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The Influence of Fluid Dynamics on Physical Uncertainties of Hydrocarbon Reservoir

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ABSTRACT - Uncertainty is often present in the relationship between physical property variables, especially the complexity increases, when mechanical properties are included. The problems becomes more interesting in cases, where fluid dynamics act as the primary contributing factor. Pore pressure changes is the main actor of every uncertainty of physical properties. Therefore, this study aimed to examine the influence of fluid dynamics on physical uncertainties of hydrocarbon reservoir. To achieve this objective, well data from production and enhanced oil recovery (EOR) operations between 1994 to 2007 were entangled. Specifically, 3D seismic data was incorporated to distribute physical and mechanical properties after well periodization. In this study, the impact of pore pressure changes on minimum horizontal stress from 1994-2017 was also examined. The results showed that changes in porosity were not significant, but variations in bulk modulus and Poisson's ratio remained observable. Furthermore, tensors field were not dominated by vertical stress, instead of horizontal stresses. Changes in pore pressure apparently had a significant impact on minimum horizontal stress. The increase of minimum horizontal stress reached approximately one third of pore pressure change. Consequently, the stress regime transitioned from the strike-slip fault in 1994 to thrust fault in 2017, emphasizing a significant increase in the influence of horizontal stress. While water injection and oil production did not lead to significant changes in physical properties, the effects were evident in the variations of Poisson's ratio.

Keywords: pore pressure, vertical stress, minimum horizontal stress, tectonic regimes.

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INTRODUCTION

Uncertainty of physical properties is often encountered as consequence of the uniqueness of geological occurence (intrinsic causalities) and the diversity of physical property estimation methods (extrinsic causalities). These uncertainties will potentially cause errors in describing relationship between variables, which is involved in physical properties modeling. These error are often not recognized, then the modeling are not correct, but these are actually built on the basis of physical property uncertainties, which may not actually be considered. Uncertainties could be observed from the inconsistency of the relationship between variables, which were occurred. The data distribution of each variables causes the parametric approach ineffectively (Ronoatmojo and Sinaga, 2022).

In terms of this matter, this paper will discuss the physical and mechanical uncertainties, due to the fluid dynamics, which filling the pores of reservoir. However, the complexity of uncertainty problems will be assumed by primary porosity, non-diagenetic factors, and no fluid expansion are found. This limitation needs to be conveyed, so it can be achieved conclusion more certainly related to tensor field. Fluid dynamics occur in production and EOR fields, over a certain time period. For this purpose, a research area was selected, which is fully controlled by primary porosity, non-diagenetic and non fluid expansion. Furthermore, this research is a continuation of it has been conducted by the authors, whereas tectonic forces can influence the relationship between pore pressure and effective stresses (Ronoatmojo et al, 2020; Ronoatmojo et al, 2021; Ronoatmojo et al, 2023). Shear tensile failure is proven to be present, due to pore pressure involvement. The pore pressure components possess similar direction with shear tensor of horizontal stresses. Consequently, matrices tend to shift and break away. Meanwhile, effective stresses changes, in terms of tectonic regimes will influence this orientation. Intrinsically, fluid dynamics will affect pore pressure and configuration of stress tensors. This study aims to determine the effect of stress fields on fluid dynamics activities, which influences changes in physical properties and mechanical properties.

Thus, fluid dynamics is an important aspect, it should not be ignored, which has implications for both, mechanical and physical properties. Fluid dynamics is represented by changes in pore pressure, instead of the position of pore pressure within a particular tectonic regimes can influence the configuration of the stresses field. The more it is important, it can be assumed that this parameter will control mechanical and physical properties of the reservoir. Pore pressure is fluid pressure, which is found in the pores of the formations. Pore pressure ranges in various number, from hydrostatic pressure, to severe overpressure (48% to 95% of the overburden stress). If the pore pressure is lower or higher than the hydrostatic pressure (normal pore pressure), it is abnormal pore pressure. When pore pressure exceeds the normal pressure, it is overpressure (Zhang, 2011). An increased occurrence of seismicity was observed in hydrocarbon production field. This refutes the assumption of rock stabilisation due to pore pressure reduction, related to the effective stresses (Terzaghi, 1943). Several authors have studied the relationship between fluid or gas extraction from subsurface reservoirs and the occurrence of seismicity and the triggering of earthquakes, respectively. Induced earthquakes and microseismicity are studied for different oil and gas fields (Segall, 1989; Doser et al., 1992; Nicholson and Wesson, 1992; Rutledge et al., 1998; Simpson, 1986).

More detailed determination of the changing in minimum horizontal stress ($\Delta\sigma_{hmin}$) and pore pressure (ΔP_p) produces pore pressure stress coupling (Hillis 2000). In the normal faulting regime, vertical stress (σ_v) is not affected by change in pore pressure (ΔP_p), therefore for increasing pore pressure, vertical effective stress ($\sigma_{v,eff}$) is reducing by the amount of pore pressure increase. Under consideration of coupling between P_p and σ_{hmin}, an increase in pore pressure leads to an increase in σ_h. The consequence is that $\sigma_{v,eff}$ decreases not by P_p, but by a reduced amount determined by the strength of the coupling, $\Delta\sigma_{hmin}/\Delta P_p$. Furthermore, in the thrust faulting regime, the effect of pore pressure stress coupling is extended to the consideration of a thrust faulting regime ($\sigma_1 = \sigma_{hmax}$; $\sigma_3 = \sigma_v$) and again under the assumption that the total vertical stress is not affected by changes in pore pressure (ΔP_p). Meanwhile in the strike slip fault regime, $\sigma_1 = \sigma_{hmax}$ and $\sigma_3 = \sigma_{hmin}$, both maximum and minimum horizontal stresses are equally affected by pore pressure stress coupling ($\Delta\sigma_{hmin}/\Delta P_p$). This means that the pore pressure - stress coupling does not have any effect on the differential stress, and thus on the size of the Mohr circle. Thus, in a strike-slip regime the Mohr circle is only horizontally shifted in the Mohr diagram during fluid injection or depletion (Altmann, 2010). Furthermore, the three conditions are integrated parts that cannot be separated from the uncertainty when encountering fluid dynamics. The conditions between changes in pore pressure and tectonic regimes influence each others, it means that when tectonic regimes are normal fault or thrust fault, the unbalanced stress field configuration can change the tensor field configuration, while in the strike slip regime, it will not have much effect.

Changes in σ_{hmin} is depend on P_p, which is described by the theory of poroelasticity (Biot, 1941), which generally explains the effect of draining or injecting fluid from/to the reservoir on the mechanical behaviour of the rock. Using the theory of poroelasticity and under uniaxial strain conditions, i.e. no lateral expansion or a horizontally infinite reservoir, Engelder and Fischer (1994) derive a space-and time-independent relationship between ,σ_{hmin} and P_p:

$$\sigma_{hmin} = \frac{v}{1-v}\sigma_v + \alpha\frac{1-2v}{1-v}P_p \quad (1)$$

$$\alpha = 1 - \frac{K_d}{K_g} \quad (2)$$

K_d is the drained bulk modulus and K_g is the bulk modulus of the granular. The vertical stress σ_v is given by the overburden weight, therefore σ_v doesn't change during fluid injection or depletion. Under this assumption and considering pore pressure change, pore pressure - stress coupling ratio by Engelder and Fischer (1994) becomes:

$$\frac{\sigma_{hmin}}{\Delta P_p} = \alpha\frac{1-2v}{1-v} \quad (3)$$

Thus, if minimum horizontal stress (σ_{hmin}) and pore pressure (P_p) can be measured from time-lapse observations, then we can obtain the coupling values. Minimum horizontal stress (σ_{hmin}) is usually assumed by measuring the fracture pressure using the LOT (leak of test) or XLOT (extended leak of test) methods. Meanwhile, maximum horizontal stress (σ_{hmax}) could be determined from re-opening hydraulic fracture, after fracture closure in the similar LOT or XLOT, and vertical stress could be estimated from RHOB log data. Pore pressure could be measured and estimated from log data.

The stress-strain relationship for fluid-saturated porous medium is identical to non-porous medium, it is expressed in terms of effective stresses as determined by the effective stresses. This is presented as:

$$\epsilon_{ij} = \frac{1+\nu}{E}\sigma'_{ij} - \frac{\nu}{E}\sigma'_{kk}\delta_{ij} \quad (4)$$

meanwhile,

$$\sigma'_{ij} = \left(K - \frac{2G}{3}\right)\epsilon_{kk} + 2G\epsilon_{ij} \quad (5)$$

therefore,

$$\epsilon_{ij} = \frac{1}{2G}\left(\sigma_{ij} - \frac{\nu}{1+\nu}\sigma'_{kk}\delta_{ij}\right) + \frac{\alpha}{3K}P_p\delta_{ij} \quad (6)$$

Equation 6 is important to show the relationship between stress-strain ratio with pore pressure of both porous and non-porous materials. Thus, any change in pore pressure can affect the elasticity ratio, and vice versa.

Finally, to relate effective stress, pore pressure with porosity, the following formula is used (Zhang, 2013):

$$P_p = \left(\sigma_v - (\sigma_v - \alpha p_n)\frac{ln\phi_0 - ln\phi}{cZ}\right)\Big/\alpha \quad (7)$$

where P_p is the pore pressure; σ_v is the overburden stress; p_n is the normal pore pressure, ϕ_0 is the porosity in the formation of the mudline; Z is the depth below mudline; c is a constant and can be obtained from the normal compaction porosity trend line. α is the Biot effective stress coefficient, and $\phi < \alpha < 1$.

The essential data collected over time is the development of pore pressure from 1930 to 2017, where the data was collected from wells around P-404 for the Z-600 reservoir layer. From the graph, we can obtain the field history. This field is positioned in North Sumatra Basin. Stratigraphicaly, the reservoir is known as Keutapang Formation (Late Miocene to Early Pliocene). It is identified as a product of deltaic sedimentation. It consists of shale interbedded with sandstone varies in size from fine sand to pebble conglomerate. The thickness of Keutapang Formation is 700 m to 1,500 m in East Aceh (Darman and Sidi, 2000) and in stress tensors it suggesting a near-equilibrium between compressive and tensile forces (Gultaf et al, 2025). This field is has been produced since early of 20th century. It was decline in production, therefore secondary recovery were carried out, with water injection.

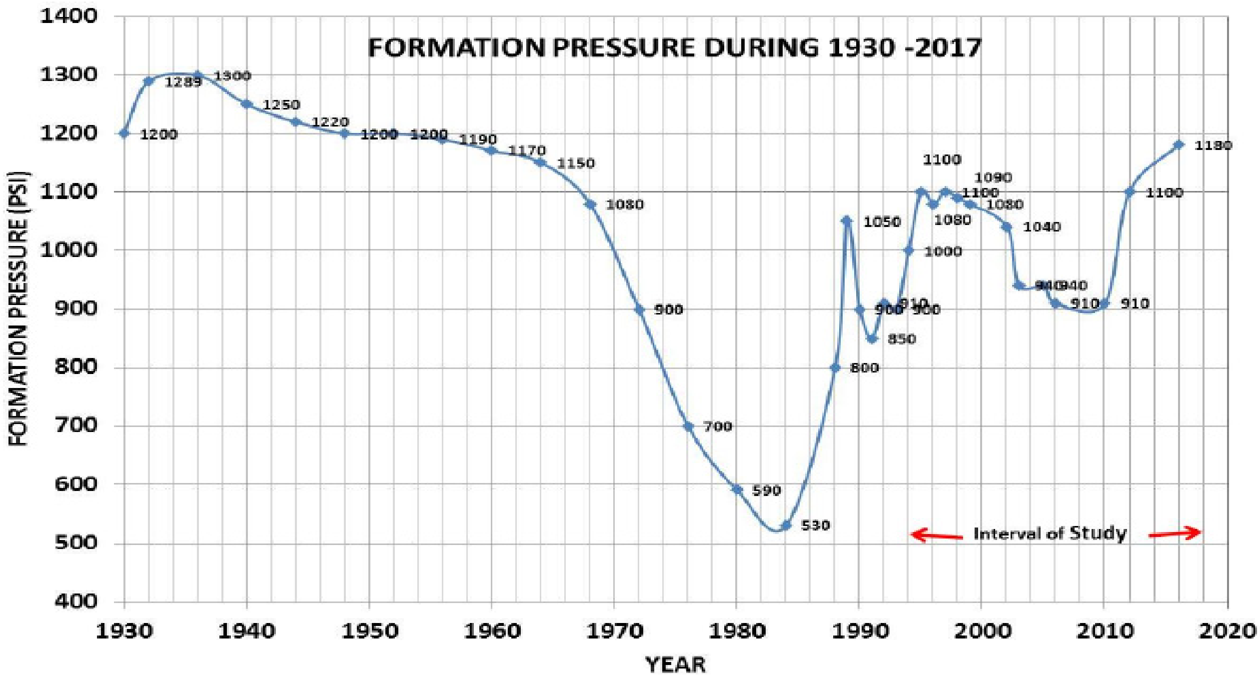

Figure 1. Formation pressure curve during period 1930 – 2017, it were collected around well P-404,. It decreased in 1984 from 1,300 psi to 530 psi, then it increased due to water injection during 1984 to 2017. Based on this time span, then period 1994 - 2017 was chosen as the time period for conducting this study, It appears that the curve is very fluctuatingd and it is indicating the intensity of fluid production and injection. it

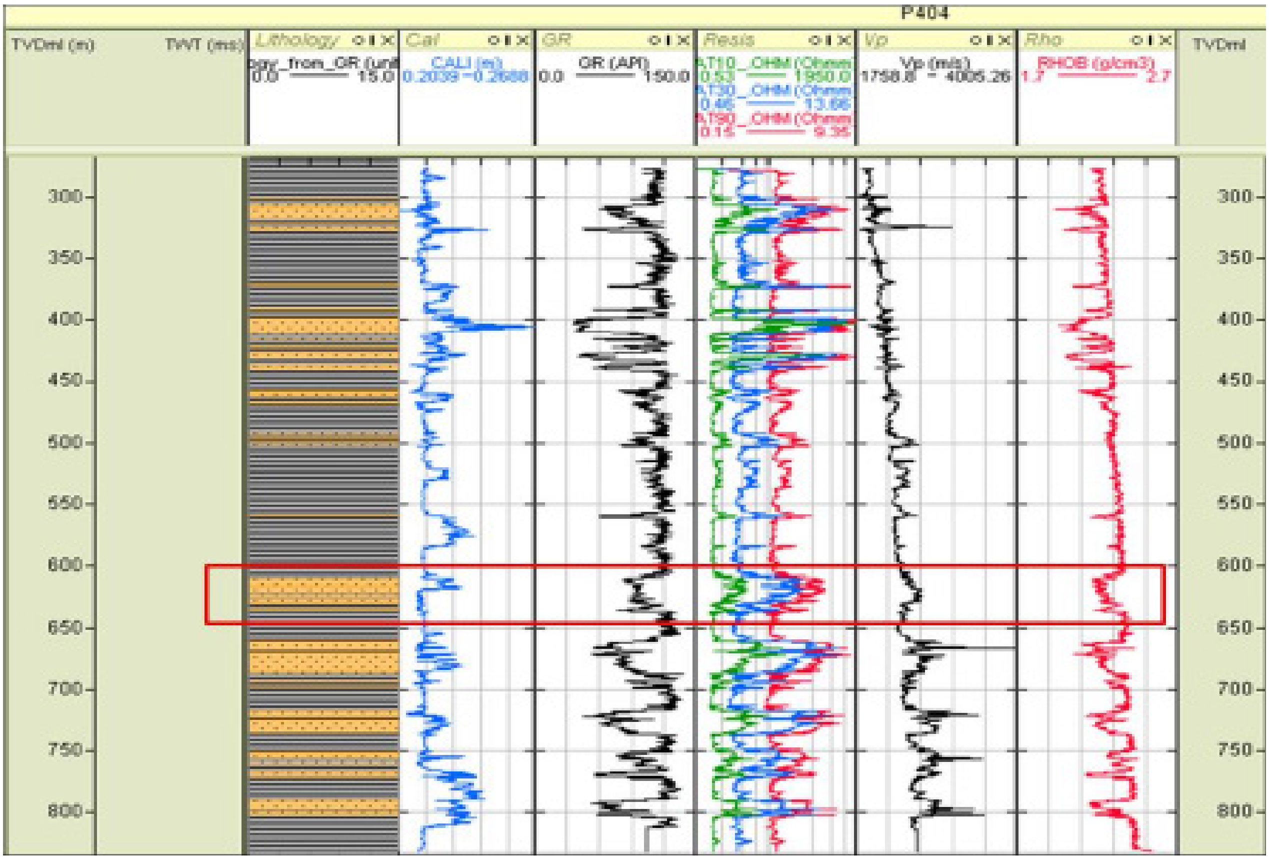

Figure 2. Data set containing log GR, caliper, log resistivity, log sonic and log RHOB of Well P-404 which appears Z-600 at depth 620 m - 640 m. This well is one of those selected in the periodization, to be integrated with seismic data.

Fig.1 shows collection of pore pressure data measured from several wells in the most dynamic area of the field. Generally, pore pressure data consists of production phase categories, namely from 1930 to 1984, where the pressure decreased from its original 1,300 psi to 530 psi. There are two plateaus in this period of decline, period 1932 - 1936 and 1948 - 1952. The lowest was in 1984. Then, pore pressure increased due to water injection, as result of EOR (enhanced oil recovery). Furthermore, a fluctuating graphs appears, due to fluid dynamics between production and fluid injection. The peak pore pressure achieved during this period was 1,180 psi.

The fluid dynamics period to be studied, occurred between production and injection, viz. post-1984, but because seismic data was acquired in 1994, therefore well data which is used from 1994 to 2017. Such as seen from Fig.1 that pore pressure in the period 1994 - 1995 increased from 1,000 psi to 1,100 psi, it is a part of the initial injection initiation phase. It plateaued until 1997, then it decreased gradually until 2010 to become 910 psi. After the initiation phase, pore pressure increased sharply during 2010 to 2016 from 910 psi to 1,180 psi, and oil production increased to become average 2,100 STB/day starting in 2011, from the previous average of 250 STB/day and then decreased to 500 STB/day in 2016.

The physical properties of Z-600 can be observed appropriately in the log data, one of them, originated from Well P-404. The sand layer with depth of 620 m - 640 m, which is indicated by the presence of low Gamma Ray, high resistivity, while increases, and low density (Figure 2). However, there is difference in the tendency between the pattern and density oppositely, but the shale density in general remains increasing, so it does not indicate any diagenetic process, which affects the pore pressure. Normal compaction trend can be observed well, from the and density.

METHODOLOGY

The objective of this study is Rantau shallow structure. This structure is located approximately 135 kilometers to the northwest from Medan (North Sumatera, Indonesia). This oil field has been produced since 1928 through R-01 well drilled by BPM and currently has 566 wells. It had been ever reached oil production peak in 1973 (32,477 BOPD and gas 27.4 MMSCFD). Before re-activated the shallow zone, it only produced 868 BOPD average from 23 wells (Shahab et al, 1994). Rantau Field is a part of North Sumatra Basin. Meanwhile, the Keutapang Formation (Late Miocene – Early Pliocene) is identified as a product of deltaic sedimentation. It consists of shale interbedded with sandstone varies in size from fine sand to pebble conglomerate. The thickness of Keutapang Formation is 700 m to 1500 m in East Aceh (Darman & Sidi 2000).

The main data needed in this study comprise of pore and fracture pressure measurements, log data estimation, well reports and core data. Meanwhile, seismic data is also used to distribute well data. Considering the data availability, it can be said that there are differences in measurement resolution and determination, this can result inaccuracy. Therefore to minimize, it is needed a strategy in modeling. Basically, it is focused on well data measurements, while log data is used to make an approach to wells which have no measurements. At least 114 well data are available, however there are not available data were used to build the initial model, only 43 wells from 1994 to 2017, after being periodized according to the year 1994 of seismic data acquisition (SN-368 HR, GS 20-DX, 5000 msec, 2 msec), with cut of 8% change in pore pressure between year to 1994 (Ronoatmojo et al. 2021).

Fig. 3 illustrates a complete picture of the research flow which is a synthesis of above problem solving, and is based on data availability. The research flow starts from learning the complete profile of pore pressure dynamics obtained from data measurements. Furthermore, an initial model is built, which based on the time period determination, after examined on the seismic data acquired in 1994, while pore pressure estimation from log data is carried out to meet periodization with a cut-off of +/- 8% from well estimation results in 1994. This number is the result of pore pressure change value is still considered to be in accordance with the change in seismic acoustic impedance, the well period was obtained from 1994 - 2001.

Furthermore, pore pressure will be estimated from log data, as well as mechanical properties, such as overburden pressure (lithostatic), maximum horizontal stress, minimum horizontal stress, Poisson's ratio and bulk modulus. 3-D modeling is based on log data that has been filtered with 8% cut off of measured pore pressure. This model is referred to as initial model for 1994. Meanwhile, the following annual model is done and examined on the pore pressure stress coupling ratio (equations 3, 4, 5 and

6). The final step is to observe horizontal slices for each mechanical and physical properties e.q porosity.

RESULT AND DISCUSSION

Pore pressure

Pore pressure estimation were done by Eaton method, which uses resistivity log, and equivalent depth using sonic log, if available. The results obtained showing relative differences, when compared with the measurement results. This is important to notify, as uncertainty related to extrinsic factors. The reason is the estimation based on both methods were greatly influenced by the recognition of normal compaction trend, while the measurement is based on transient observation of the time of pore pressure flowing fluids (Figure 4). It appears that the pore pressure at Z-600 is not too high compared to the hydrostatic pressure, indicated by the total gas rising, and at the same time, drilling break is occurred.

Pore pressure is the main indicator to define the presence of fluid dynamics, if there is a change in pore pressure, it is certain that there has been change in fluid mass and volume that fills pores. These changes can be triggered by fluid flow, stresses change or temperature change. Physically, the dynamics of pore pressure will also change physical properties. During this decade, there has been rapid development of methods for identifying a pore pressure system, especially in the growth of overpressure. Beside of Bowers method, the porosity correlation method, and other empirical methods proposed in the mid and late 1990s, several new approaches have been introduced and applied, such as the density-velocity crossplot method, which has proven effective in identifying the origin of overpressure (Bowers 2011).

Basically, pore pressure prediction method is based on determining normal compaction trend (NCT) that occurs globally during sedimentary deposition (Tribuana et al. 2016), which is dominated by impermeable rocks. These sediments are described as shale, and they are recognized from gamma-ray log observations. Thus, pore pressure estimation is placed as modeling tools by utilizing the relationship between pore pressure and acoustic impedance from seismic data, while measurement is allocated to carry out the process of selecting pore pressure, in accordance with seismic data, i.e filtering with a cut-off of 8%.

Figure 5 illustrates the relationship between pore pressure and acoustic impedance. Generally, there is proportional relationship. It can be understood, this tendency arises due to compaction, which increases acoustic impedance that occurs in the shale lithology, whereas fluids cannot flow, thus increasing pore pressure. However, the reservoir layer at 600 meters, seems increase in pore pressure, but acoustic impedance tends to be constant. Fig.5a shows the

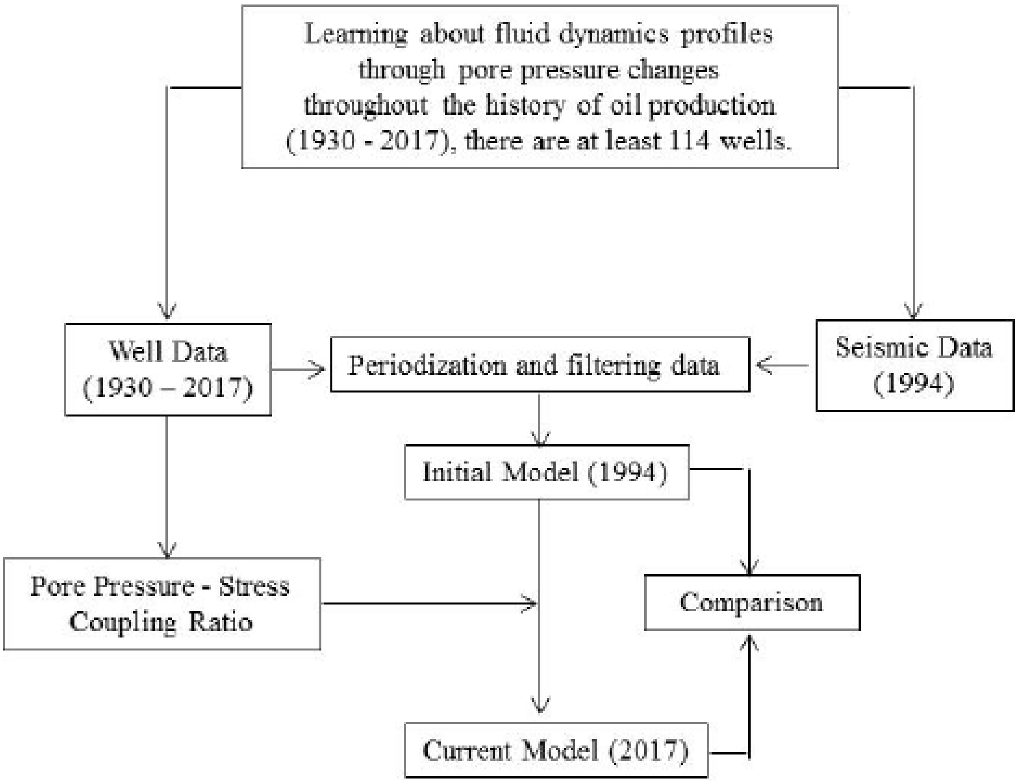

Figure 3. Diagram describing the methodological flow of this study.

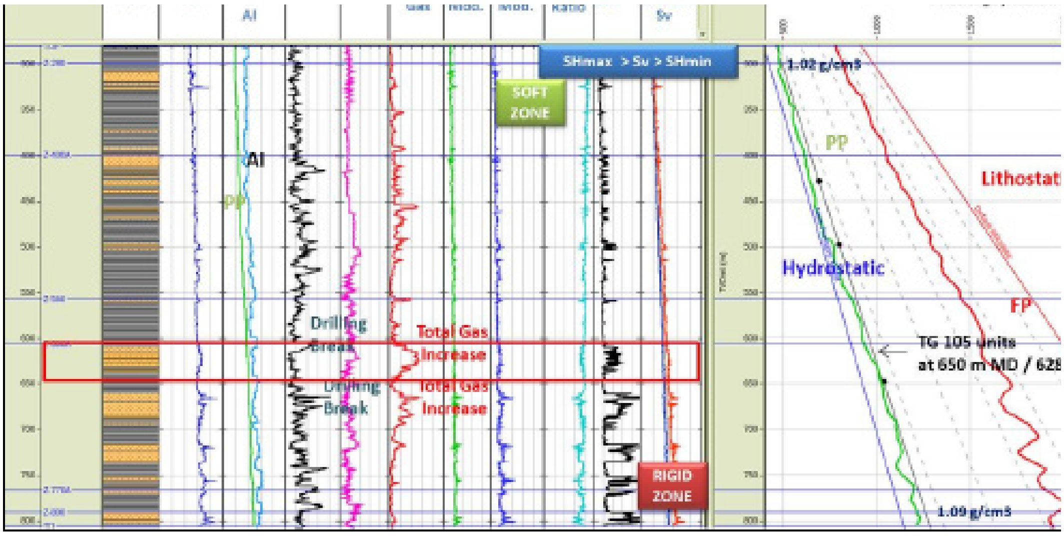

Figure 4. Mechanical properties of Z-600 in P-404, which are characterized by the presence of drilling breaks and increasing total gas, while it is observed that fracture pressure is close to lithostatic pressure, and σ_shmax>σ_shmin>σ_v which is called strike slip fault regime.

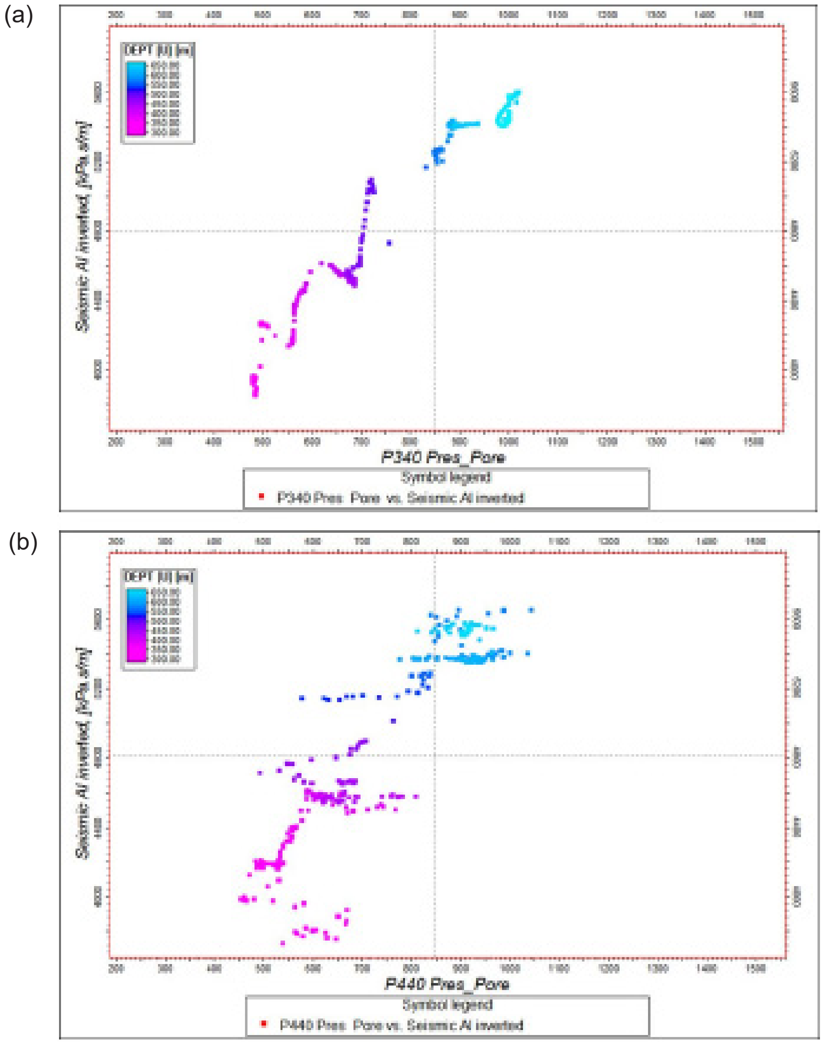

Figure 5. Crossplot AI versus Pore Pressure (a) filtered wells (P-340) (b) un-filtered wells (P-440). It appears that there is a strong relationship between AI and pore pressure in Well P-340, so it can be used to build an initial model, while Well P-440 could not be used for this work.

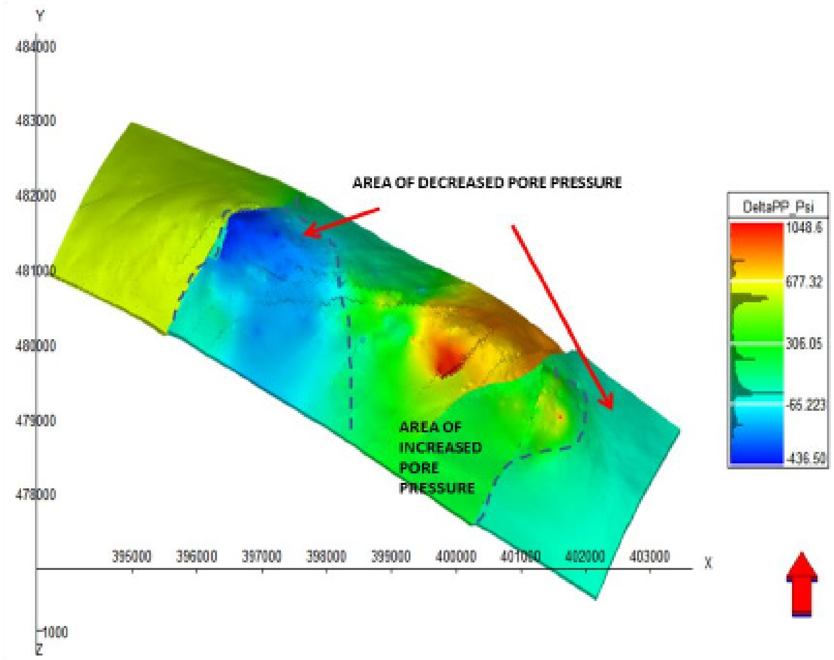

Figure 6. The difference of pore pressure during 1994 – 2017. The green, yellow and red areas are increase, otherwise the blue area is decrease. The area where pore pressure increase is related to the intensity of water injection activities, it appears that the effect of water injection is restricted by a structural compartments.

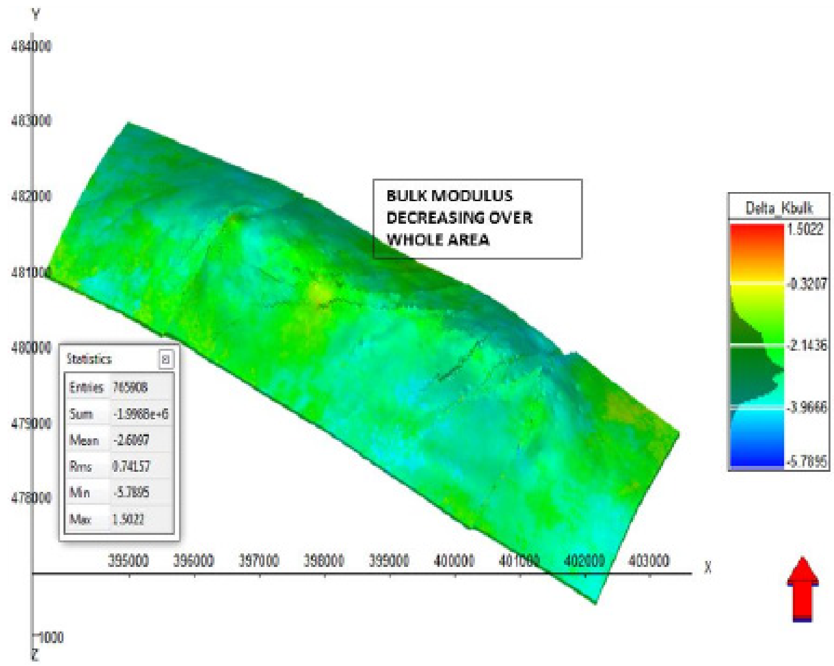

Figure 7. The difference of Bulk modulus during 1994 - 2017. It appears decreasing over whole area. Somewhat surprisingly, in areas where pore pressure was reduced, but Bulk modulus also was reduced.

relationship for one well (P-340) which can be included in the 3D seismic modeling, meanwhile Fig.5b shows the relationship for well is not suitable (P-440).

According to pore pressure changes modeling, during 1994-2017, it appears that there is not only area with increased pore pressure, but also area with decreased pore pressure. It might be due to structural compartments. In the area of increased pore pressure is located on the water injection platform, while in the area of decreased pore pressure is outside of the injection sweep influence.

Mechanical properties

Mechanical properties can be known from the ability of lithology to withstand the influence of tension during drilling, and reflected when drilling mud pressure is excessive, appearing as drilling induced tensile fracture (DITF). Fracture pressure is measured in leak of test (LOT) procedure. However, pore pressure prediction can be done using log data.

Fig.4 illustrates fracture pressure prediction from log data, where fracture pressure appears to be higher than pore pressure. In the drilling tradition, the value of mudweight is designed to be between pore pressure and fracture pressure values. If the mudweight value tends to be close to the pore pressure, breakout will be occurred. Conversely, if the value is close to fracture pressure, drilling induced tensile fracture will be occurred, respectively on the drilling wall.

Several mechanical properties could be estimated from the initial modeling from seismic and log data, including minimum horizontal stresses, maximum horizontal stresses, overburden pressure, bulk modulus and Poisson's ratio. Regarding to initial model, other models will be built, related to changes in mechanical properties, due to fluid dynamics, which are reflected in pore pressure changing. Furthermore, by using Eq.6 which denotes relation between effective stress and pore pressure, therefore mechanical attributes would be obtained. Fig.7 and Fig.8 illustrate the difference of Bulk modulus and Poisson's ratio changing of 1994 and 2017. It is important to notify that in areas where pore pressure was reduced, but Bulk modulus also was reduced, it is not usual.

Physical properties

After initial modeling of mechanical properties, the implications for changes over time triggered by the dynamics of pore pressure, then the physical property e.g. porosity also experiences to change. Porosity estimation is based on filtered log data on seismic data in 1994, then porosity changes are based on Eq.7 which relates porosity to pore pressure, overburden pressure and normal pressure (hydrostatic). Finally, time lapse physical modeling is applied to simulate physical property in 2017. The difference between attributes is shown in Fig.9.

In term of the increased porosity, it is associated with the increased pore pressure, unless in the north west area, where the pore pressure increases, but the porosity decreases. It is important to be notified that there might be the different tectonic regime is still ongoing in this field.

Discussion

The relation between pore pressures that describe fluid dynamics and other mechanical properties of the attributes have been produced, will be used to describe the influence of the stresses constellation of particular tectonic regime, here lies the answer to the uncertainty due to fluid dynamics. Berglar et al. (2008) found that strike-slip faulting has controlled the evolution of the fore-arc basin since the Late Miocene. The Mentawai Fault Zone extends north of Simeulue Island and was likely connected further north to the Sumatra Fault Zone until the late Miocene. Since then, this northern branch has thrust westward, initiating the West Andaman Fault in the Aceh region. The connection to the Mentawai Fault Zone is a left-hand stepover.

Effect of Fluid Dynamics on Pore Pressure

Fluid dynamics is a trigger for mechanical and physical property changes, which pore pressure is the most responsible variable or agent of change. Every changes can be measured and estimated to predict the dynamic of mechanical and physical properties changes.

In this study, the lithology studied is Z-600 sand reservoir, which is permeable, so that pores are connected. Fig.5a shows, there is strong relationship between pore pressure with acoustic impedance, meanwhile, it is not occurred if wells are outside of filtered data as shown in Fig.5b. That is why, we cannot use log data from wells whose characteristics are already very different from seismic data. In other words, changes in pore pressure have resulted in physical changes, which can be observed from their compatibility with seismic data over a certain period. Thus, if the log data obtained from hydrocarbon production field, it must be periodized firstly, with changes in formation pressure during production, before it being used for modeling. In reality, it is still common to use various log data without considering the effects of fluid dynamics. This is important to underline as a result of this research. It is observed from Fig.6 that the increase in pore pressure occurred in the period 1997 - 2017 in the green, yellow and red areas, while in the blue area there was a decrease in pore pressure, this indicates that the water runoff area from enhanced oil recovery (EOR) treatment is limited by compartmentalization due to the presence of fault structures.

Regarding to this phenomenon, it can be summarized that the change in pore pressure which is occurred during fluid dynamics, it tends to be more certain, which is triggered by the presence of permeability and compartments due to the structure. If there is a conduit for fluid to flow, so pore pressure will increase or decrease, depending on fluid injection or fluid production.

Effect of pore pressure on porosity

Furthermore, it can be seen from Fig. 9, the increase of pore pressure in the green, yellow and red areas, it did not have a significant impact on changes in porosity. Likewise, there was also no significant change in the blue area, which is an area with a decrease in pore pressure,. However, this is not similar if we observed from elastic modulus. It is a change on a small scale

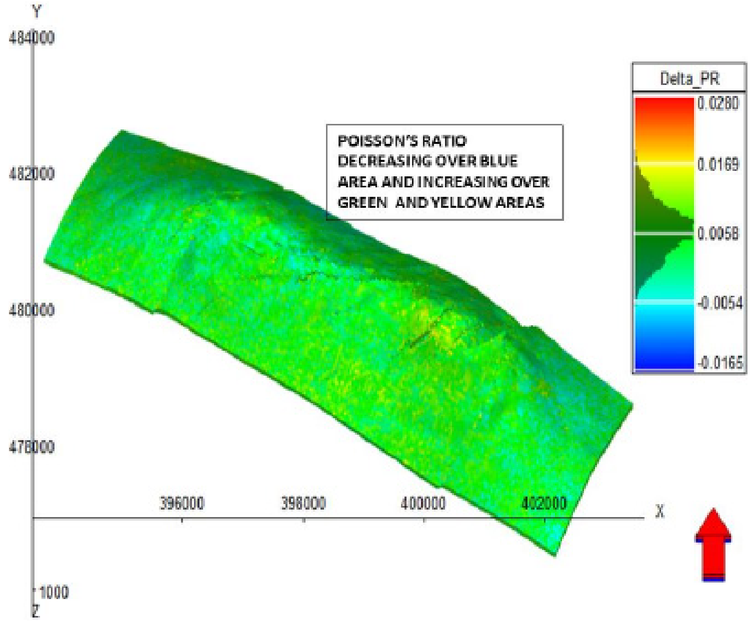

Figure 8. The difference of Poisson's ratio during 1994 - 2017. It appears decreasing over blue area and increasing over green and yellow areas. In this case the response of Poisson's ratio is different from the Bulk modulus.

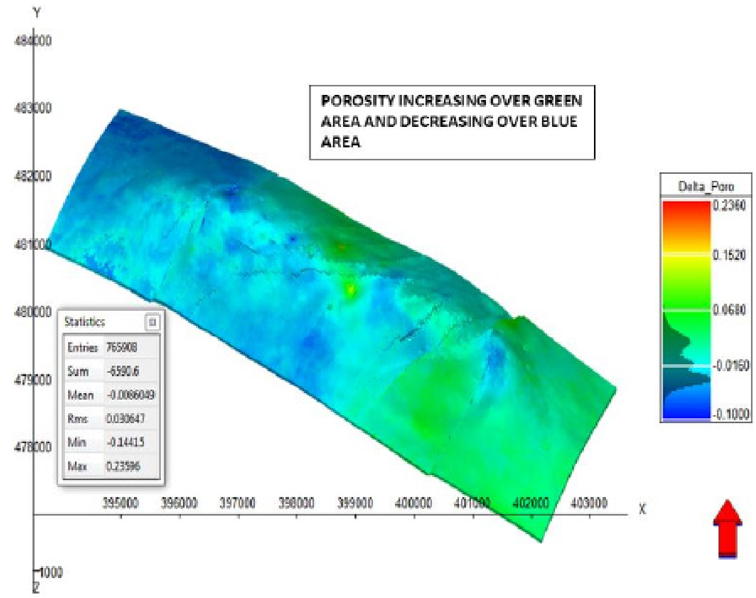

Figure 9. The difference of porosity during 1994 - 2017. It appears increasing over green area and decreasing over blue area. In this case, the area of increased porosity is associated with an area of increased pore pressure, unless in the north west area, where the pore pressure increases, but the porosity decreases.

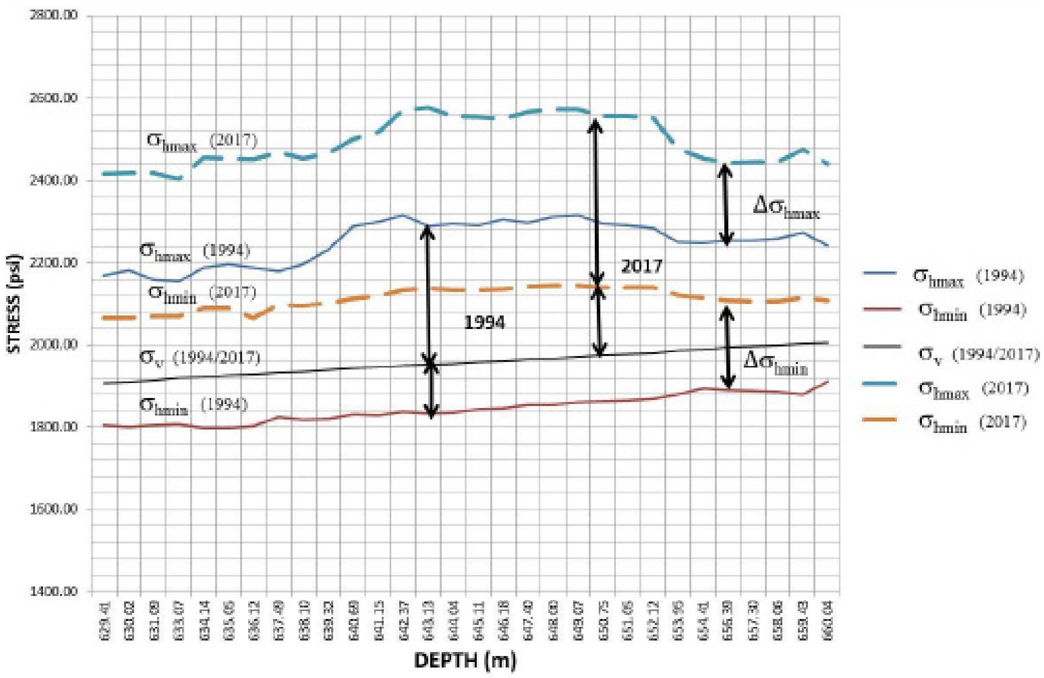

Figure 10. The stresses profile of Z-600 (P-404), it appears that fluid dynamics has increased the maximum horizontal stress (σ_{hmin}) and minimum stress (σ_{hmin}) during 1994 - 2017, so the tectonic regime changed from strike slip fault to thrust fault. The increase in stress value indicates that the intensity of water injection is very dominant during this period, but it should be noted that the value of its influence on the two stresses is proportional, only becausevertival stress (σ_v) is relatively constant, it is exceeded by minimum horizontal stress (σ_{hmin}).

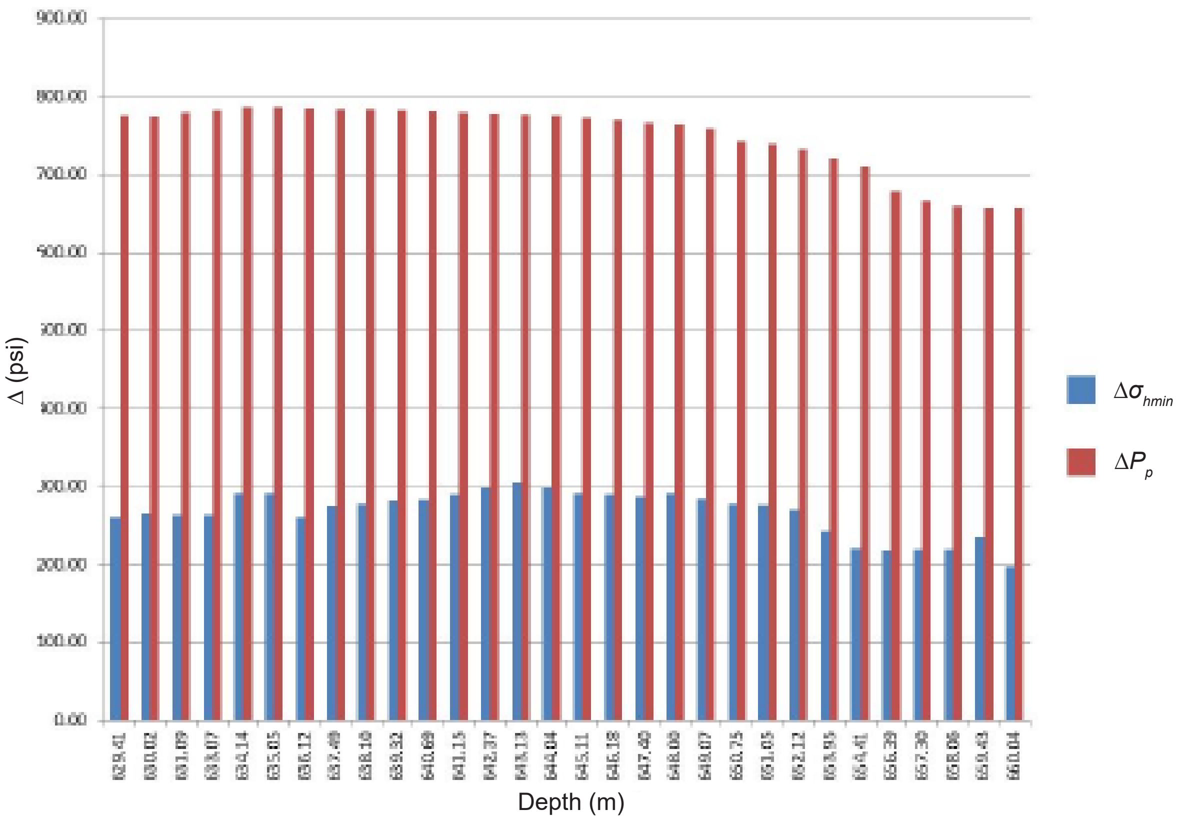

Figure 11. Pore pressure changes (ΔP_p) of Z-600 (P-404) during 19941994 - 2017, which resulted the minimum horizontal stress changes ($\Delta\sigma_{hmin}$).

decreasing of bulk modulus (Fig.7) and increasing in green and yellow areas and decreasing in blue area of Poisson's ratio (Fig.8). It is very interesting that several changes in pore pressure were actually not only in a certain period of time entirely, but there are dynamic increasing and decreasing, as shown in the curve (Fig.1), which pore pressure pattern experiences plateau, then decreases until 2006, and finally increases until 2017.

Thus, an important point to note is fluid dynamics that occurred up and down does not have significant impact on changes in physical properties, but its dynamics can still be observed in its mechanical properties. In addition, we can also observe that decreasing in pore pressure does not necessarily result in decreasing in porosity, as occurred in the normal fault tectonic regime, but it can be occurred oppositely,it indicates that the maximum principal stress in this configuration of the tectonic regime is no longer vertical stress (σ_v), but maximum horizontal stress (σ_{hmax}).

Effect of fluid dynamics on pore pressure stress coupling ratio

Studies on the influence of fluid dynamics on physical and mechanical properties can be held by observing changes in pore pressure and stresses. The present-day maximum horizontal stress (σ_{hmax}) in Thailand, Vietnam and the Malay Basin is predominately north-south, consistent with the radiating stress patterns arising from the eastern Himalayan syntaxis (Tingay et al, 2012). Meanwhile, Krishna and Sanu (2002) compiled 92 moment tensors of events occurring in this region from various sources, indicating a strike-slip fault regime. Furthermore, it is observed from the stress configuration that during the period 1994 - 2017, there was regime changing from the strike-slip fault regime ($\sigma_{hmax} > \sigma_v > \sigma_{hmin}$) to the thrust fault regime ($\sigma_{hmax} > \sigma_{hmin} > \sigma_v$). The data used to make observations is Well P-404 data (Fig.10). It can be seen that maximum horizontal stress (σ_{hmax}) and minimum horizontal stress (σ_{hmin}) increased in 2017, so this is reliable with the increase in pore pressure.

The maximum horizontal stress (σ_{hmax}) and minimum horizontal stress (σ_{hmin}) in 2017 are shown by the dot line (Fig. 10), while the vertical stress (σ_v) is considered constant. The difference that exists in 2017, the minimum horizontal stress (σ_{hmin})values has exceeded the the vertical stress (σ_v), this is possible due to the water injection activities for 23 years. It is interesting to relate to the insignificant changes in physical properties, but can still be observed in changes in mechanical properties. Regarding to the discussion above, it appears that fluid dynamics causes decrease in bulk modulus and increase in Poisson's ratio.

Meanwhile, Fig. 11 illustrates the change of pore pressure (ΔP_p) is greater than minimum horizontal stress ($\Delta\sigma_{hmin}$). Minimum horizontal stress change reached at least one third of pore pressure. If we observe more detail, the strike-slip fault regime gradually changes to the thrust fault regime, which maximum horizontal stress (σ_{hmax}) is the major principal stress, while the smallest stress is minimum horizontal stress (σ_{hmin})changes to become vertical stress (σ_v). This means that the increase of pore pressure in 1994 - 2017 will actually increase the minimum horizontal stress (σ_{hmin}) so that the tectonic regime becomes thrust fault.

The failure found in this case is the presence of sand-production, which the grain bounding is broken, due to shear tensile failure (Ronoatmojo et al, 2020), Hence, minimum horizontal stress (σ_{hmin}) influencing more dominant than vertical stress (σ_v). It is reflected by an increase of Poisson's ratio, however insignificantly change the porosity value. Due to the tectonic regime not being a normal fault regime where vertical stress (σ_v) is the major principal stress (σ_1), so the increase in Poisson's ratio is caused by the minimum horizontal stress (σ_{hmin}), this is commonly referred to as simple shear (Thiel et al, 2018).

CONCLUSION

Maximum horizontal stress (σ_{hmax}) as the primary principal stress exceeds vertical stress (σ_v), which is the tectonic configuration of this area of study, is an important factor. The uncertainty of physical and mechanical properties that occurs in the reservoir, when there is fluid dynamics, is closely related to the intensity of injection and production, as seen from the pore pressure curve, which is presented fluctuatively. In addition, the existing tensor field framework also influences, which vertical stress (σ_v) is not the primary principal stress, then pore pressure change will result significantly, in the minimum horizontal stress change ($\Delta\sigma_{hmin}$). Thus, it will increase the potential of shear tensile failure. But it does not leave any significant changes in physical properties such as porosity. It is different, if the vertical stress (σ_v) is the primary principal stress.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
σ_1	Primary Principal Stress	MPa or psi
σ_2	Secondary Principal Stress	MPa or psi
σ_3	Tertiary Principal Stress	MPa or psi
σ_{hmax}	Maximum Horizontal Stress	MPa or psi
σ_{hmin}	Minimum Horizontal Stressn	MPa or psi
σ_v	Overburden/Vertical Stress	MPa or psi
σ'_{ij}	Effective Stress	MPa or psi
P_p	Pore Pressure	MPa or psi
P_n	Normal Pore Pressure	MPa or psi
ϵ_{ij}	Stress to Strain Ratio	Newton/m^2
α	Biott-Willis coefficient	none
υ	Poisson's ratio	none
K_d	Bulk modulus (drained)	Newton/m^2
K_g	Bulk modulus (granular)	Newton/m^2
E	Young Modulus	Newton/m^2
G	Shear Modulus	Newton/m^2
ϕ	Porosity	Percentage
Z	Depth	meter

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