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HORIZONTAL STRESS ORIENTATION FROM BOREHOLE BREAKOUT ANALYSIS IN WEST NATUNA BASIN, INDONESIA

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Abstract - The West Natuna Basin is an intracontinental basin that characterized by number of Eocene – Oligocene half grabens, which inverted during Miocene time. West Natuna Basin formed under transtensional conditions, featuring half grabens trending in a SW-NE direction, accompanied by sinistral (left-lateral) wrench zones striking NW-SE. The inversion reactivates mainly the border fault formed during rifting and resulted in the similar SW-NE structural trend. This research aims to investigate the stress orientation from borehole breakout data that might be responsible for the structural formation in West Natuna area.

Borehole breakout data in this research comprise into different types of data, image processed log from one well and caliper log (four arms and six arms) from eight vertical wells. The analysis performed differently for both of the data sets. The image processed log (FMI) data will give the indication of breakout and induced tensile clearly, while the breakout from caliper is interpreted based on some typical shape representing the borehole condition. The analysis from the borehole breakout will implies the minimum horizontal stress (S_{hmin}) orientation that perpendicular to the maximum horizontal stress orientation (S_{Hmax}).

The analysis resulted in a breakout trend N 36° to 79.5° with standard deviation 4.3-26.1°. The results of breakout analysis are comparable with the existing structure trend in southwestern part of West Natuna Basin that also showing similar trend SW-NE. Implied S_{Hmax} orientation at NW-SE trend is coincidence with major strike slip fault that believed the main force for the inversion occurred in West Natuna Basin. As comparison, the regional main fault at neighborhood Malay Basin is relatively parallel with the maximum horizontal stress (S_{Hmax}) orientation resulting the basin keep opened and subside until present day time.

Key words: West Natuna Basin, borehole breakout, horizontal stress, inversion

Sari - Cekungan Natuna Barat adalah cekungan intrabenua yang ditandai oleh sejumlah *half graben* dari Eosen - Oligosen, yang terinversi selama periode Miosen. Cekungan Natuna Barat terbentuk dalam kondisi transtensional, menampilkan *half graben* yang bergerak dalam arah SW-NE, disertai dengan *sinistral (left-lateral) wrench zones* yang sejajar dengan arah NW-SE. Inversi ini mereaktivasi *border fault*s yang terbentuk selama *rifting* dan menghasilkan tren struktural serupa SW-NE. Penelitian ini bertujuan untuk menyelidiki orientasi stress dari data *breakout* sumur bor yang mungkin bertanggung jawab terhadap pembentukan struktural di area Natuna Barat.

Data *breakout* sumur bor dalam penelitian ini terdiri dari berbagai jenis data, seperti data log yang diproses gambar dari satu sumur dan data log caliper (empat lengan dan enam lengan) dari delapan sumur vertikal. Analisis dilakukan secara berbeda untuk kedua set data tersebut. Data log yang diproses gambar (FMI) akan memberikan indikasi *breakout* dan regangan yang diinduksi dengan jelas, sementara *breakout* dari caliper diinterpretasikan berdasarkan beberapa bentuk khas yang mewakili kondisi lubang bor. Analisis dari *breakout* sumur bor akan menyiratkan orientasi tegangan horizontal minimum (Shmin) yang tegak lurus dengan orientasi tegangan horizontal maksimum (S_{Hmax}).

Analisis ini menghasilkan tren breakout N 36° hingga 79,5° dengan deviasi standar 4,3-26,1°. Hasil analisis *breakout* dapat dibandingkan dengan tren struktur yang ada di bagian barat daya Cekungan Natuna Barat yang juga menunjukkan tren serupa SW-NE. Orientasi S_{Hmax} yang tersirat pada tren NW-SE bersesuaian dengan sesar geser utama yang diyakini menjadi gaya utama untuk inversi yang terjadi di Cekungan Natuna Barat. Sebagai perbandingan, sesar utama regional di sekitar Cekungan Malaya relatif sejajar dengan orientasi tegangan horizontal maksimum (SHmax), menghasilkan cekungan tetap terbuka dan tenggelam hingga saat ini.

Kata kunci: Cekungan Natuna Barat, *breakout* sumur bor, *stress* horizontal, inversi

1. INTRODUCTION

The West Natuna Basin is known as one of Indonesia's highly productive petroleum basins. Situated in the offshore region of the northernmost border between Indonesia and Malaysia, it extends in a northeast-southwest direction (**Figure 1**). The Natuna Arc serves as a divider between the West Natuna Basin and the East Natuna Basin. To the

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north, the basin is bordered by the Khorat Swell, while the Anambas Arch lies to the south. In the west, the West Natuna Basin is adjacent to the southern part of the Malay Basin. The region of SE Asia and SW Pacific is structurally complex and at least includes two major continental regions, Sundaland-Eurasia and Australia (Hall, in Clements 2004). The margins of these continental regions are composed of mosaic fragments.

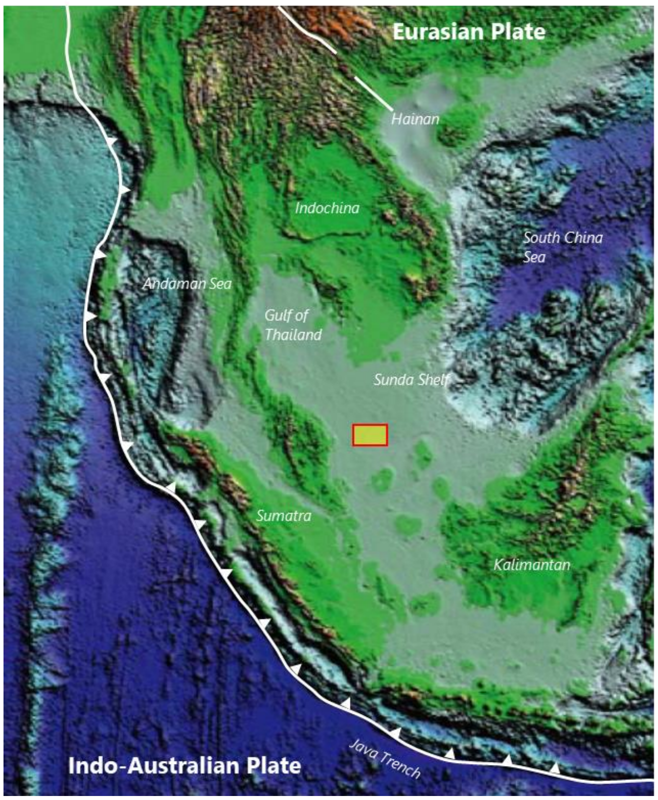

Figure 1 West Natuna Basin Location (Clements modified after Hall, 2004).

The West Natuna Basin is an intracontinental basin that characterized by several Eocene – Oligocene half grabens, which experienced compression during the Miocene forming complex inversion structures. During the Eocene-Early Oligocene period, initial rifting occurred under regional extension directed in a north-south orientation, utilizing pre-existing structures in the basement. As a result, structures in the West Natuna Basin (WNB) formed under transtensional conditions, featuring half grabens trending in a SW-NE direction, accompanied by sinistral (left-lateral) wrench zones striking NW-SE (Manur and Jacques, 2014).

The basin has been tectonically quiescent during the late early to late Oligocene period, followed by inversion during early Miocene until reached its maximum inversion in the middle Miocene time. The maximum sediment inverted located at the deepest of the graben formed a new high. The Muda Formation was formed during the Late Miocene to the present day and marks the quite tectonic activity in West Natuna Basin, where sediment predominantly controlled by the eustacy. No significant structural feature could be observed in the Muda Interval. The hydrocarbon accumulation is mostly related to biogenic gas accumulation in the gentle drapes anticline. However, some minor strike-slip features still could be observed in the central of the West Natuna area that might be still related to the old dextral strike slip fault crossing NW-SE of the basins.

In the southwestern most of the area, the structural trend is still dominated by the SW-NE trending fault and inverted anticline. At the maximum inversion, the syn-rift sediment even reached the base of unconformity and post rift sediment was completely eroded. However, there are still several structural trends that experienced only mild inversion, such as Belida - Sembilang structure, despite it still the most prolific field in the West Natuna area. This research is targeted to see the stress orientation that might be responsible for the structural complex formation in West Natuna area.

2. DATA AND METHODOLOGY

Borehole breakout data in this research comprise into different types of data, image processed log and caliper log (four arms and six arms) from nine vertical wells. The borehole data are the main indicator for stress orientation from drilled well. Borehole breakouts are stress-induced enlargements of the wellbore cross-section (Bell and Gough, 1979). When a borehole is drilled the material removed from the subsurface is no longer supporting the surrounding rock. As a result, stress becomes concentrated in the borehole wall (Reinecker et.al., 2003). 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 concentration of stress around wellbores can lead to compressive failures known as stress-induced breakouts and/or tensile failure of the borehole wall that will be referred as drilling-induced tensile wall fractures. Breakouts are quite common in many wells and yield important information about both stress orientation and magnitude (Zoback, 2007). In vertical wells, the occurrence of tensile fractures usually implies that S_{hmin} is the minimum principal stress, where the maximum principal stress S_{Hmax} will be perpendicular from S_{hmin}.

Image Log

Image logs are basically measuring the resistivity contrast that represent smoothness of the borehole wall and quite sensitive to any spalling at the borehole wall. The tool is the best to measure the induced breakout and tensile which represents the S_{Hmax} and S_{hmin} orientation respectively. Not only the orientation, the magnitude of the S_{Hmax} could be calculated based on angle of borehole breakout (Barton et al., 2003).

Caliper Log

Four-arm caliper tools are commonly used for formation evaluation during well drilling for strike and dip on the bedding (in dip meter) or to evaluate more proper the volume of cement required to set casing. However, the unprocessed four-arm caliper can also be used to interpret borehole breakouts (Reinecker et al., 2003). Typically, the diameter of the calipers in four-arm tools is represented by C1 paired with C3, and C2 paired with C4, with the angle between the pad is constant at 90°. In order to calculate the orientation, it needs the azimuth orientation of one of the pads, usually pad 1 (P1AZ) which represents the azimuth relative to magnetic north, borehole deviation (DEVI), azimuth of borehole drift (HAZI), and bearing of pad 1 relative to the high side of the bore hole (RB). The tool schematic shown in **Figure 2**.

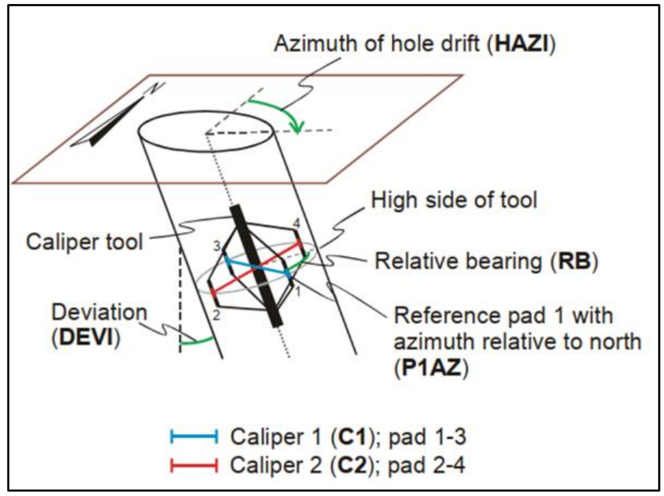

Figure 2 Caliper Schematic Tool (Reinecker et al., 2003).

The P1AZ could be calculated using this equation (Reinecker et al., 2003):

P1AZ = HAZI + atan (tan RB/cos DEVI)

It needs careful attention to interpret the breakout from caliper data, therefore several criteria summarized by Reinecker based on Plumb and Hickman (1985), Bell (1990), Zajak and Stock (1997). Plumb and Hickman (1985) also categorized common types of enlarged borehole and their caliper response. The proper breakout zone is when one pair of pad area close to the bit size, while other pair showing the breakout (**Figure 3**).

In this study, the four-arms caliper data from eight wells with various quality have been analyzed. The standard deviation will represent the clarity of the interpretation, therefore the uncertainty of well with high standard deviation need to be considered.

The six-arms caliper data only sourced from one well in this study. The interpretation of six-arms caliper will be more difficult as the tool will easily decentralize particularly in highly deviated wells, and need special tools to calibrate as explained by Wagner et al. (2004), which has performed the test for correcting six-arm caliper data.

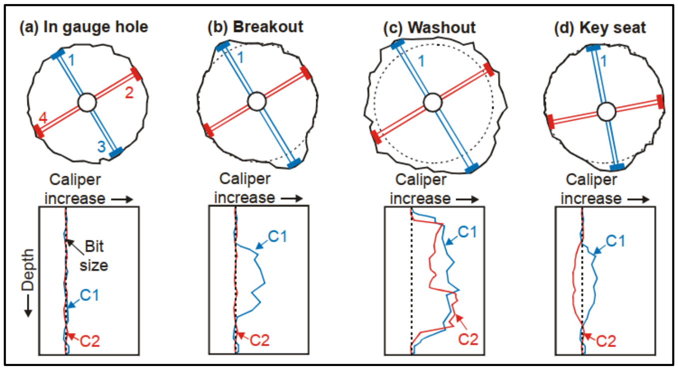

Figure 3 Common types of enlarged borehole and their caliper log respond (Plumb and Hickman, 1985).

However, in this study, as the well is relatively vertical, it is assumed that the effect of decentralization will not be that much. Even so, need to be considered that the results of interpretation from the six-arms caliper might be uncertain.

3. RESULTS

The interpretation of breakout orientation from caliper data from eight wells vary from 33-79.5° with standard deviation 4.3-26.1°. The **Figure 4** giving the example of the interpretation of four arm caliper logs from BO-1 well.

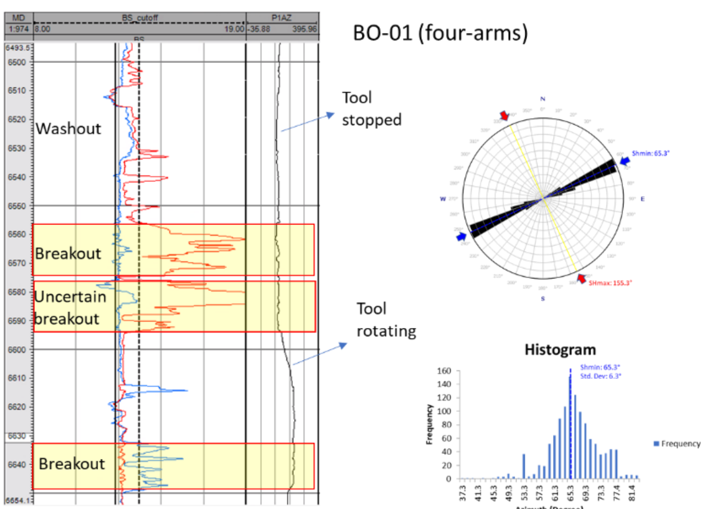

Figure 4 Four-arms caliper breakout interpretation from BO-1 well

In this study, only BK-5 well has the image log (FMI) to define the borehole breakout orientation, with the results of the orientation mode at N 72.5° E (**Figure 5**)

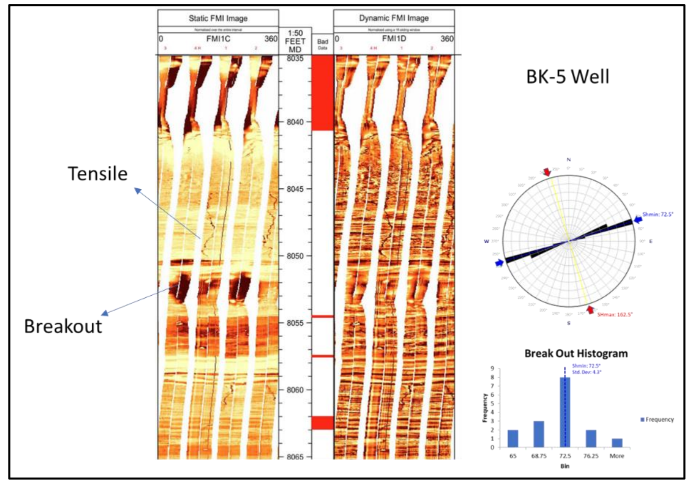

Figure 5 FMI Breakout interpretation from BK-5 well.

Based on World Stress Map (WSM) quality ranking, the standard deviation of all calculated breakout is still fair quality (C-Quality), with range 4.3 to 26.1°. However, if the reference is the total length of the borehole, even the best data in this research (KS-2 and BO-1) will only categorized as C-Quality and the rest of the data categorized as D-Quality. Despite this classification, the results showing consistence orientation with existing structure in this research area.

Table 1 Breakout Tabulation

Well	Bo Az	Std Dev	Length (m)
BK-5	72.5	4.3	3
TK-4	36	17.5	4
KS-2	73.6	11.5	40
CC-1	34.8	26.1	16
KJ-1	61.8	13.1	4
TB-1	79.5	21.4	17
BD-19	67.3	21.5	23
BO-1	65.3	6.3	48
KB-1	52.8	18.4	21

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Table 2 WSM Quality Ranking

A-Quality	B-Quality	C-Quality	D-Quality	E-Quality
Wells that have ten or more distinct breakout zones with a combined length > 300 m; and with s.d. ≤ 12°	Wells that have at least six distinct breakout zones with a combined length > 100 m; and with s.d. ≤ 20°	Wells that have at least four distinct breakouts zones with a combined length > 30 m; and with s.d. ≤ 25°	Wells that have less than four breakouts zones or a combined length < 30 m or with s.d. > 25°	Wells with no reliable breakouts detected or with extreme scatter of breakout orientations (s.d. > 40°)

4. DISCUSSION

The SW-NE structural trend is existed since the beginning of basin formation (Eocene -Oligocene) in West Natuna, as the product of transtensional movement forming a series of half graben in Natuna such as Anambas, Kakap, NB, and KB Graben (**Figure 6**). This half graben series, were reactivated during late Oligocene-Miocene inversion, resulting in similar trend with inheritance structures. Implied S_{Hmax} orientation at NW-SE trend is coincidence with major strike slip fault that believed the main force for the inversion occurred in West Natuna Basin.

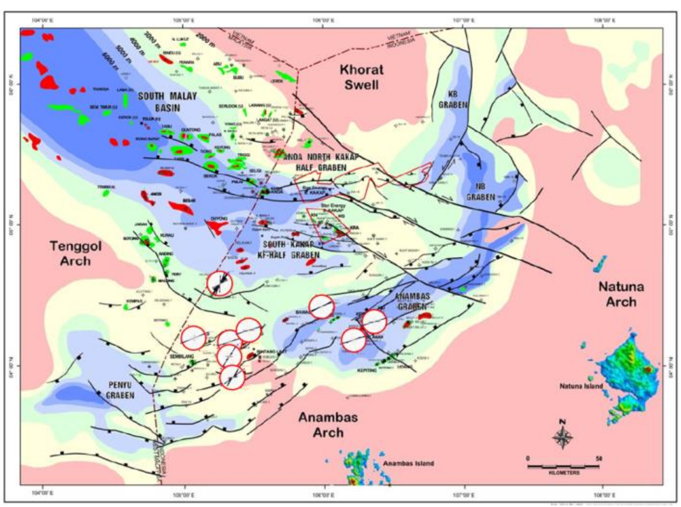

Figure 6 Breakout Plot in Regional structural framework (modified from Manur and Jacques, 2014).

Solisa et al. (2022) have interpreted that the inversion timing are related to the NW-SE strike slip fault movement. The most extensive inversion are the thickest sediment close to the major strike-slip fault, and become less inverted as the location is far from the major strike slip. Seismic cross-section within the study area (**Figure 7**) indicating the presence of a series of Paleogene half-grabens that were inverted during the Middle Miocene tectonic event. The location map also display the start timing of the structuration. The red color indicates an earlier inversion, while the green color indicates a later inversion.

The neighbourhood basin, such as Penyu Graben (sub-basin) and Malay Basin showing different structural orientations from West Natuna. Madon (2021) explained that the Malay Basin is a large NW-trending basin which developed along a major left-lateral strike-slip fault system that extends southeastwards across the present-day Gulf of Thailand towards Natuna. The structural pattern during basin formation might be the effect of inheritance configuration of amalgamated terrain from the pre-tertier basement creating several different structure. The Malay Basin keep opening and subsiding until present day with due to extension. It might be the results of maksimum horizontal orientation is almost parallel with the regional main fault, while in the natuna was highly inverted due to the major regional fault is perpendicular or oblique with maksimum horizontal stress.

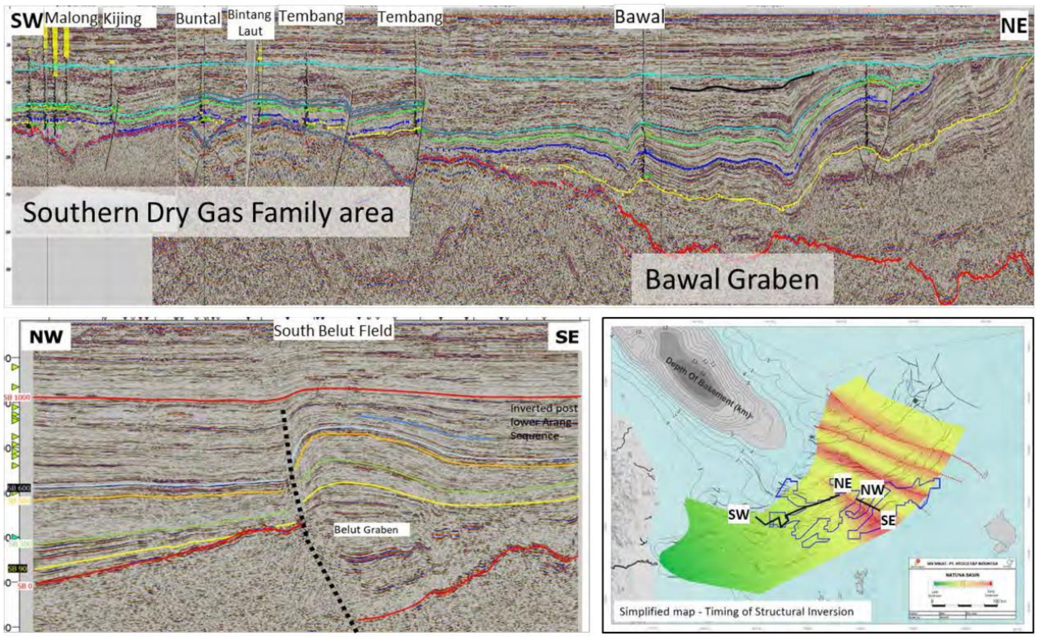

Figure 7 Regional seismic section across WNB area (Solisa et al., 2022).

5. CONCLUSION

Borehole breakout orientation from nine wells in research area showing consistence results with the orientation of the existing structures in the West Natuna Basin. The results show the major SW-NE trending fault is relatively parallel with present day minimum horizontal stress and perpendicular to the NW-SE maximum horizontal stress orientation, which responsible to the structural configuration in the West Natuna Basin.

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