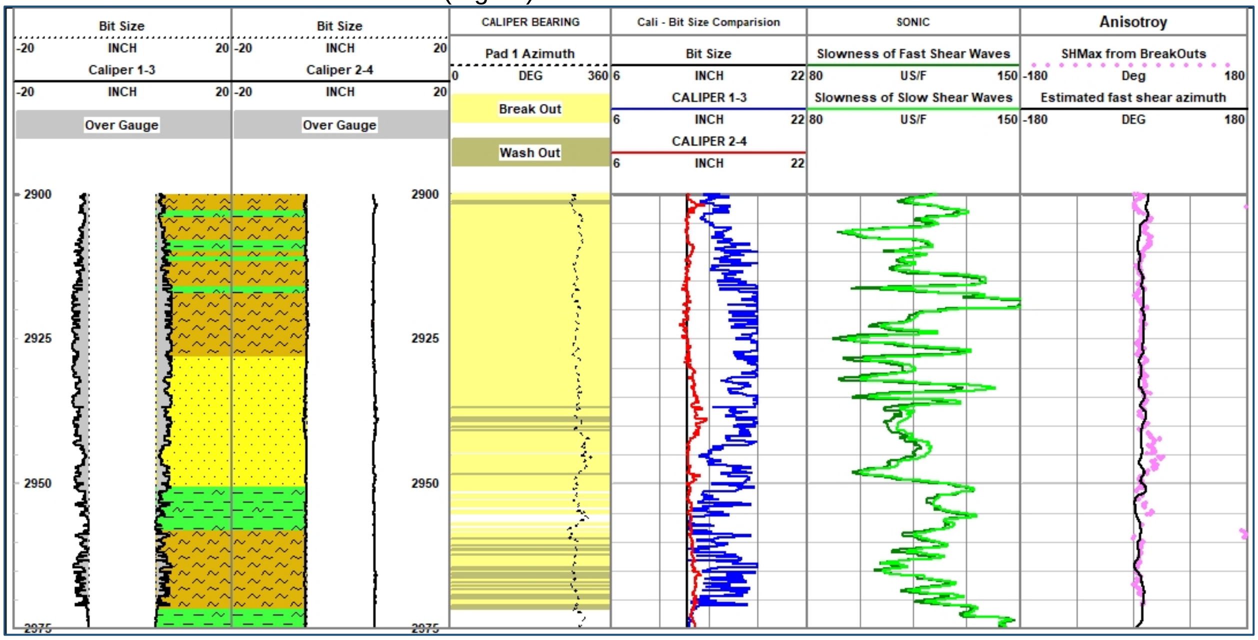

Fig 3. Fast Shear azimuth (from sonic anisotropy analysis) and Interpreted SH_{Max} from breakouts (pink dots) using Sonic scanner data from one of the studied wells in Kutch-Saurashtra area

Stress Direction from Shear Anisotropy;

Anisotropy data (from DSI tool) was available in a few studied wells (Four wells). The maximum horizontal stress direction from fast shear azimuth is interpreted as N10°E to N20°E **(Fig 4b).**

Stress direction from Density Image Log;

Distinct wellbore breakouts have been identified in Density Image logs along N110°E direction (Fig 4c), representing minimum horizontal stress direction (Sh_{min}).

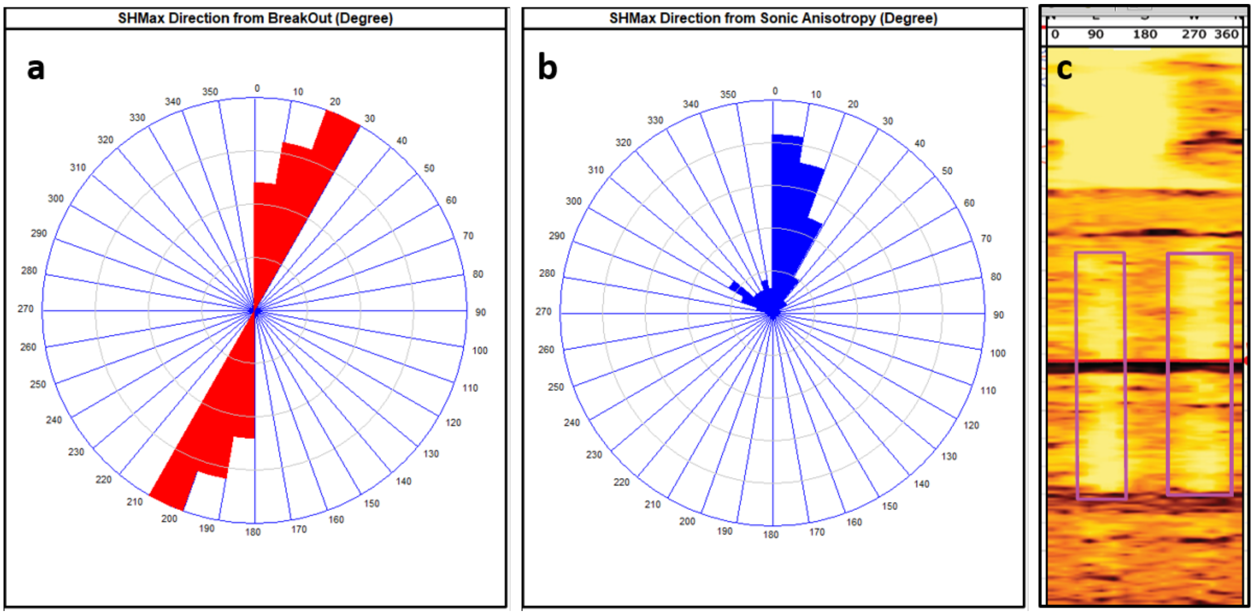

Fig 4a. SH_{Max} azimuth rose plot for Breakouts interpreted from four arm caliper logs, 4b. SH_{Max} orientation from Shear anisotropy analysis, 4c. Breakouts interpreted (Sh_{min} azimuth) from Azimuthal Density Image log

Validation with World Stress Map (WSM):

The World Stress Map (WSM) is the global compilation of information on the present-day stress field in the Earth's crust. It is a collaborative project between academia, industry and government that aims to characterize the crustal stress pattern and to understand the sources of tectonic stress. Wellbore breakouts are one of the significant contributing sources of stress directions in World Stress Map. (**Figure 5)** represents the SH_{Max} directions available from WSM in and around Indian continent. Our study area has been demarcated in red, and WSM database provides a NNE SH_{Max} azimuth in Kutch-Saurashtra area, based on earthquake focal mechanism method. The horizontal stress direction azimuth, interpreted from breakouts in 14 wells are in line with the WSM output and confirms maximum horizontal stress orientation in NNE.

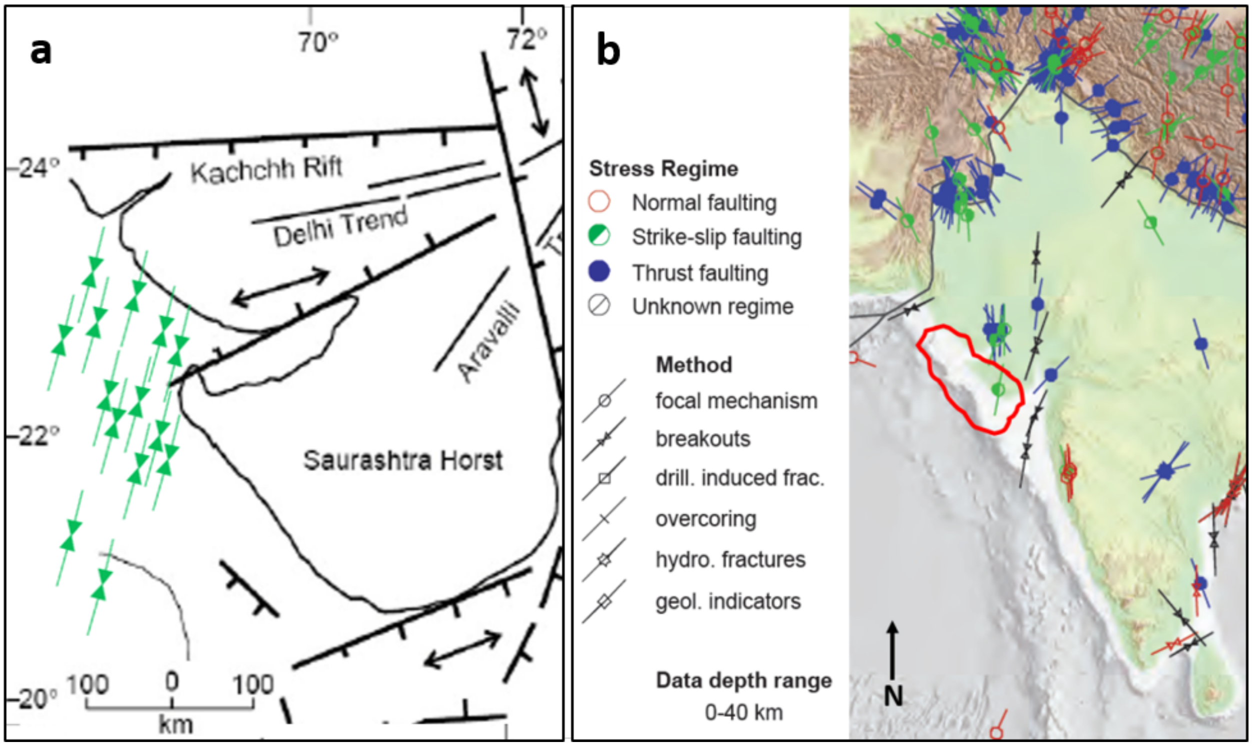

Fig 5a. Interpreted regional SH_{Max} orientation and stress regime (Strike-slip faulting) in studied wells of Kutch-Saurashtra area. **5b.** World Stress Map, based on the WSM database release 2009 (Available from Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences) and study area marked in red WSM stress orientation

Conclusion;

Determination of both horizontal stress orientation and magnitudes are important parameters for trouble-free well placement, optimum hydro-fracturing jobs and sand-free completions through oriented perforations. A precise measurement of the same can be successfully achieved through tests like LOT-XLOT, downhole direct formation pressure measurements and logs like 4-arm caliper along with azimuth, image logs and shear sonic anisotropy, drilling induced fractures. Such measurements can be planned in the exploratory/appraisal or offset wells so that the information can be used during the Exploration and Development phase of the field. Understanding and anticipating drilling problems, understanding their causes, and planning solutions are necessary for overall-well-cost control and for successfully reaching the target zone.

This study of in-situ stresses in Kutch-Saurashtra area from offshore (SW) exploratory wells integrated multiple high resolution data sources (conventional wireline logs along with advanced logs, i.e. four arm caliper logs, image logs, sonic anisotropy). Estimated pore pressure and minimum horizontal stresses were precisely finalized with the help of extensive downhole formation pressure measurements and LOT-XLOT, FIT datasets. Prominent wellbore breakouts have been interpreted from four arm caliper logs and density image logs, which yielded consistent SH_{Max} direction in Tertiary sequence across the study area; the same was greatly supported by the shear sonic anisotropy analyses.

Our study interprets the stress regime of Kutch-Saurashtra to be in strike-slip faulting domain and deciphers a regional maximum stress direction (SH_{Max}) direction along N10°E to N20°E. Both the outputs shows impressive validation with World Stress Map **(Fig 5a and b)**, which gives great confidence on the outputs. With further data availability in the area, such study can be extended laterally to have the full scale regional stress state throughout the basin. These outputs are critically important while planning future wells in Kutch-Saurashtra Basin (would be youngest producing basin in India) in terms of mitigating wellbore stability issues, better planning of deviated wells and successful execution of stimulation procedures such as Hydraulic Fracturing in tight formations.

Acknowledgement

We would like to convey our sincere thanks to Oil and Natural Gas Corporation Limited, Mumbai for providing us the infrastructural facilities. The interpretation presented in this paper are solely of the authors and do not necessarily represent the organization.

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