Analysis of Wellbore Breakouts and Determination of Horizontal Stress Direction from Four Arm Calipers– A study from Gulf of Kutch, Western Offshore Basin

Ashani Kundan*[1], A.K Vinod[1], PNS Bose[1], Souvik Sen[2], Mithilesh Kumar[2]
[1]Geology Operations Group, Western Offshore Basin, ONGC, Priyadarshini, Mumbai – 400002, Maharashtra, India
[2]Geologix Ltd., Dynasty Building, Andheri Kurla Road, Andheri (E), Mumbai – 400059, Maharashtra, India
kundan_a@ongc.co.in, ashani.kundan@gmail.com

Keywords

Breakouts, Washouts, Breakout azimuth, Horizontal stress directions, Stress magnitude, Four arm calipers, Non Productive Time (NPT)

Abstract

Wellbore instability costs includes billions of dollar per year worldwide because of down hole drilling problems and majority of problems occurring are related to mechanical instability of wellbore. When the stresses exceed the limit of rock strength it fails and if failure is too severe drilling problems occur. It is nearly impossible to drill perfectly gauge hole without any wellbore breakouts, but our aim should be to avoid catastrophic failure and to keep the borehole in the ambit of modest intensity of breakouts and successfully drill the well with limited complications. Each drilled well provides tremendous amount of information about stresses around wellbore. If subsurface Geological and Geophysical data is studied clinically, prevention of catastrophic wellbore failure can be ensured.
Breakout data analysis of drilled wells is an important tool in understanding present-day stress conditions in areas where more detailed stress measurements are not available. An understanding of in situ stress conditions is essential to evaluate the potential for slip on existing faults.
In petroleum industry, knowledge of borehole stress conditions can be critical in placement of platform and well profile as well as hydraulic-fracturing treatments. The direction of horizontal stresses can be determined with the help of four arm caliper by analyzing borehole ovalisation.

In the present study, we have analyzed two recently drilled wells (Well-A & Well-B) in Gulf of Kutch areas of Western Offshore Basin. Both the wells are drilled by ONGC as an operator. Indications of severe borehole breakouts and washouts observed during analysis of Well-A and Well-B.

Well-A drilled to its target depth 4250m with occurrences of modest to severe breakouts and washout enlargements in the well. Attempt has been made to identify and distinguish washouts and breakout zones and determine the directions of horizontal stresses from four arm caliper data recorded in the wells.
Well-B could not be drilled to the target depth due to high intensity wellbore failure during drilling igneous intrusive rock, in addition to several drilling complications such as abnormal toque, frequent drill string stalling, drill string stuck ups, drill bit balding and drill collar wear. The well had to be abandoned prematurely.
Wellbore instability occurred in study Well-B prompted us to analyze the mechanical integrity of the rock and understand both magnitude and orientations of horizontal stresses in the field.

Introduction

Kutch basin is a western margin pericratonic rift basin of India. The rift is bounded by Nagar Parkar uplift in the north and Kathiawar uplift in the south. The evolution of the western continental margin basins of India is related to the breakup of Eastern Gondwanaland from Western Gondwanaland in the Late Triassic/Early Jurassic and major tectonic events in brief can be summarized in following steps.

I. Initiation of protracted extensional tectonics leading to the eventual cleavage of east and west Gondwana.
II. A second phase of rifting/drifting separated Seychelles/India from Madagascar creating the Mascarene basin
III. A third and final phase of rifting/drifting led to the opening of the southwest Indian ocean

Figure: 1 Location Map showing Well-A, Well-B, Gulf of Kutch Basin

The study well–A and Well-B drilled in Kutch Saurashtra block of Western offshore Basin of ONGC.

Well-A & Well-B is situated around 10 km and 32km respectively from the landfall. The distance between Well-A and Well-B is about 33km. Well–A drilled up to 4250m, whereas, Well-B drilled up to 3452m. Both the wells drilled in shallow water regime with water depth ranges from 13m and 18m respectively.

The study wells were drilled through Miocene to Jurassic in different order of sequences including 600 to 700m of Deccan trap (Early to Middle Cretaceous) and igneous intrusive (Dykes-Sills) which are episodically placed throughout the Mesozoic section. This Dyke-Sill complex cuts across sedimentary section ranging from Jurassic to Late Cretaceous.

In well –A, splinters of a sill (igneous intrusive) were observed at depths 2130-2145m, 2155-2160m and 2330-2345m. Breakouts/washouts are seen in igneous intrusive but did not contribute much to drilling related complications, whereas in Well-B, an intrusive was encountered at 3240m and series of drilling complications pertaining to abnormal toque, frequent drill string stalling, drill string stuck ups, drill bit balding and drill collar wear were observed.

Numerous borehole stress studies (Cox, 1970; Brown, 1978; Bell and Gough, 1979, 1982; Gough and Bell, 1981, 1982; Hickman et al., 1985; Plumb and Hickman, 1985; Teufel, 1985; Zoback et al., 1985) and theoretical and laboratory studies simulating borehole stress conditions (Mastin, 1984; Haimson and Herrick, 1985; Zoback et al., 1985) show that wellbore breakouts are stress-induced spall zones that typically elongate vertically within the wellbore and are the result of compressional shear failure of the wellbore associated with unequal horizontal compressive stresses around the wellbore.

To avoid avoidable nonproductive time (NPT) caused due to Pore pressure and Geomechanical issues in drilling the wells, each drilled well shall be candidly considered as a reliable candidate for analytical study of pore pressure-fracture pressure and rock mechanics to establish a comprehensive pore pressure and Geomechanical forward model for future wells.

A systematic collation of subsurface geological & geophysical information produced by action of drilling, LWD or wireline logging must be brought into ambit of Geomechanical study for measuring orientations and magnitude of the stresses. Comprehensive analysis of wellbore failure as revealed from four arms/six arms calipers and wellbore images (FMI logs) provides agility to the analyst to determine orientations of in situ stresses at a particular depth.

The way in which a formation responds to the stress concentrations is a function of both the stress field and the rock strength.

The idea that breakouts reflect local in situ stress conditions is supported by the agreement between stress directions inferred from breakouts and stress orientations obtained using other types of stress data such as earthquake focal mechanisms, hydraulic-fracturing measurements and geological stress indicators (Gough and Bell, 1981, 1982; Hickman et al., 1985; Plumb and Hickman, 1985; Dart and Zoback, 1989).

Wellbore Breakouts & Wellbore Stability

The concentration of stress around wellbores can lead to compressive failure which is called stress induced breakouts and drilling induced borehole breakouts commonly known as tensile failure. Wellbore breakouts are very common during drilling the well but its orientation and magnitude might differ extensively. An unstable well is one in which excess breakout of the formation produces so much failed material from around the wellbore that the total volume of cuttings in the hole cannot be circulated out by the mud circulations. Due to excessive wellbore failure, the velocity of drilling mud in the annulus decreases reducing the ability of the mud to clean the cuttings and debris out of the hole, as in case of **Well-B** while drilling the igneous intrusive body.

When a borehole is drilled, the material removed from the subsurface is no longer supporting the surrounding rock. As a result, the stresses become concentrated in the surrounding rock (i.e. the wellbore wall). Borehole breakout occurs when the stresses around the borehole exceed that required to cause compressive failure of the borehole wall (Zoback et al., 1985; Bell, 1990). The enlargement of the wellbore is caused by the development of intersecting conjugate shear planes that cause pieces of the borehole wall to spall off (Figure 2).

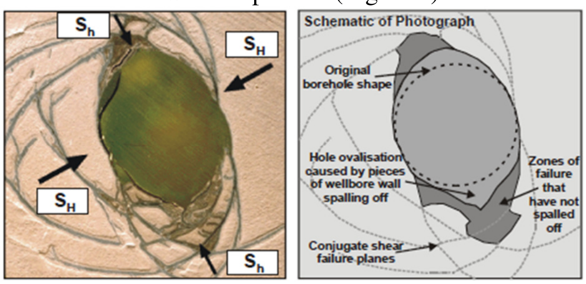

Figure: 2. *Schematic diagram of break out from lab experiments, SH and S_h refer to the orientations of maximum and minimum horizontal stress respectively.*

Around a vertical borehole stress concentration is greatest in the direction of the minimum horizontal stress (S_{hmin}). Hence, the long axes of borehole breakouts are oriented approximately perpendicular to the maximum horizontal stress orientation (S_{Hmax}) (Plumb and Hickman, 1985).

Importance of Horizontal Stress Directions

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. 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 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.
Likewise, in unconsolidated sand reservoirs, initiation of sanding starts in the direction of minimum horizontal stress and hence if the perforations are carried out in the direction of maximum horizontal stress only (oriented perforation), the problem can be averted for some time. Hence, understanding horizontal stress direction is important for well planning as well as well completion.

Interpreting Breakouts from Four-Arm Caliper logs

The four-arm caliper tool will rotate as it is pulled up the borehole due to cable torque. However, the tool stops rotating in zones of borehole enlargement if one caliper pair becomes 'stuck' in the enlargement direction (Plumb and Hickman, 1985). To identify zones of breakout and the orientation of the enlargement, the criteria are as follows (based on Plumb and Hickman, 1985; Bell, 1990; Zajac and Stock, 1997):

- ❖ Tool rotation must cease in the zone of enlargement (can be checked from Pad1 azimuth curve or relative bearing curve). This is because the larger caliper falls in the breakout groove and does not allow the tool to rotate. If, however, the tool motion is not arrested then it may be a hole enlargement (washout) or key-seat, and not necessarily a breakout.
- ❖ There must be clear tool rotation into and out of the enlargement zone.
- ❖ The smaller caliper reading is close to bit size. If it is larger, then it should not exceed 1.1 times the bit size.
- ❖ Caliper difference has to be 10 %.
- ❖ The enlargement orientation should not coincide with the high side of the borehole in wells deviated by more than 5°.
- ❖ The length of the enlargement zone must be greater than 1 m.

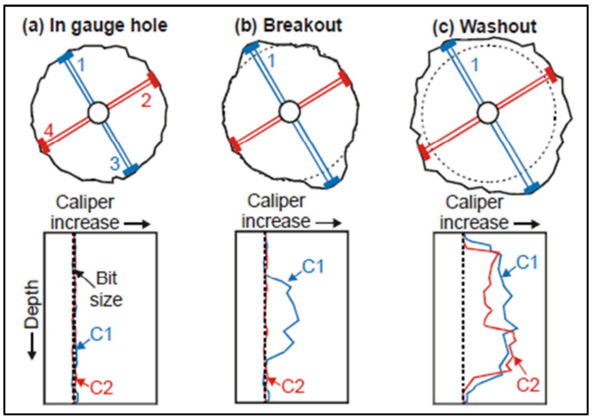

Figure: 3 Common types of enlarged borehole and their caliper log response (after Plumb and Hickman, 1985), C1 and C2 are caliper 1 and 2 respectively

In breakout zones one pair of caliper arms measures the size of drill bit, whereas the orthogonal pair measures a larger diameter. Washouts essentially imply complete failure of the wellbore such that both sets of arms of the four arm caliper are larger than the diameter of the drill bit. Keyseats are an asymmetrical notching of the well caused by mechanical wear of the wellbore at its top or bottom (or on the side of the well if there is a rapid turn in the well trajectory). It is also useful to use a wellbore deviation criterion to help distinguish keyseats from breakouts. Keyseat breakouts may show false Shmin stress orientations in wellbore. Utmost care is required while considering wellbore breakouts for plotting rose diagram to determine stress orientation.
Breakout orientations can rotate in inclined boreholes and may not always directly yield the horizontal stress orientations (Mastin, 1988; Peska and Zoback, 1995). Hence, the maximum horizontal stress orientation can only be reliably estimated from breakouts in approximately vertical boreholes (less

than 5° deviation from vertical). All orientations measured from four-arm caliper tools need to be corrected for the local magnetic declination at the time of measurement.

Study of wellbore breakouts in Well-A and Well-B drilled in Gulf of Kutch, Western Offshore Basin

Traditionally, most of the data inputs used to determine the orientations of borehole breakouts and to establish the direction of two principal horizontal stresses (S_{hmin} and S_{Hmax}) acting in wellbore comes from magnetically oriented four arm caliper data (sonic scanner) and six arm caliper (FMI) are commonly used in petroleum industry.
It is pertinent to mention that, while analysis of wellbore breakouts from four arm caliper data, it is important not to misinterpret keyseats (grooves in the side of the well caused by the rubbing pipe) or washouts (enlargements of the entire wellbore circumference) as stress induced breakouts. (Reservoir Geomechanics, Mark .D Zoback, chapter-6). Accordingly, maximum precaution has been taken while interpreting four arm caliper data derived from sonic scanner logs recorded in the study wells.
An exclusive borehole analysis template was designed in GEO suite of software (Geologix software being used in Western Offshore Basin) to bring all the basic data inputs required for analysis at one platform. The template helped the analysts to distinguish the breakouts and washouts plotted by computing C1-C3 and C2-C4 caliper data with reference to bit size and pad1 azimuth. The facility to show lithology along with contiguous hole enlargement curves and azimuth in the template made interpretation more easy.

Well- A recorded four arm calipers data from 410m to 4250m (drilled depth) and in **Well-B** four arm calipers available from 400m to 3285m.
Well-A shows very prominent breakouts and washout zones from 410m to 660m and 980m to 1100m in tertiary sediments. Significant indications of borehole breakouts zones were also observed in trap section (Basalt from 1115m to 1900m). Wellbore failure in the form of breakouts and washouts were also encountered from 2100m to 2970m which includes igneous intrusive (sills) at three different depths and sediments of Early Cretaceous.
Notable amounts of breakouts also observed from 3525m to 4250m (in Jurassic Sediments)
Similarly in Well-B, four arm calipers also shows significant amount of wellbore failure zones from 400m to 940m (Tertiary Sequence) and 1940m to 2600m which includes trap (Deccan Basalt) and carbonates underneath trap section. Catastrophic wellbore failure occurred when the wellbore entered in igneous intrusive (i.e sill) at 3240m.
This intruded igneous body (dolerite sill) might have developed vertical fractures caused by cooling of intruding dolerite body. Generally orthogonal to columnar joints, brittle fractures develop in the igneous rock body due to internal tensile stresses on account of shrinkage caused by the cooling or desiccation of a rock body whose outside boundaries remained fixed. Probably the sloughing or falling of dolerite pieces along these fracture plane dislodged during drilling. This igneous body (dolerite sill) is expected to undergo tectonic stresses also. The stress induced breakouts cannot be ruled out in the intrusives encountered at 3240m.
Well-B could not be recovered from continuous borehole collapse due to mechanical integrity disruption of dolerite sill which resulted premature abandonment of the well. However, it has been studied to identify washout and breakout zones from four arm caliper data (Figure 4 & 5) to identify zones of breakout and the orientation of the enlargement. The above mentioned criteria have been followed and computed in GEO suite of software. Washout and breakout zones have been distinguished by shading grey and yellow respectively as shown in figure-4 & 5

Determination of Maximum Horizontal Stress ($S_{H\ max}$) direction from Breakouts

Once the breakouts and washout zones have been identified based on the required criteria from four arm caliper data, the pad azimuths (P1AZ- on 4th track of figure-4 &5) against break out zones have been plotted in rose diagram to get the idea of minimum and maximum horizontal stress directions. When analyzed, it is observed that the breakouts occurred at the azimuth of minimum horizontal stress (Shmin) shows a remarkably consistent orientation in both the wells. The rose diagram construed from breakouts in Well-A and Well-B of study area attributes that the maximum horizontal stress (SHmax) direction is along N10°E which is also in close proximity of generalized world stress map.
The azimuth and width of breakouts (wBO) could not be determined due to non-availability of borehole image data (ultrasonic or FMI) of study wells.

Pore Pressure, Fracture Pressure and Overburden pressure behavior of study wells was also analyzed to understand the magnitudes of vertical stress (Sv) and two horizontal (Sh and SH) stresses.
Overburden, Pore pressure and Fracture pressure was calculated using Drillworks predict software whereas

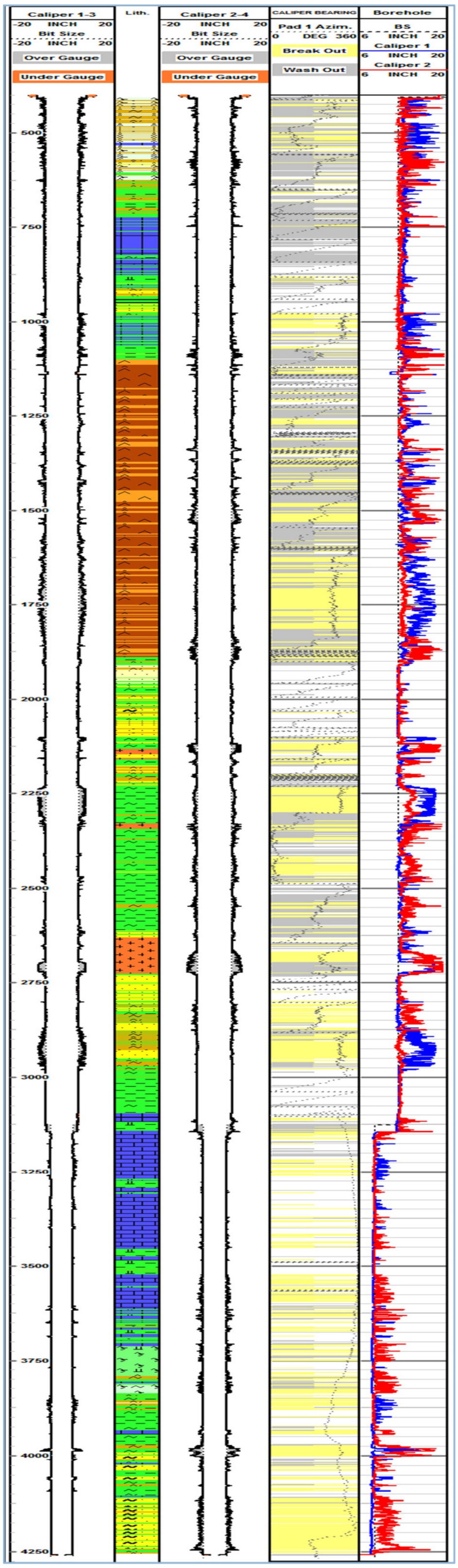

Figure: 4 Well-A showing breakouts (yellow shade) & washouts (grey shade) Output taken from GEOSUITE software by Geologix

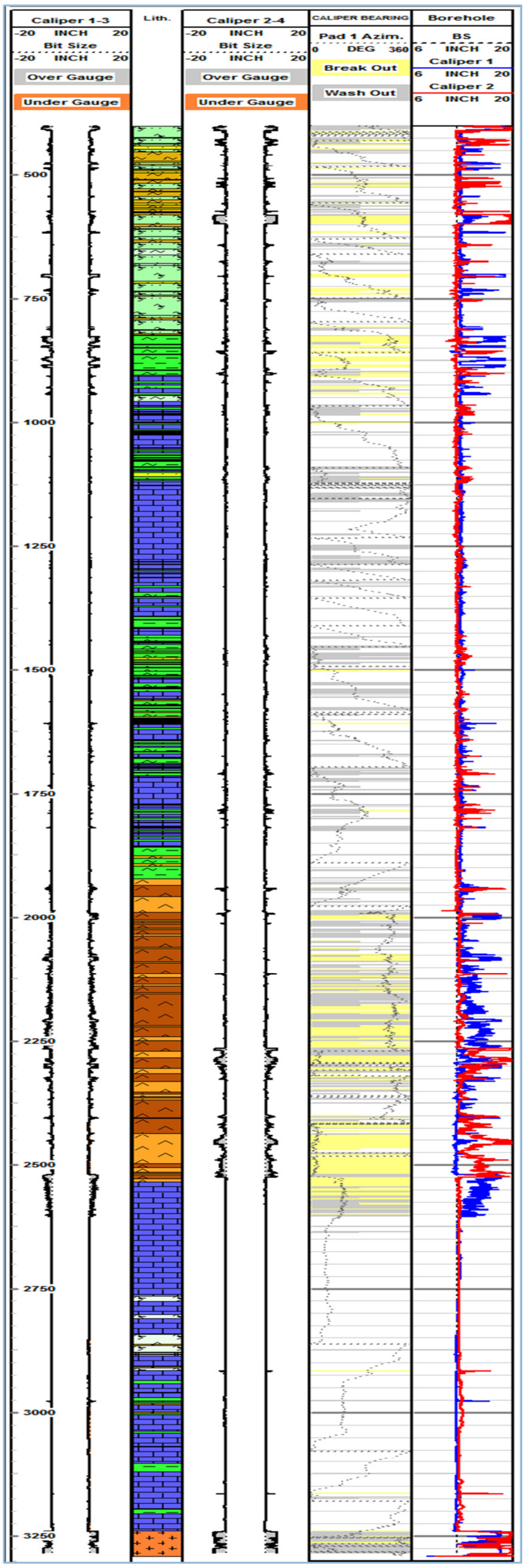

Figure: 5 Well-B showing breakouts (yellow shade) & washouts (grey shade) Output taken from GEOSUITE software by Geologix

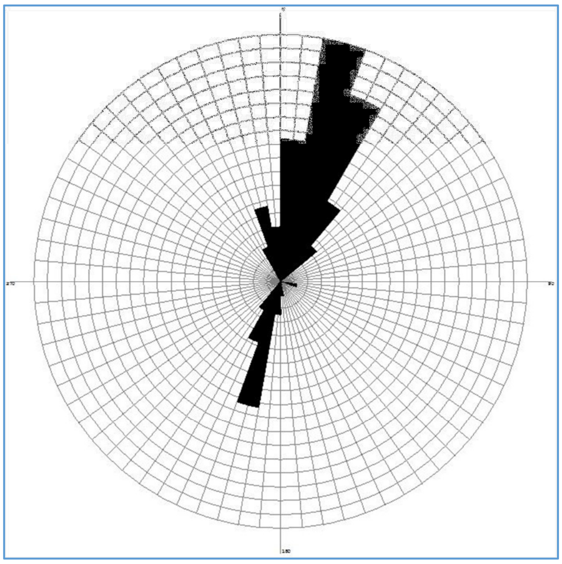

*Figure: 6. Rose diagram showing S_{Hmax} direction from four arm caliper of **Well-A**, study area.*

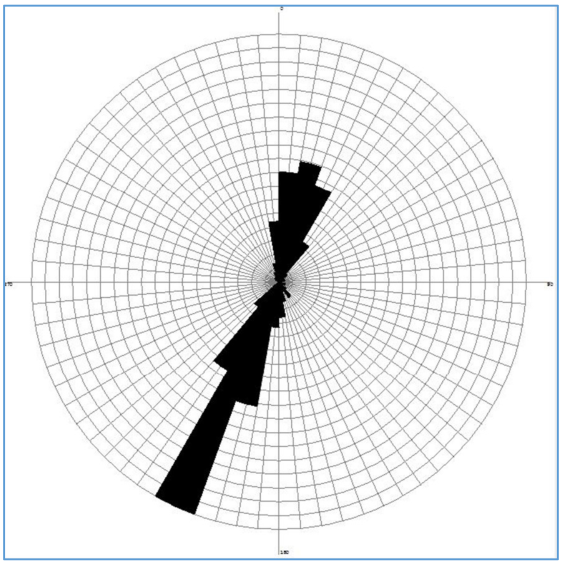

*Figure: 7. Rose diagram showing S_{Hmax} direction from four arm caliper of **Well-B**, study area.*

Stress magnitude calculated by Drillworks Geostress module using sonic scanner processed data inputs.

Pore pressure (Pp) analysis of **Well-A** was carried out and it appears to be in normal pressure regime up to 3993m. However, at 3993m, the well became active while drilling with 10.3ppg mud and was controlled by increasing the mud weight to 13.3ppg. The same mud weight was used to TD without any further complications.

The overburden gradient in **Well-A** appears to be around 23.5Mpa/km, maximum horizontal stress (S_{Hmax}) magnitude 22.75Mpa/km and minimum i.e

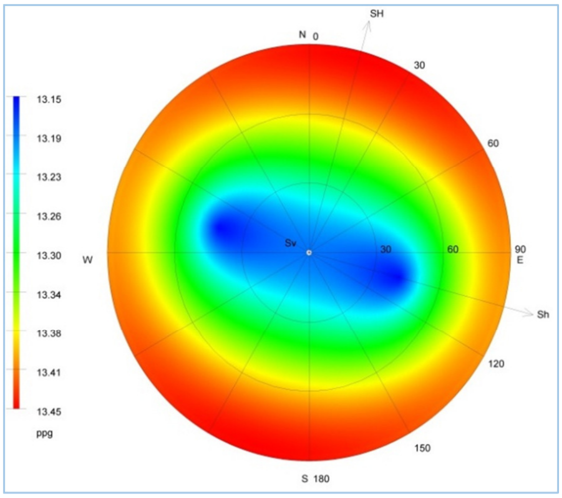

*Figure: 8. Mud weight required in **Well-A** at 4000m.*

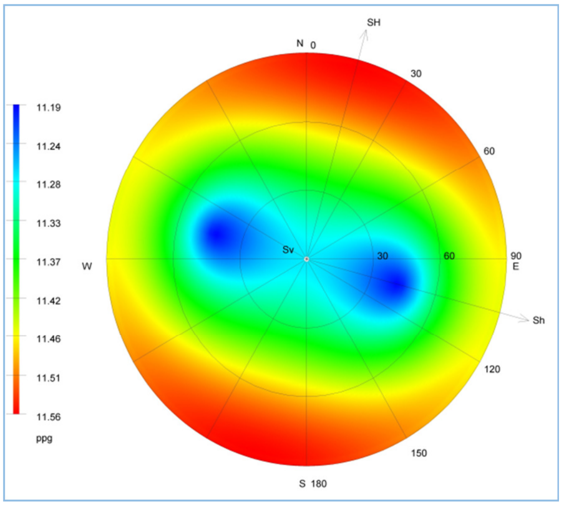

*Figure: 9. Mud weight required in **Well-B**.at 3200m*

(S_{hmin}) approximately 22Mpa/km. The greatest (Sv), intermediate ((S_{Hmax}) and least (S_{hmin}) principal stress at depth was plotted in E.M Anderson's stresspolygon to determine faulting stress environment of the area of drilled wells. The **Well-A** falls in normal faulting stress regime, but there are indications of slippage towards strike slip fault system.

Well-B didn't indicate abnormal pore pressure and was drilled down to 3367m by maintaining wellbore pressure ranging from 9.3ppg to 10.4ppg (400m to 3367m). Severe wellbore failure occurred during drilling intrusive igneous body (dolerite sill) from 3240m-3305m and finally drilling was terminated at 3452m.

The **Well-B** also falls in normal faulting stress regime however; there are indications of slippage towards strike slip fault system.

Analysis and 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 extended leak off tests and logs like 4-arm caliper, resistivity or ultrasonic images and shear sonic recorded in cross-dipole mode. Such measurements can be planned in the 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.

Unbroken borehole not only reduces drilling related risks, but also improves quality acquitions of G&G data such as wireline logs, MDT/RCI pretests and samples and aids proper representative cutting sample analysis.

Study shows that both **Well-A & Well-B** are located in tectonically stressed regime where maximum horizontal stress (S_{Hmax}) direction is along N10°E which is in close proximity of generalized world stress map and stress orientations inferred from breakouts inferred from nearby drilled wells and earthquake focal mechanisms.

Analysis of breakouts zones in study wells demand slightly more mud weight to prevent undesirable breakouts.

Wells planned in the area of Well-A & Well-B should be drilled with higher mud weight to prevent breakouts and unwanted wellbore enlargements. However, LOT (Leak off Test) limit determined at previous casing shoe depth shall also be considered prior to increase mud weight.

Geomechanical study will provide agility to prevent NPT (nonproductive time) and to avoid log interpretational issues.

Acknowledgement

We would like to extend special thanks to Mr. Prasanta Seal, DGM (Geol.), Mr. B.S Reddy, DGM (Wells), Mr.Manoj Kumar, Mr.L.B Rana, Mr.Bidesh Bandyopadhay, Mr.Vikrant Kalpande of Geology Operations Groups for sharing valuable experiences with us.

We would like to convey our sincere thanks to Oil and Natural Gas Corporation Limited, Mumbai and M/s Geologix Ltd. for providing us the infrastructural facilities.

References

Bell, J.S., 1990, Investigating stress regimes in sedimentary basins using information from oil industry wireline logs and drilling records. - In: Hurst, A., M. Lovell and A. Morton (eds.): Geological applications of wireline logs, Geol. Soc. Lond. Spec. Publ., 48, 305-325.

Gough, D.I., and Bell, J.S., 1981, Stress orientations from oil-well fractures in Alberta and Texas: Canadian Journal of Earth Science, v. 18, p. 638-645.

Bell, J.S., and Gough, D.I., 1982, The use of borehole breakouts in the study of crustal stress, in Zoback, M.D., and Haimson, B.C., eds., Proceedings of Workshop XVII Workshop on hydraulic fracturing stress measurements: U.S. Geological Survey Open-File Report 82-1575, p. 539-557.

Brown, R.O., 1978, Application of fracture identification logs in the Cretaceous of north Louisiana and Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 28, p. 75-91.

Cox, J.W., 1970, The high resolution dipmeter reveals dip related borehole and formation characteristics: Society of Professional Well Log Analysts Annual Logging Symposium, 11th, May 3-6, 1970, p. 1-25.

Dart, R.L., and Zoback, M.L., 1989, Well bore-breakout stress analysis within the Continental United States: The Log Analyst Journal, v. 30, no. 1, p. 12-25.

Haimson, B.C., and Herrick, C.G., 1985, In situ stress evaluation from borehole breakouts, experimental studies: U.S. Symposium on Rock Mechanics, 26th, Rapid City, South Dakota, 1985, Proceedings, v. 2, p. 1207-1218.

Hickman, S.H., Healy, J.H., and Zoback, M.D., 1985, In situ stress, natural fracture distribution, and borehole enlargement in the Auburn geothermal, New York: Journal of Geophysical Research, v. 90, no. B7, p. 5497-5512.

Mark D.Zoback, Reservoir Geomechanics, Determination of S3 from mini fracs and extended leak –off tests and constraining the magnitude of SHmax from wellbore failures in vertical wells.

Mark D.Zoback, Reservoir Geomechanics, wellbore stability- preventing wellbore instability during drilling and measuring stress orientations and magnitude.