AIP Conference Proceedings

scitation.org/journal/apc

Volume 2245

2nd International Conference on Earth Science, Mineral, and Energy

---

Yogyakarta, Indonesia • 3 October 2019

Editors • Johan Danu Prasetya, Tedy Agung Cahyadi,
Isara Muangthai, Lilik Eko Widodo, Aldin Ardian,
Syafrizal Syafrizal and Robbi Rahim

ICEMINE 2019
2nd INTERNATIONAL CONFERENCE ON EARTH SCIENCE,
MINERAL AND ENERGY

FACULTY OF
MINERAL TECHNOLOGY

AIP
Publishing

AIP Conference Proceedings

scitation.org/journal/apc

Volume 2245

2nd International Conference on Earth Science, Mineral, and Energy

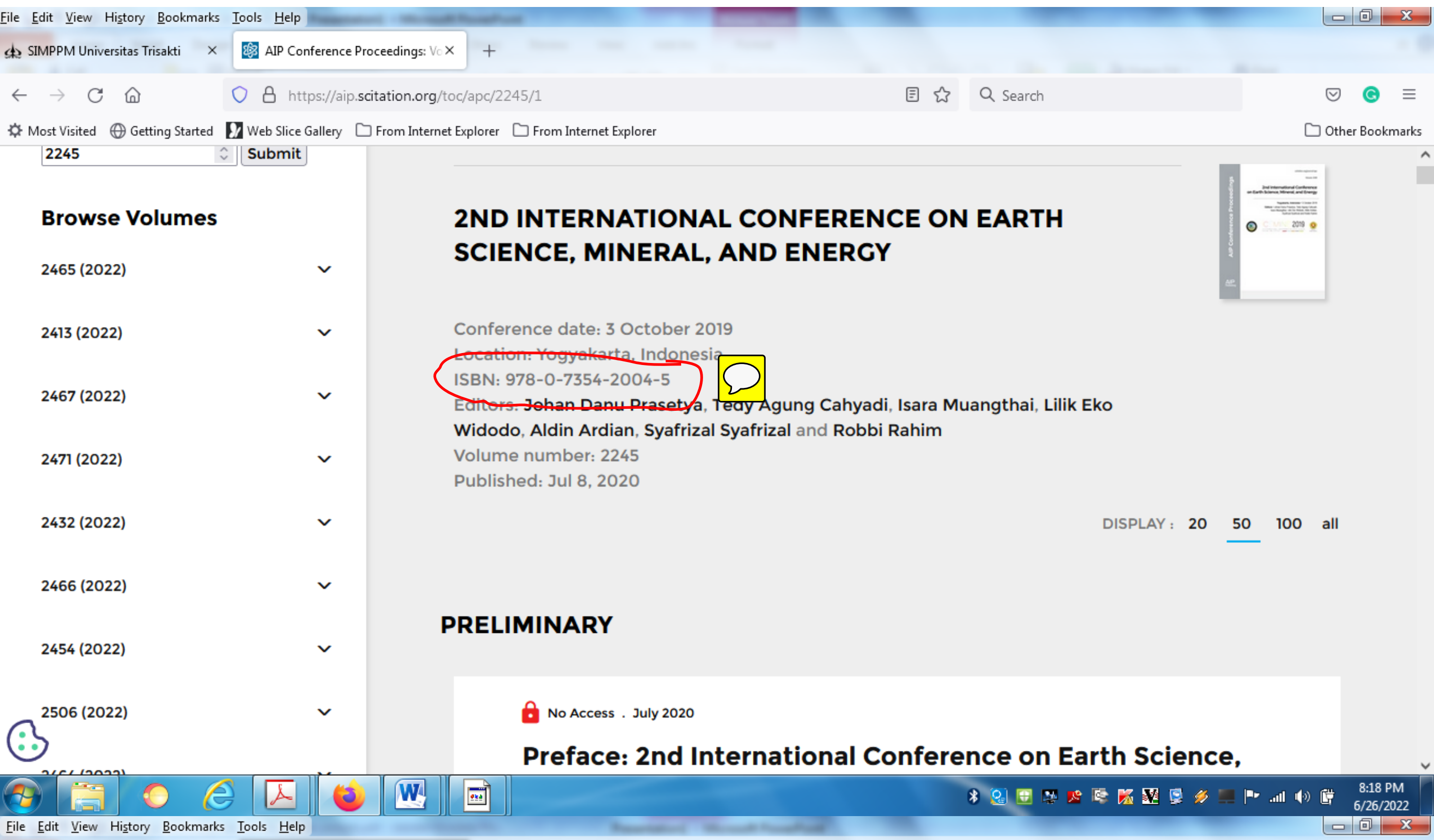
Yogyakarta, Indonesia • 3 October 2019

Editors • Johan Danu Prasetya, Tedy Agung Cahyadi, Isara Muangthai, Lilik Eko Widodo, Aldin Ardian, Syafrizal Syafrizal and Robbi Rahim

ICEMINE 2019
2nd INTERNATIONAL CONFERENCE ON EARTH SCIENCE, MINERAL AND ENERGY

FACULTY OF MINERAL TECHNOLOGY

AIP Publishing



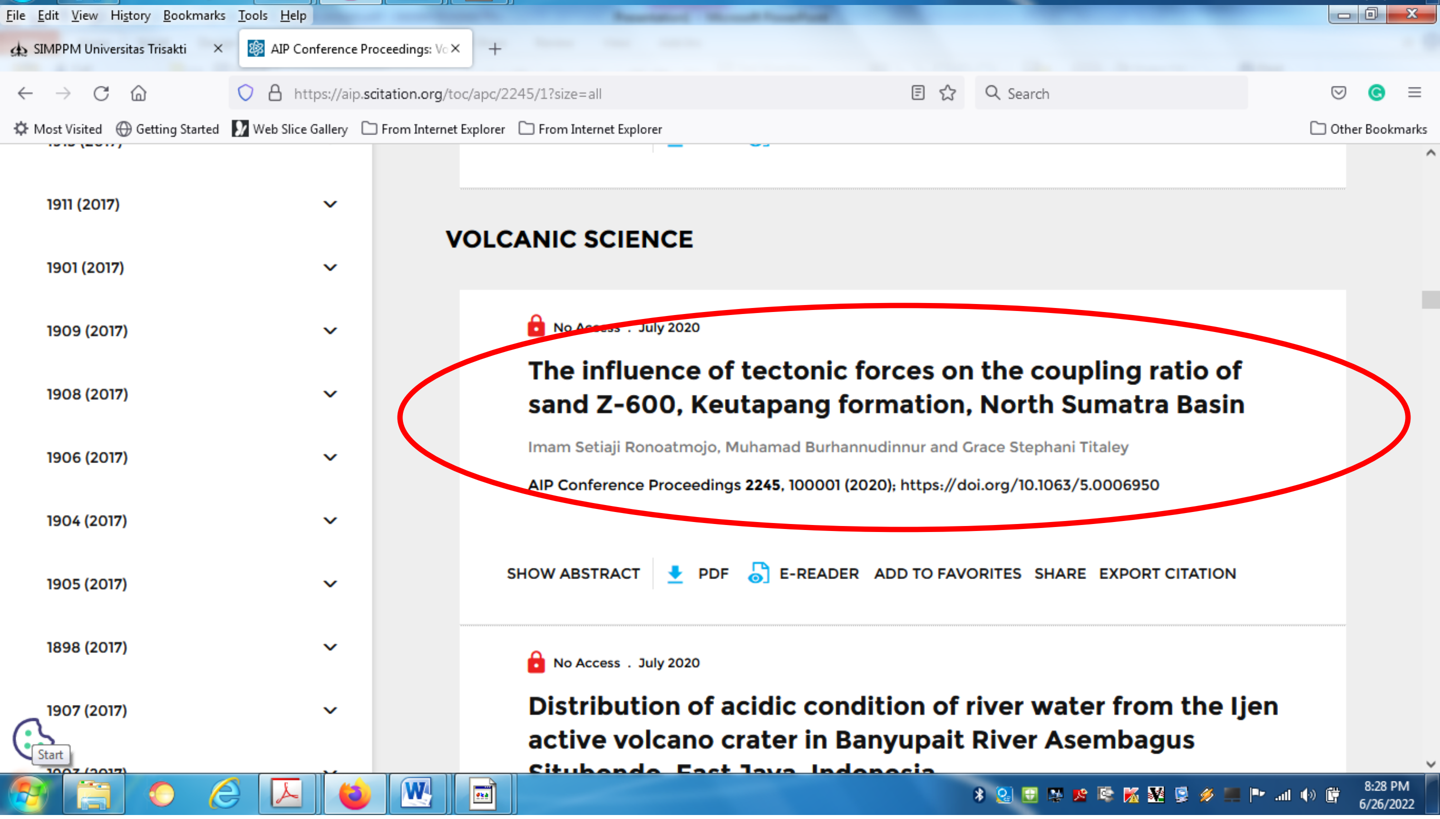
2ND INTERNATIONAL CONFERENCE ON EARTH SCIENCE, MINERAL, AND ENERGY

Conference date: 3 October 2019
Location: Yogyakarta, Indonesia
ISBN: 978-0-7354-2004-5
Editors: Johan Danu Prasetya, Tedy Agung Cahyadi, Isara Muangthai, Lilik Eko Widodo, Aldin Ardian, Syafrizal Syafrizal and Robbi Rahim
Volume number: 2245
Published: Jul 8, 2020

PRELIMINARY

No Access . July 2020

Preface: 2nd International Conference on Earth Science,



VOLCANIC SCIENCE

No Access . July 2020

The influence of tectonic forces on the coupling ratio of sand Z-600, Keutapang formation, North Sumatra Basin

Imam Setiaji Ronoatmojo, Muhamad Burhannudinnur and Grace Stephani Titaley

AIP Conference Proceedings **2245**, 100001 (2020); https://doi.org/10.1063/5.0006950

No Access . July 2020

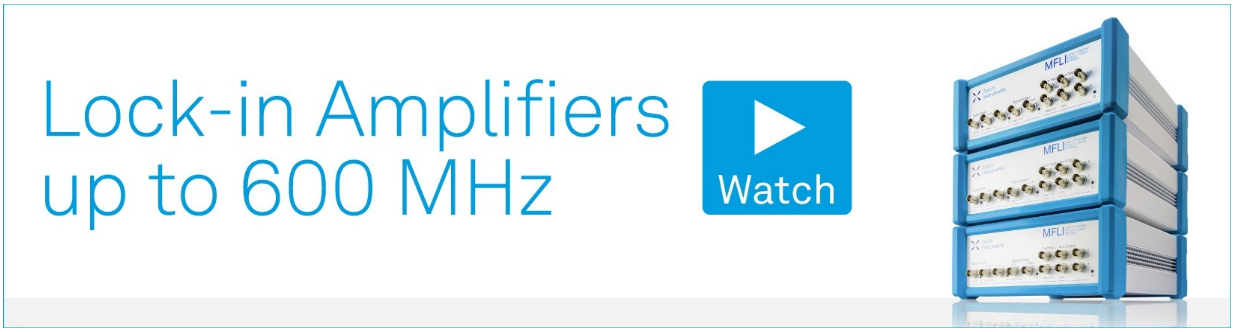
Distribution of acidic condition of river water from the Ijen active volcano crater in Banyupait River Asembagus Situbondo, East Java, Indonesia

AIP Conference Proceedings

The influence of tectonic forces on the coupling ratio of sand Z-600, Keutapang formation, North Sumatra Basin

Cite as: AIP Conference Proceedings **2245**, 100001 (2020); https://doi.org/10.1063/5.0006950
Published Online: 08 July 2020

Imam Setiaji Ronoatmojo, Muhamad Burhannudinnur, and Grace Stephani Titaley



The Influence of Tectonic Forces on the Coupling Ratio of Sand Z-600, Keutapang Formation, North Sumatra Basin

Imam Setiaji Ronoatmojo[1, a)], Muhamad Burhannudinnur[1)] and Grace Stephani Titaley[2)]

[1] Faculty of Earth Technology and Energy, Universitas Trisakti, Jl. Kyai Tapa No.1, Jakarta 11440, Indonesia
[2] PT. Pertamina EP, Menara Standard Chartered No. 164, Lt 16, Jl. Prof. Dr. Satrio, Jakarta 12950, Indonesia

[a)]Corresponding author: aji.rono@trisakti.ac.id

Abstract. The tectonic mechanism is a mechanism that involves tectonic conditions in the area which affects the dynamics of poroelasticity. Elastic modulus in the porous medium will go through change along with fluid dynamics. The loading factor in the tectonic mechanism is followed by the tectonic forces. The aim of this study is to learn the impact of a tectonic mechanism on the coupling ratio during oil production and water injection. The objective zone of this study is a part of thrust fault regime, which is changed to be strike-slip fault regime. The sand reservoir of Z-600 is in the transition condition so that the dominance of S_V and S_{hmin} has a strong influence on a coupling ratio change. The fluid dynamics occurring during this period are oil production and water injection. Observations were made on mechanical properties and pore pressure changes. The coupling ratio estimation starting from 1994 until 2017 refers to a historical production matching, which demonstrates a rock strength response in the variation of existing tectonic regime position. Mohr diagram analysis was done, based on the Coulomb failure criterion. It reveals that pore pressure change is not always equal to the change in stress difference or deviatoric stress, due to the nature of irreversible porosity change during fluid dynamics. The horizontal stress might cause shear-tensile failure, it initiates a sanding problem potential.

Keywords: tectonic mechanism, coupling ratio, rock strength, shear-tensile failure, sanding problem

INTRODUCTION

A homogeneous material modifies shape vertically and horizontally under a constant burden whilst the horizontal stress is zero, and the vertical stress in each location is equal to the overburden pressure. If the horizontal stress components are compressive and equal to a fixed ratio of the top-burden and the side boundaries, the Poisson ratio ν is a material constant which generates stress ratios:

$$S_{hmin}/S_V = \nu/(1 - \nu) \tag{1}$$

The situation of fixed stable with vertical load is similar to the non-tectonically influenced basins, which increase linearly with depth. The geomechanical properties heterogeneity causes a different stress ratio and the principal stress axis rotation. Fault plane disrupts homogeneous tendencies in stress. Tectonic processes generally insert compressive stress or tensile stress to the horizontal component. The expansion of the model to reduce horizontal stress can return a compressive (positive) stress into a tensile (negative) stress, while the compressive boundaries can enlarge the horizontal stresses so that it exceeds the vertical stress and develop the maximum principal stress [1].

Pore pressure is the pressure value measured in pore fluid. It is mostly due to the weight of top-burden, but fluid run along with compaction can reduce pore pressure. The pressure is usually smaller than lithostatic pressure. In

2nd International Conference on Earth Science, Mineral, and Energy
AIP Conf. Proc. 2245, 100001-1–100001-9; https://doi.org/10.1063/5.0006950
Published by AIP Publishing. 978-0-7354-2004-5/$30.00

porous rock that can not be compacted, the lithostatic pressure and the pore pressure are both equal to the top-burden. Fluid outflow tolerates grain rotation to a more compacted platform, which reduces pressure and porous porosity [2]. So, the difference between lithostatic pressure and pore pressure is a amount of compaction. Ideal compaction does not reduce pore pressure to zero. Instead, the hydrostatic pressure remains is equal with the weight of the overlay water column. In general, hydrostatic pressure is defined as part of pore pressure that does not contribute to water flow. The hydrostatic zero level can be ascertained arbitrarily, because it is only a gradient and not an absolute value of pressure that rules the flow of pore water. The groundwater table is not proper as a constant reference level, because this varies on the basin scale. Conversely, sea level is used as a hydrostatic zero level. The hydrostatic pressure is then equivalent to the weight of the water column measured by the level of seawater and therefore depends on the density of seawater and pore. It should be underlined that hydrostatic pressure is a theoretical pressure. It is not measurable pressure for the ideal solid layer or slow sedimentation [3, 4, 5, 6].

The different oilfields depletion can produce the different coupling between pore pressure and S_{hmin}, this coupling is also called stress-depletion response of reservoirs or reservoir stress path. Three mechanisms regulate reservoir stress path are normal compaction, normal faulting, and poroelasticity. It delivers the equation for $\Delta S_{hmin}/\Delta P$ for each mechanism. Reservoir depletion, which results in a pore pressure reduction initiates the mean effective stress to increase. Thus, normal compaction is mechanical compaction caused by irreversible porosity reduction due to the mean effective stress increasing [7, 8, 9]. Then, the sediments suffer normal compaction during production by losing irreversible porosity. Normal faulting defines the active faulting in rocks due to reservoir depletion. Poroelastic mechanisms are based on Biot's poroelasticity theory following pore pressure coupling equation [10]:

$$\Delta S_{hmin}/\Delta P = \alpha \frac{1-2\nu}{1-\nu} \tag{2}$$

with the Biot-Willis coefficient α, defined as $\left(1-{K_d}/{K_g}\right)$ where K_d is the drained bulk modulus and K_g is the bulk modulus of the grains.

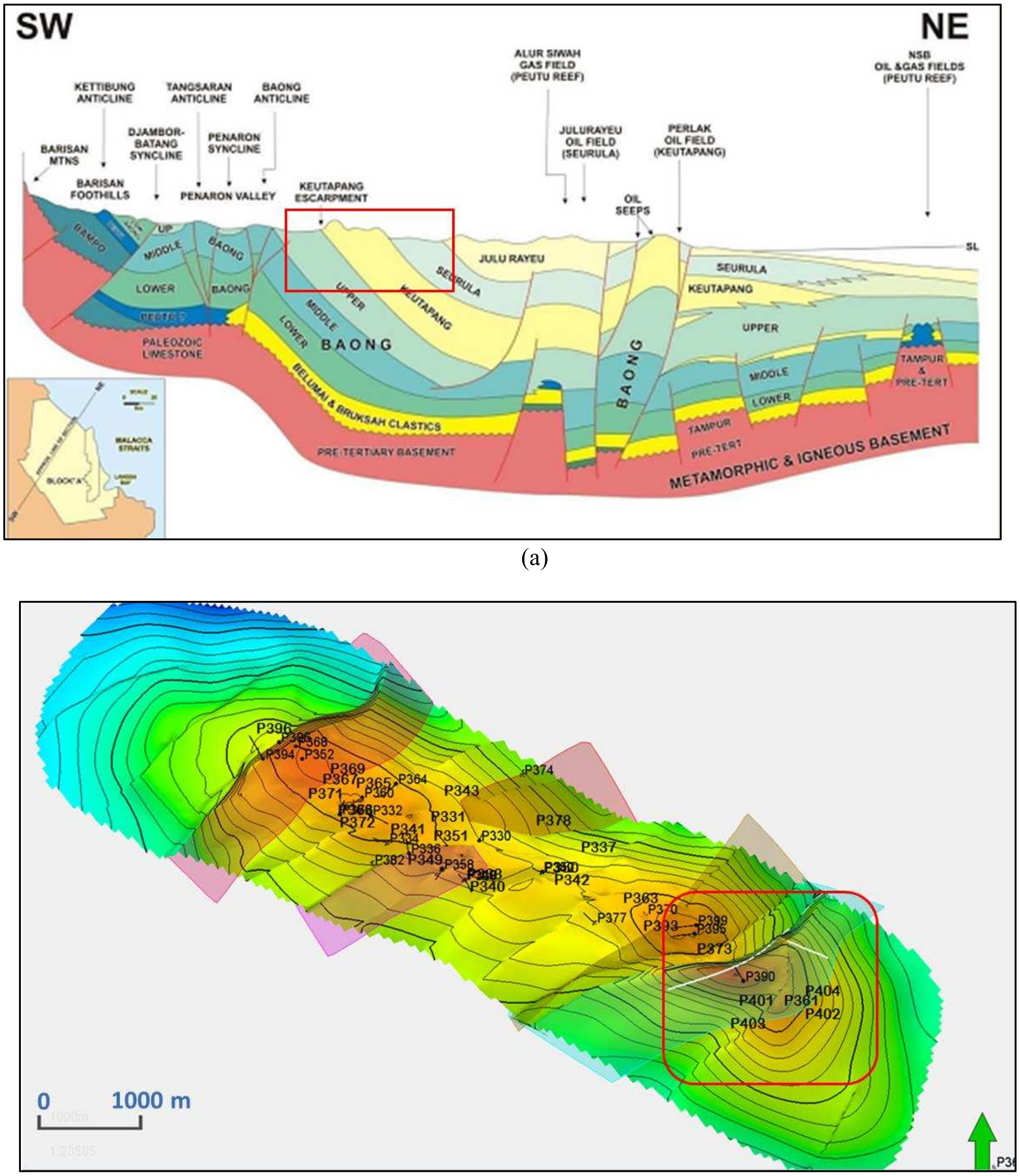
In this paper, the effect of this tectonic background to the stress ratio change will be studied, it has an impact on the coupling ratio during the hydrocarbon production and water injection takes place.

MATERIALS AND METHODS

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 [11]. 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 [12].

The island of Sumatra, tectonically, is a part of Sunda Shelf which is separated from Eurasian Plate by Malacca Strait. Longitudinal parallel with Sumatra Island in the western part is subduction zone, Indo-Australian Oceanic Plate overlaid by Eurasian Continental Plate. It is associated with the volcanic arc, together with the huge structural zone, Semangko Fault, which places the physiographic position, Bukit Barisan. Lifting has been going on since Early Eocene to present. There are three deformations, namely Pre-tertiary Deformation, Tertiary Deformation, and Quarter Deformation. However, a little bit knowledge of the Paleozoic (Tapanuli Group) structure which includes Bahorok Formation, probably NW-SE structure is associated with the direction of cleavage axial planar from Kluet Formation which is consist of schist and gneiss. Tertiary Deformation is characterized by the presence of a transcurrent fault structure, namely the Simpang Kanan Monocline, which has similar direction with Pre-tertiary Deformation. The presence of NW-SE structure can trace this deformation. Some derivatives from Simpang Kanan Monocline also appeared on the surface, and some are still active today. Quaternary Deformation occurs in Pleistocene, which is a continuation of lifting period with a similar axis with the direction of Bukit Barisan and transcurrent fault (Simpang Kanan Monocline) [13].

Fig. 1a points out the principal NE-SW stress after the initial tectonic period and continues to the present. The Rantau structure is divided into several compartments, which are bounded by general direction NE-SW oblique faults while the fold axis direction is NW-SE (**Fig. 1b**). This hydrocarbon structure is still actively produced and even to be enhanced by carrying out water injection activities on several structural heights, such as occur in the South-Eastern part of the block. Water injection successfully increases pore pressure as observed from the production data [14, 15].



(a)

(b)

FIGURE 1. The Rantau Field structure is observed in SW-NE section (a); this structure is divided into several compartments, which is bordered by NE – SW oriented fault plane (b). These faults are mostly oblique strike-slip faults. Our objective is in the South-Eastern part of this structure (red box).

There are 114 wells data available to characterize pore pressure and mechanical properties. But, not all of data were used to build initial model, it is only 43 wells from 1994 to 2017, after periodized according to the seismic data acquisition year with 8% cut-off in pore pressure change between years. The next step is to do initial mechanical modeling with the support of seismic data through the physical properties co-variance analysis, where the initial physical properties relationships are examined, such as the relationship between velocity and pressure. It is needed to consider most robust relationship between physical properties.

Historical production matching is used to bring fundamental physical properties such as porosity at the initial pore pressure value to the current pore pressure. It will bring consequences to the transformation of initial strain to the current strain. Every strain transformation will reflect stress change that can be identified as the stress ratio change between horizontal stress and vertical stress as shown in Eq. 1 above, reflected by the change of v. Meanwhile, a pore pressure change is directly revealed from historical matching from production data by an updated reservoir simulation. If there has not been a match between production data and pore pressure data, so it needs to be re-iterated until both are genuinely matching. Thus, mechanical properties and physical properties can be updated as well. This repetition is carried out so that the actual coupling ratio, which is used as the observation object with the accurate Mohr diagram. Validation is also accomplished using core, which is observed in the laboratory with both uniaxial and triaxial measurement.

There are two aspects, regarding above explanation, tectonic regimes and pore pressure. Are there interdependent or independent? It might be reflected from internal and external dynamics of the reservoir body, which affects coupling ratio. If the internal dynamics of the reservoir body in the loading mechanism will oppose vertical load that is identic to overburden pressure itself. Conversely, the resistance is aimed at the horizontal force in the tectonic mechanism.

Schematically, several steps carried out in this study are described in the following workflow (**Fig. 2**), where input data is originated from well data and seismic data.

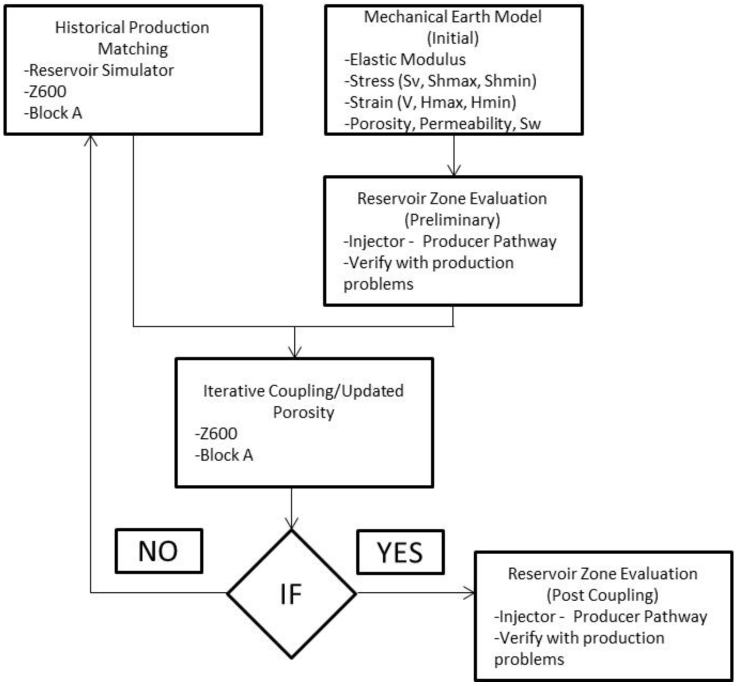


FIGURE 2. Workflow

RESULTS AND DISCUSSION

Based on the seismic cross-section and other geophysical data, it appears clearly that some thrust faults are obtained, even the oblique strike fault slip is revealed on the surface. The result of elastic modulus and strain calculation illustrate that the tectonic regime near the surface is a thrust fault regime, where $S_{HMax} > S_{hmin} > S_V$. The deeper S_V value will increase with increasing overburden pressure, but never exceeds S_{HMax}. The cross-over point position between two tectonic regimes at a depth approximately 450 meters means that Z-600 target layer placed at the strike-slip tectonic regime where $S_V > S_{hmin}$, this condition is still under the tectonic mechanism, because the S_V value is still smaller than the S_{HMax} value.

Once $S_{hmin} > S_V$, therefore υ is higher than when $S_{hmin} < S_V$, it means that the material is facing compaction due to top-loading will reduce the rate of S_{hmin} increase, where S_{hmin} reflects the S_{HMax} response. The S_{HMax} value in this case is triggered by the tectonic activity of burden from the Indo-Australian Oceanic Plate towards Eurasian Continental Plate, where it is quite intensive in the northern end of Sumatra Island, as evidenced by the large scale earthquakes found in this area, which is moment tensor describes once the Thrust Fault Regime produced the Aceh Tsunami in 2004; likewise another earthquake occurred on land.

Fig. 3 shows S_v curve and S_{hmin} curve intersect but both never cut S_{HMax} curve; this indicates that horizontal force is still dominant to influence; however, the deeper vertical force influence can not be ignored. In this case, there are two types of deviatoric stress, namely deviatoric stress before intersection point, which is the difference between S_{HMax} and S_V and the deviatoric stress after intersection point which is between S_{HMax} and S_{hmin}. The deviatoric stress which is mentioned later, it will be reviewed considering the Z-600, which is placed below that point. Physically, the higher value of deviatoric stress will describe the more rigid property with higher rock strength values. In this case, we can observe that deeper deviatoric stress is more significant. Thus, when we observe coupling ratio change; therefore, S_{hmin} value also incidentally reflects the value of deviatoric stress changes, because S_{hmin} value as the least principal stress affects rock strength value; or in other words, S_{hmin} value will be very susceptible in determining mechanical properties. Accordingly, the dynamics of physical properties will be observed throughout time changes. The dynamics can be either hydrocarbon production or water injection, which causes pore pressure change.

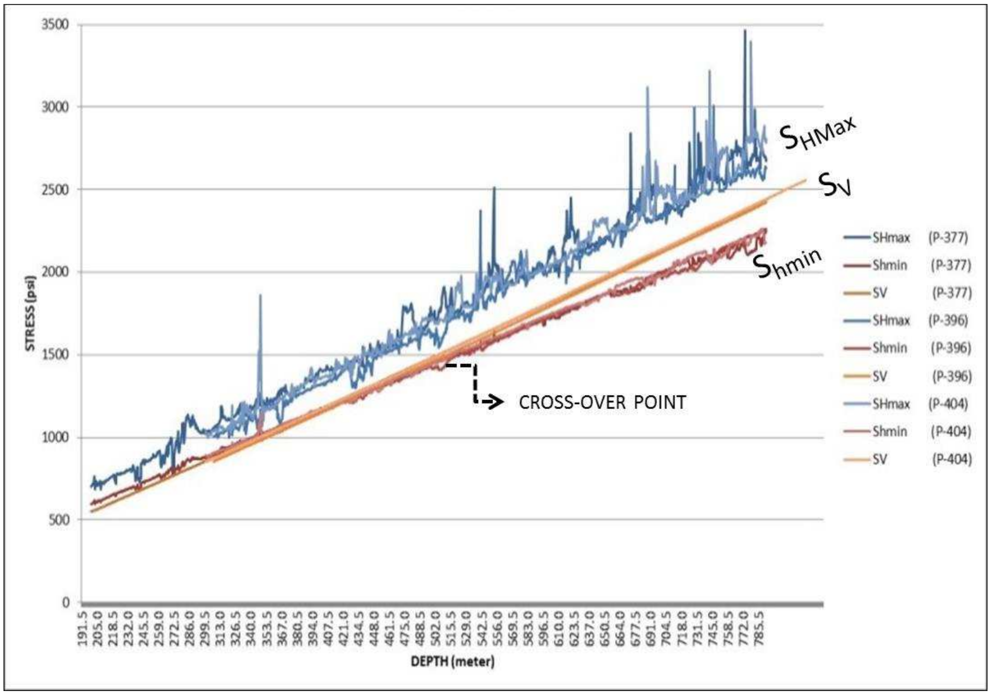


FIGURE 3. The stress curves at depth variation of several wells, which include S_V, S_{Hmax}, and S_{hmin}. It shows that S_V and S_{hmin} curves intersect, which indicates tectonic regime-changing.

If we review pore pressure change, it will appear pore pressure decreased from 1994 to 2014, ultimately in the crest of structure, which is identified by green color changes to blue color and then increased from 2014 to 2017 which is identified from blue color changes to green (**Fig. 4**). It illustrates the oil production activities from 1994 to 2014 and water injection activities from 2014 to 2017. However, in the North-Eastern part remains unaffected by water injection activities, where pore pressure continues to decrease. These dynamics will positively affect elastic modulus and rock strength.

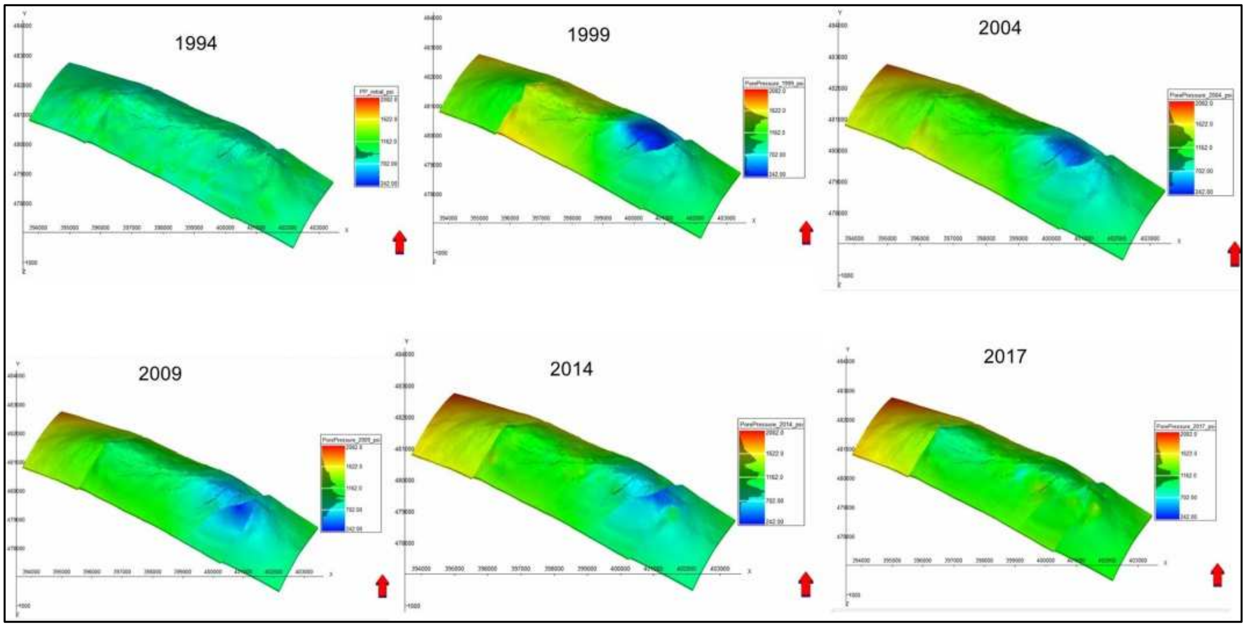
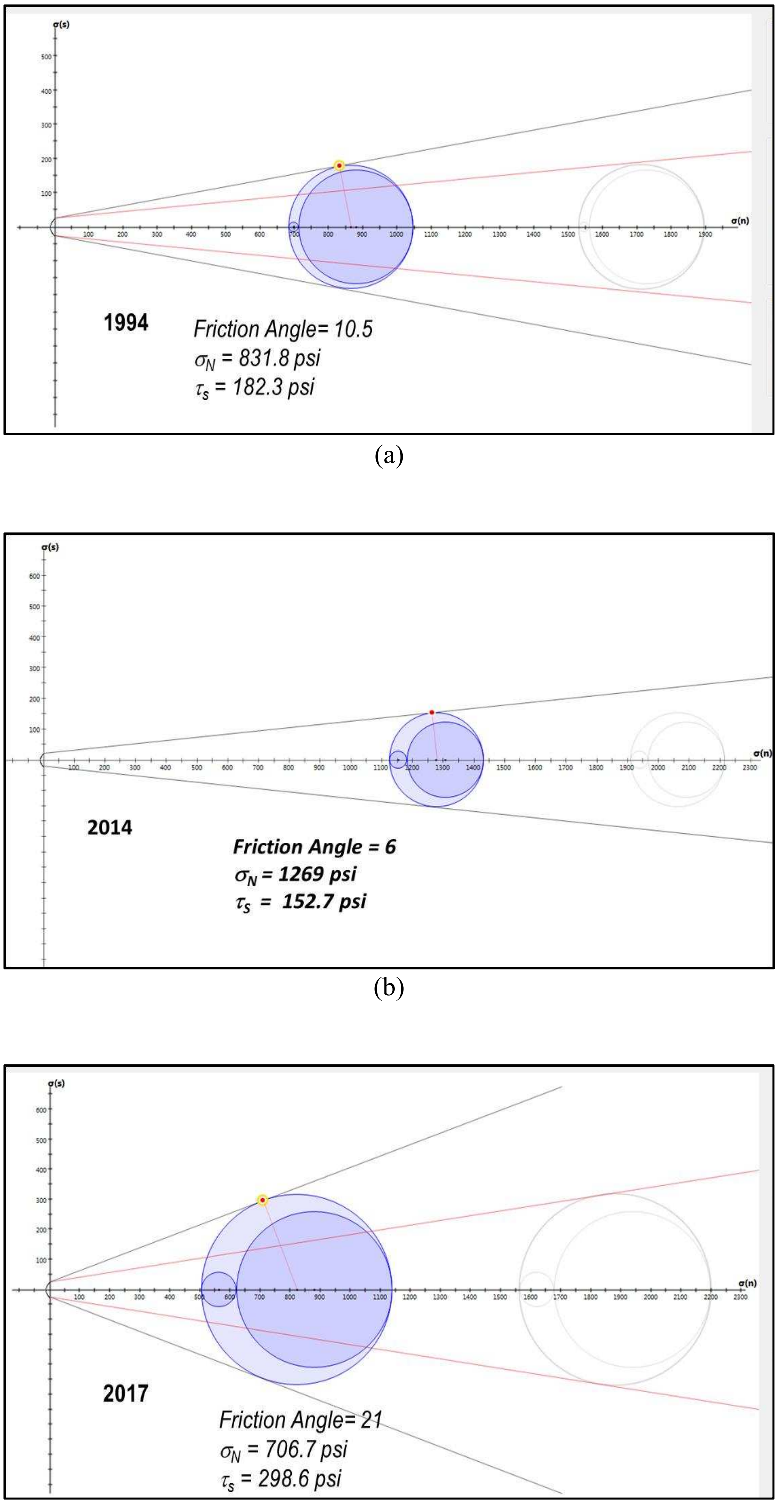


FIGURE 4. Several maps of pore pressure distribution during 1994 to 2017. There is a fluid dynamics, either fluid draining or water injection.

Furthermore, each principal stress values can be determined from the calculation of elastic modulus and strain, so this can be related to the changes of pore pressure. Pore pressure changes have pore pressure implication on the mechanical properties, which affects deviatoric stress circle pattern in the Mohr Diagram. The pore pressure addition will move the circle to the left; and otherwise, the pore pressure reduction will move the circle to the right. The pore pressure reduction, which is observed during the period 1994 to 2014, as shown in **Fig. 5**, so the circle moves to the right and otherwise, the pore pressure addition during the period 2014 to 2017, so the circle moves to the left or suffers a principal stress decrease. If it is more closely observed, the friction angle decreases firstly from 10.5^0 to 6^0, and then increases to be 21^0, which normal stress decreasing, but shear stress increasing. Thus, it can be said here that the potential failure occurs when facing shear stress.

It is interesting to discuss, if the pore pressure addition is occurring in loading mechanism so that the normal vertical stress will resist the lateral shear stress deformation. This situation will also be counter-balanced by the deviatoric stress value, which is the difference between S_{HMax} and S_{hmin}. The increasing deviatoric stress values will cause increased shear stress; and more considerable deviatoric stress value occurs in the relax basin, which is far away from the tectonic activity. Furthermore, it is found in the tectonic mechanism that there is the shear failure, which is caused by the addition of pore pressure. The pore pressure components which are similar direction with shear tensor of horizontal stresses will strengthen these tensors. Consequently, the granules will shift and break away.



(a)

(b)

(c)

FIGURE 5. The change of deviatoric stress from (a) triaxial 1994, (b) triaxial 2014 and (c) triaxial 2017 on Mohr Diagram from Z-600 at 561.98 meters depth. Data obtained from Well P-408.

According to the coupling ratio distribution map as shown in **Fig. 6**, a dark blue color illustrates a low coupling ratio, it means that there is a progression of pore pressure addition which is much higher than S_{hmin}, this is as previously explained that shear failure has the potential to increase in a dark blue area. This tendency illustrates a sanding problem potential. Therefore production scenario must be designed so that the drawdown pressure should not exceed the shear-tensile failure. Thus, the estimation of coupling ratio is essential especially in strike-slip fault tectonic regime and thrust fault regime; tectonic mechanism will increase the risk factor of the sanding problem, which deviatoric stress addition will increase the risk factor.

Based on Eq. 2 which illustrates Biot-Willis coefficient α, defined as $\left(1 - {}^{K_d}\!/_{K_g}\right)$ where K_d is the drained bulk modulus and K_g is the bulk modulus of the grains, the smaller coefficient value, then K_d and K_g values will be closer, or it has a lower porosity. It appears that even though pore pressure value increases, but it can not return the porosity value. In tectonic mechanism, an increase of pore pressure does not loosen the bond, but it makes the granular bond-slip laterally. Consequently, the granules will shift and break away. The grain size and sortation pattern also demonstrate each different response such as sand and shale. Sand is very responsive to this matter.

However, rock strength seems to increase, in this case, but it turns out that shear-tensile failure will also increase. Every failure will result in a sanding problem. We can not reduce water injection efforts, but we can reduce the potential slightly by reducing drawdown pressure. The effect of the tectonic mechanism, the higher deviatoric stress, the more it will increase shear-tensile failure, and this is not associated with pore pressure increase, but instead associated with tectonic regime factors, Rantau Field has dominant tectonic factors, so that it will have a substantial impact on the shallow layers, because the difference value between S_{HMax} and S_V or S_{hmin} is higher.

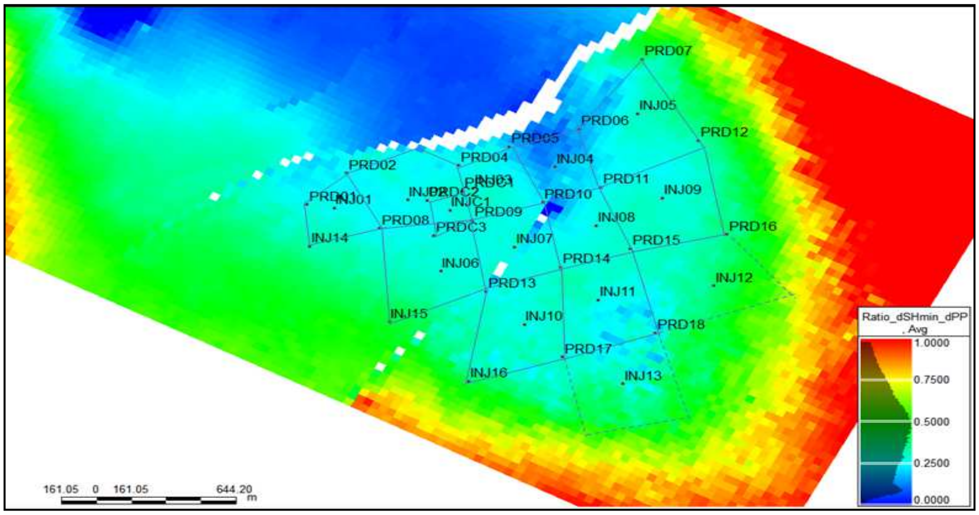


FIGURE 6. Coupling ratio map of Rantau Field shows a small value (dark blue color) indicates a water injection activity.

CONCLUSIONS

It can be concluded that the tectonic mechanism can influence a fluid dynamics by the horizontal stress impact, which is reflected from deviatoric stress. Moreover, pore pressure change is not always equal to the change of stress difference or deviatoric stress change, due to the nature of irreversible porosity change during fluid dynamics. The horizontal stress might cause shear-tensile failure, which strengthening pore pressure and it can initiate a sanding problem potential. Even though we can not avoid pore pressure addition, but we can manage drawdown pressure to keep away from sanding problem.

ACKNOWLEDGMENT

The authors would like to acknowledge PT. Pertamina EP, which permitting their data to be studied. We also would like to thank to Dr. Ir. Afiat Anugrahadi, MS as Dean of Faculty of Earth Technology and Energy, Universitas Trisakti, for a great deal of support. Last but not least, we would like to thank to our colleagues Amalia Nurani, Rischa Jayanti and Aris Endartyanto in PT. Elnusa Tbk for their valuable assistance.

REFERENCES

[1] T. Hantschel and A.I. Kauerauf, *Fundamentals of Basin and Petroleum Systems Modeling* (DOI 10.1007/978-3-540-72318-9 2, © Springer-Verlag Berlin Heidelberg, 2009.
[2] C. Hilgers, S. Nollet, J. Schonherr and J. L. Urai. Paleo–Overpressure Formation and Dissipation in Reservoir Rocks. *OIL GAS European Magazine*, vol. 2, pp. 68–73, 2006.
[3] X. Luo and G. Vasseur. Contributions of Compaction and Aquathermal Pressuring to Geopressure and the Influence of Environmental Conditions. *AAPG Bulletin*, vol. 76, no.10, pp. 1550–1559, 1992.
[4] W. D. McCain Jr. *The Properties of Petroleum Fluids*. Pennwell Books, second edition, 1990.
[5] J. E. Smith. The dynamics of Shale Compaction and Evolution of Pore Fluid Pressure. *Mathematical Geology* vol. 3, pp.239–263, 1971.
[6] R. E. Swarbrick, M. J. Osborne, and Gareth S. Yardley. Comparison of Overpressure Magnitude Resulting from the Main Generating Mechanism*s*. in A. R. Huffmann and G. L. Bowers, editors, *Pressure regimes in sedimentary basins and their prediction*, vol. 76, AAPG Memoir, 2002, pp. 1–12.
[7] M.A. Addis, Reservoir Depletion and Its Effect on Wellbore Stability Evaluation , *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, pp. 3 – 4, 1997.
[8] R. Hillis, Pore Pressure/Stress Coupling and Its Implications For Seismicity. *Exploration Geophysics*, vol. 31, pp. 448-454, 2000.
[9] N.R. Goulty, Reservoir Stress Path During Depletion of Norwegian Chalk Oilfields. *Petroleum Geoscience,* vol. 9, pp. 233-241, 2003.
[10] T. Engelder and M.P. Fischer, Influence of Poroelastic Behavior on the Magnitude of Minimum Horizontal Stress, Sh, in Overpressured Parts of Sedimentary Basin, Geology, vol. 22, pp. 949-952, 1994.
[11] I. Shahab, I. Suhartanto, R.R. Wathan and M.D. Junaidi, Reaktivasi Shallow Zone dalam Upaya Pencarian Sisa-sisa dan Peningkatan Produksi Minyak di Struktur Rantau, Prosiding IATMI 2004 Bandung, 2005, pp. 1-10.
[12] H. Darman and F.H. Sidi, *An Outline of the Geology of Indonesia*, IAGI, 2000.
[13] J.D. Bennett, D. McC. Bridge, N.R.C. Cameron, A. Djaenuddin, S.A Ghazali,.D.H. Jeffrey, W. Kartawa, W. Keats, N.M.S. Rock and S.J. Thompson, Geologi Lembar Langsa, Sumatera (The Geology of the Langsa Quadrangle, Sumatera), Pusat Penelitian dan Pengembangan Geologi, Direktorat Jenderal Pertambangan Umum, Departemen Pertambangan dan Energi, 1981.
[14] A.F. Rahman, A. Haris and I.S. Ronoatmojo, Determining the Reservoir Compartments Based on Fault Sealing Analysis Studying of Tamiang Field North Sumatera Basin, Indonesia. AIP Conference Proceeding 2023, 020262, 2018, pp. 1-5.
[15] I.S. Ronoatmojo, G.S. Titaley, A. Widianto, W. Silvia, A. Nurani and R. Jayanti, The Case Study of Empirical Relation Between Pore Pressure and P-Impedance in Shallow Layer, JCM HAGI – IAGI – IAFMI- IATMI 2017 Malang, 2017, pp. 1-4.

The Influence of Tectonic Forces on the Coupling Ratio of Sand Z-600, Keutapang Formation, North Sumatra Basin

Imam Setiaji Ronoatmojo[1, a)], Muhamad Burhannudinnur[1)] and Grace Stephani Titaley[2)]

[1] Faculty of Earth Technology and Energy, Universitas Trisakti, Jl. Kyai Tapa No.1, Jakarta 11440, Indonesia
[2] PT. Pertamina EP, Menara Standard Chartered No. 164, Lt 16, Jl. Prof. Dr. Satrio, Jakarta 12950, Indonesia

[a)]Corresponding author: aji.rono@trisakti.ac.id

Abstract. The tectonic mechanism is a mechanism that involves tectonic conditions in the area which affects the dynamics of poroelasticity. Elastic modulus in the porous medium will go through change along with fluid dynamics. The loading factor in the tectonic mechanism is followed by the tectonic forces. The aim of this study is to learn the impact of a tectonic mechanism on the coupling ratio during oil production and water injection. The objective zone of this study is a part of thrust fault regime, which is changed to be strike-slip fault regime. The sand reservoir of Z-600 is in the transition condition so that the dominance of S_V and S_{hmin} has a strong influence on a coupling ratio change. The fluid dynamics occurring during this period are oil production and water injection. Observations were made on mechanical properties and pore pressure changes. The coupling ratio estimation starting from 1994 until 2017 refers to a historical production matching, which demonstrates a rock strength response in the variation of existing tectonic regime position. Mohr diagram analysis was done, based on the Coulomb failure criterion. It reveals that pore pressure change is not always equal to the change in stress difference or deviatoric stress, due to the nature of irreversible porosity change during fluid dynamics. The horizontal stress might cause shear-tensile failure, it initiates a sanding problem potential.

Keywords: tectonic mechanism, coupling ratio, rock strength, shear-tensile failure, sanding problem

INTRODUCTION

A homogeneous material modifies shape vertically and horizontally under a constant burden whilst the horizontal stress is zero, and the vertical stress in each location is equal to the overburden pressure. If the horizontal stress components are compressive and equal to a fixed ratio of the top-burden and the side boundaries, the Poisson ratio ν is a material constant which generates stress ratios:

$$S_{hmin}/S_V = \nu/(1 - \nu) \tag{1}$$

The situation of fixed stable with vertical load is similar to the non-tectonically influenced basins, which increase linearly with depth. The geomechanical properties heterogeneity causes a different stress ratio and the principal stress axis rotation. Fault plane disrupts homogeneous tendencies in stress. Tectonic processes generally insert compressive stress or tensile stress to the horizontal component. The expansion of the model to reduce horizontal stress can return a compressive (positive) stress into a tensile (negative) stress, while the compressive boundaries can enlarge the horizontal stresses so that it exceeds the vertical stress and develop the maximum principal stress [1].

Pore pressure is the pressure value measured in pore fluid. It is mostly due to the weight of top-burden, but fluid run along with compaction can reduce pore pressure. The pressure is usually smaller than lithostatic pressure. In

2nd International Conference on Earth Science, Mineral, and Energy
AIP Conf. Proc. 2245, 100001-1–100001-9; https://doi.org/10.1063/5.0006950
Published by AIP Publishing. 978-0-7354-2004-5/$30.00

porous rock that can not be compacted, the lithostatic pressure and the pore pressure are both equal to the top-burden. Fluid outflow tolerates grain rotation to a more compacted platform, which reduces pressure and porous porosity [2]. So, the difference between lithostatic pressure and pore pressure is a amount of compaction. Ideal compaction does not reduce pore pressure to zero. Instead, the hydrostatic pressure remains is equal with the weight of the overlay water column. In general, hydrostatic pressure is defined as part of pore pressure that does not contribute to water flow. The hydrostatic zero level can be ascertained arbitrarily, because it is only a gradient and not an absolute value of pressure that rules the flow of pore water. The groundwater table is not proper as a constant reference level, because this varies on the basin scale. Conversely, sea level is used as a hydrostatic zero level. The hydrostatic pressure is then equivalent to the weight of the water column measured by the level of seawater and therefore depends on the density of seawater and pore. It should be underlined that hydrostatic pressure is a theoretical pressure. It is not measurable pressure for the ideal solid layer or slow sedimentation [3, 4, 5, 6].

The different oilfields depletion can produce the different coupling between pore pressure and S_{hmin}, this coupling is also called stress-depletion response of reservoirs or reservoir stress path. Three mechanisms regulate reservoir stress path are normal compaction, normal faulting, and poroelasticity. It delivers the equation for $\Delta S_{hmin}/\Delta P$ for each mechanism. Reservoir depletion, which results in a pore pressure reduction initiates the mean effective stress to increase. Thus, normal compaction is mechanical compaction caused by irreversible porosity reduction due to the mean effective stress increasing [7, 8, 9]. Then, the sediments suffer normal compaction during production by losing irreversible porosity. Normal faulting defines the active faulting in rocks due to reservoir depletion. Poroelastic mechanisms are based on Biot's poroelasticity theory following pore pressure coupling equation [10]:

$$\Delta S_{hmin}/\Delta P = \alpha \frac{1-2\nu}{1-\nu} \qquad (2)$$

with the Biot-Willis coefficient α, defined as $\left(1 - {K_d}/{K_g}\right)$ where K_d is the drained bulk modulus and K_g is the bulk modulus of the grains.

In this paper, the effect of this tectonic background to the stress ratio change will be studied, it has an impact on the coupling ratio during the hydrocarbon production and water injection takes place.

MATERIALS AND METHODS

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 [11]. 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 [12].

The island of Sumatra, tectonically, is a part of Sunda Shelf which is separated from Eurasian Plate by Malacca Strait. Longitudinal parallel with Sumatra Island in the western part is subduction zone, Indo-Australian Oceanic Plate overlaid by Eurasian Continental Plate. It is associated with the volcanic arc, together with the huge structural zone, Semangko Fault, which places the physiographic position, Bukit Barisan. Lifting has been going on since Early Eocene to present. There are three deformations, namely Pre-tertiary Deformation, Tertiary Deformation, and Quarter Deformation. However, a little bit knowledge of the Paleozoic (Tapanuli Group) structure which includes Bahorok Formation, probably NW-SE structure is associated with the direction of cleavage axial planar from Kluet Formation which is consist of schist and gneiss. Tertiary Deformation is characterized by the presence of a transcurrent fault structure, namely the Simpang Kanan Monocline, which has similar direction with Pre-tertiary Deformation. The presence of NW-SE structure can trace this deformation. Some derivatives from Simpang Kanan Monocline also appeared on the surface, and some are still active today. Quaternary Deformation occurs in Pleistocene, which is a continuation of lifting period with a similar axis with the direction of Bukit Barisan and transcurrent fault (Simpang Kanan Monocline) [13].

Fig. 1a points out the principal NE-SW stress after the initial tectonic period and continues to the present. The Rantau structure is divided into several compartments, which are bounded by general direction NE-SW oblique modeling with the support of seismic data through the physical properties co-variance analysis, where the initial physical properties relationships are examined, such as the relationship between velocity and pressure. It is needed to consider most robust relationship between physical properties.

Historical production matching is used to bring fundamental physical properties such as porosity at the initial pore pressure value to the current pore pressure. It will bring consequences to the transformation of initial strain to the current strain. Every strain transformation will reflect stress change that can be identified as the stress ratio change between horizontal stress and vertical stress as shown in Eq. 1 above, reflected by the change of v. Meanwhile, a pore pressure change is directly revealed from historical matching from production data by an updated reservoir simulation. If there has not been a match between production data and pore pressure data, so it needs to be re-iterated until both are genuinely matching. Thus, mechanical properties and physical properties can be updated as well. This repetition is carried out so that the actual coupling ratio, which is used as the observation object with the accurate Mohr diagram. Validation is also accomplished using core, which is observed in the laboratory with both uniaxial and triaxial measurement.

There are two aspects, regarding above explanation, tectonic regimes and pore pressure. Are there interdependent or independent? It might be reflected from internal and external dynamics of the reservoir body, which affects coupling ratio. If the internal dynamics of the reservoir body in the loading mechanism will oppose vertical load that is identic to overburden pressure itself. Conversely, the resistance is aimed at the horizontal force in the tectonic mechanism.

Schematically, several steps carried out in this study are described in the following workflow (**Fig. 2**), where input data is originated from well data and seismic data.

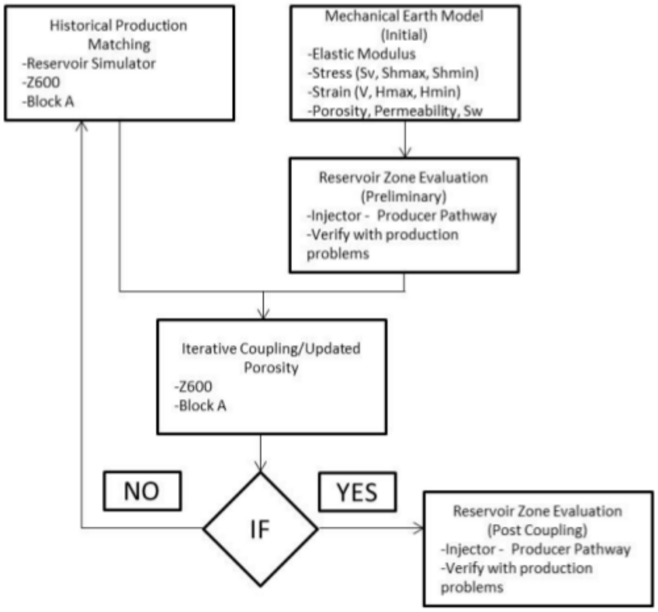


FIGURE 2. Workflow

RESULTS AND DISCUSSION

Based on the seismic cross-section and other geophysical data, it appears clearly that some thrust faults are obtained, even the oblique strike fault slip is revealed on the surface. The result of elastic modulus and strain calculation illustrate that the tectonic regime near the surface is a thrust fault regime, where $S_{HMax} > S_{hmin} > S_V$. The deeper S_V value will increase with increasing overburden pressure, but never exceeds S_{HMax}. The cross-over point position between two tectonic regimes at a depth approximately 450 meters means that Z-600 target layer placed at the strike-slip tectonic regime where $S_V > S_{hmin}$, this condition is still under the tectonic mechanism, because the S_V value is still smaller than the S_{HMax} value.

Once $S_{hmin} > S_V$, therefore υ is higher than when $S_{hmin} < S_V$, it means that the material is facing compaction due to top-loading will reduce the rate of S_{hmin} increase, where S_{hmin} reflects the S_{HMax} response. The S_{HMax} value in this case is triggered by the tectonic activity of burden from the Indo-Australian Oceanic Plate towards Eurasian Continental Plate, where it is quite intensive in the northern end of Sumatra Island, as evidenced by the large scale earthquakes found in this area, which is moment tensor describes once the Thrust Fault Regime produced the Aceh Tsunami in 2004; likewise another earthquake occurred on land.

Fig. 3 shows S_v curve and S_{hmin} curve intersect but both never cut S_{HMax} curve; this indicates that horizontal force is still dominant to influence; however, the deeper vertical force influence can not be ignored. In this case, there are two types of deviatoric stress, namely deviatoric stress before intersection point, which is the difference between S_{HMax} and S_V and the deviatoric stress after intersection point which is between S_{HMax} and S_{hmin}. The deviatoric stress which is mentioned later, it will be reviewed considering the Z-600, which is placed below that point. Physically, the higher value of deviatoric stress will describe the more rigid property with higher rock strength values. In this case, we can observe that deeper deviatoric stress is more significant. Thus, when we observe coupling ratio change; therefore, S_{hmin} value also incidentally reflects the value of deviatoric stress changes, because S_{hmin} value as the least principal stress affects rock strength value; or in other words, S_{hmin} value will be very susceptible in determining mechanical properties. Accordingly, the dynamics of physical properties will be observed throughout time changes. The dynamics can be either hydrocarbon production or water injection, which causes pore pressure change.

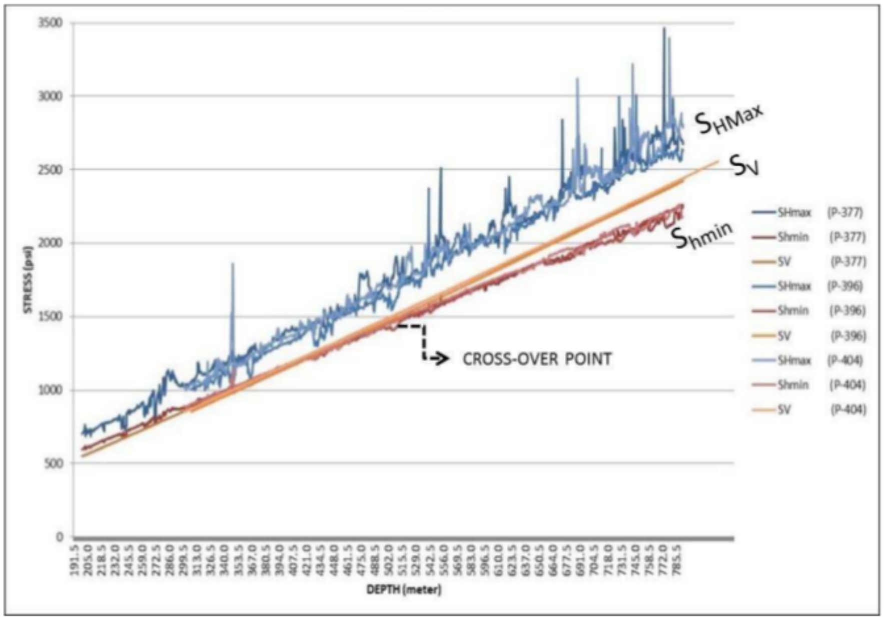
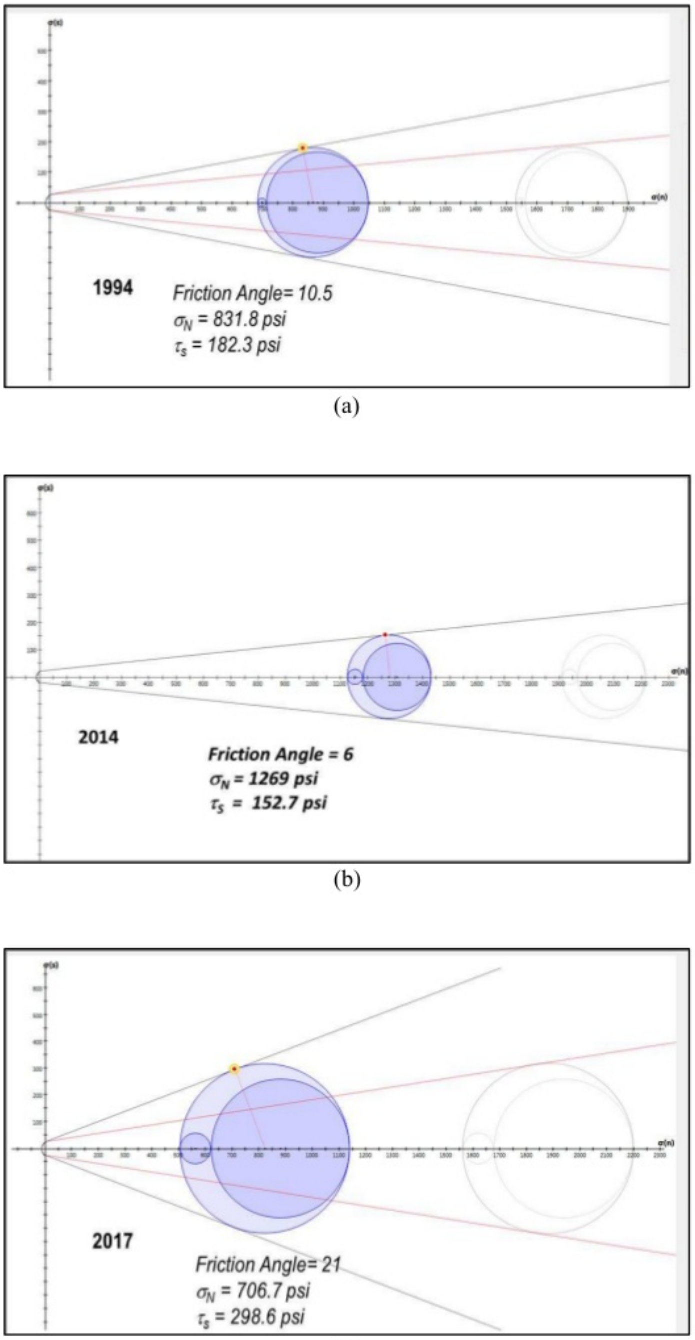


FIGURE 3. The stress curves at depth variation of several wells, which include S_V, S_{Hmax} , and S_{hmin}. It shows that S_V and S_{hmin} curves intersect, which indicates tectonic regime-changing.

If we review pore pressure change, it will appear pore pressure decreased from 1994 to 2014, ultimately in the crest of structure, which is identified by green color changes to blue color and then increased from 2014 to 2017 which is identified from blue color changes to green (**Fig. 4**). It illustrates the oil production activities from 1994 to 2014 and water injection activities from 2014 to 2017. However, in the North-Eastern part remains unaffected by water injection activities, where pore pressure continues to decrease. These dynamics will positively affect elastic modulus and rock strength.



(a)

(b)

(c)

FIGURE 5. The change of deviatoric stress from (a) triaxial 1994, (b) triaxial 2014 and (c) triaxial 2017 on Mohr Diagram from Z-600 at 561.98 meters depth. Data obtained from Well P-408.

According to the coupling ratio distribution map as shown in **Fig. 6**, a dark blue color illustrates a low coupling ratio, it means that there is a progression of pore pressure addition which is much higher than S_{hmin}, this is as previously explained that shear failure has the potential to increase in a dark blue area. This tendency illustrates a sanding problem potential. Therefore production scenario must be designed so that the drawdown pressure should not exceed the shear-tensile failure. Thus, the estimation of coupling ratio is essential especially in strike-slip fault tectonic regime and thrust fault regime; tectonic mechanism will increase the risk factor of the sanding problem, which deviatoric stress addition will increase the risk factor.

Based on Eq. 2 which illustrates Biot-Willis coefficient α, defined as $\left(1 - {}^{K_d}\!/_{K_g}\right)$ where K_d is the drained bulk modulus and K_g is the bulk modulus of the grains, the smaller coefficient value, then K_d and K_g values will be closer, or it has a lower porosity. It appears that even though pore pressure value increases, but it can not return the porosity value. In tectonic mechanism, an increase of pore pressure does not loosen the bond, but it makes the granular bond-slip laterally. Consequently, the granules will shift and break away. The grain size and sortation pattern also demonstrate each different response such as sand and shale. Sand is very responsive to this matter.

However, rock strength seems to increase, in this case, but it turns out that shear-tensile failure will also increase. Every failure will result in a sanding problem. We can not reduce water injection efforts, but we can reduce the potential slightly by reducing drawdown pressure. The effect of the tectonic mechanism, the higher deviatoric stress, the more it will increase shear-tensile failure, and this is not associated with pore pressure increase, but instead associated with tectonic regime factors, Rantau Field has dominant tectonic factors, so that it will have a substantial impact on the shallow layers, because the difference value between S_{HMax} and S_V or S_{hmin} is higher.

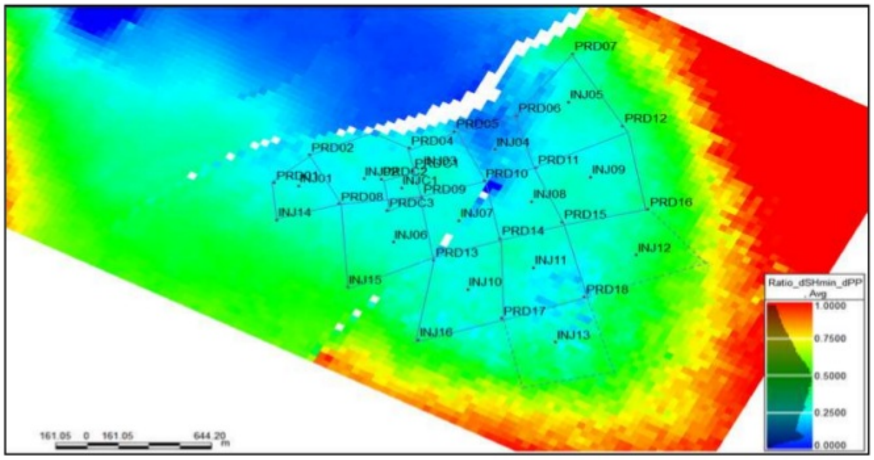


FIGURE 6. Coupling ratio map of Rantau Field shows a small value (dark blue color) indicates a water injection activity.

CONCLUSIONS

It can be concluded that the tectonic mechanism can influence a fluid dynamics by the horizontal stress impact, which is reflected from deviatoric stress. Moreover, pore pressure change is not always equal to the change of stress difference or deviatoric stress change, due to the nature of irreversible porosity change during fluid dynamics. The horizontal stress might cause shear-tensile failure, which strengthening pore pressure and it can initiate a sanding problem potential. Even though we can not avoid pore pressure addition, but we can manage drawdown pressure to keep away from sanding problem.

ACKNOWLEDGMENT

The authors would like to acknowledge PT. Pertamina EP, which permitting their data to be studied. We also would like to thank to Dr. Ir. Afiat Anugrahadi, MS as Dean of Faculty of Earth Technology and Energy, Universitas Trisakti, for a great deal of support. Last but not least, we would like to thank to our colleagues Amalia Nurani, Rischa Jayanti and Aris Endartyanto in PT. Elnusa Tbk for their valuable assistance.

REFERENCES

[1] T. Hantschel and A.I. Kauerauf, *Fundamentals of Basin and Petroleum Systems Modeling* (DOI 10.1007/978-3-540-72318-9 2, © Springer-Verlag Berlin Heidelberg, 2009.

[2] C. Hilgers, S. Nollet, J. Schonherr and J. L. Urai. Paleo–Overpressure Formation and Dissipation in Reservoir Rocks. *OIL GAS European Magazine*, vol. 2, pp. 68–73, 2006.

[3] X. Luo and G. Vasseur. Contributions of Compaction and Aquathermal Pressuring to Geopressure and the Influence of Environmental Conditions. *AAPG Bulletin*, vol. 76, no.10, pp. 1550–1559, 1992.

[4] W. D. McCain Jr. *The Properties of Petroleum Fluids*. Pennwell Books, second edition, 1990.

[5] J. E. Smith. The dynamics of Shale Compaction and Evolution of Pore Fluid Pressure. *Mathematical Geology* vol. 3, pp.239–263, 1971.

[6] R. E. Swarbrick, M. J. Osborne, and Gareth S. Yardley. Comparison of Overpressure Magnitude Resulting from the Main Generating Mechanisms. in A. R. Huffmann and G. L. Bowers, editors, *Pressure regimes in sedimentary basins and their prediction*, vol. 76, AAPG Memoir, 2002, pp. 1–12.

[7] M.A. Addis, Reservoir Depletion and Its Effect on Wellbore Stability Evaluation , *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, pp. 3 – 4, 1997.

[8] R. Hillis, Pore Pressure/Stress Coupling and Its Implications For Seismicity. *Exploration Geophysics*, vol. 31, pp. 448-454, 2000.

[9] N.R. Goulty, Reservoir Stress Path During Depletion of Norwegian Chalk Oilfields. *Petroleum Geoscience*, vol. 9, pp. 233-241, 2003.

[10] T. Engelder and M.P. Fischer, Influence of Poroelastic Behavior on the Magnitude of Minimum Horizontal Stress, Sh, in Overpressured Parts of Sedimentary Basin, Geology, vol. 22, pp. 949-952, 1994.

[11] I. Shahab, I. Suhartanto, R.R. Wathan and M.D. Junaidi, Reaktivasi Shallow Zone dalam Upaya Pencarian Sisa-sisa dan Peningkatan Produksi Minyak di Struktur Rantau, Prosiding IATMI 2004 Bandung, 2005, pp. 1-10.

[12] S. Darman and F.H. Sidi, *An Outline of the Geology of Indonesia*, IAGI, 2000.

[13] J.D. Bennett, D. McC. Bridge, N.R.C. Cameron, A. Djaenuddin, S.A Ghazali,.D.H. Jeffrey, W. Kartawa, W. Keats, N.M.S. Rock and S.J. Thompson, Geologi Lembar Langsa, Sumatera (The Geology of the Langsa Quadrangle, Sumatera), Pusat Penelitian dan Pengembangan Geologi, Direktorat Jenderal Pertambangan Umum, Departemen Pertambangan dan Energi, 1981.

[14] A.F. Rahman, A. Haris and I.S. Ronoatmojo, Determining the Reservoir Compartments Based on Fault Sealing Analysis Studying of Tamiang Field North Sumatera Basin, Indonesia. AIP Conference Proceeding 2023, 020262, 2018, pp. 1-5.

[15] I.S. Ronoatmojo, G.S. Titaley, A. Widianto, W. Silvia, A. Nurani and R. Jayanti, The Case Study of Empirical Relation Between Pore Pressure and P-Impedance in Shallow Layer, JCM HAGI – IAGI – IAFMI- IATMI 2017 Malang, 2017, pp. 1-4.

The influence of tectonic forces on the coupling ratio of sand Z-600, Keutapang formation, North Sumatra Basin

ORIGINALITY REPORT

13%	10%	12%	9%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	digbib.ubka.uni-karlsruhe.de Internet Source	2%
2	Regawa Bayu Pamungkas, Bakti Jos, Mohammad Djaeni, Ken Arus Dwi Saputri. "Granulation processing variables on the physical properties of granule slow release urea fertilizer", AIP Publishing, 2020 Publication	1%
3	sinta3.ristekdikti.go.id Internet Source	1%
4	Ali Mortazavi, Hadi Atapour. "An experimental study of stress changes induced by reservoir depletion under true triaxial stress loading conditions", Journal of Petroleum Science and Engineering, 2018 Publication	1%
5	eprints.kfupm.edu.sa Internet Source	1%
	Submitted to University of Leeds	

6	Student Paper	1%
7	Submitted to Universiti Teknologi Petronas Student Paper	1%
8	M.R. Wajzer, A.J. Barber, S. Hidayat, Suharsono. "Accretion, collision and strike-slip faulting: the Woyla group as a key to the tectonic evolution of North Sumatra", Journal of Southeast Asian Earth Sciences, 1991 Publication	1%
9	Thomas Hantschel. "Migration and Accumulation", Fundamentals of Basin and Petroleum Systems Modeling, 2009 Publication	1%
10	Junliang Yuan, Jingen Deng, Yong Luo, Shisheng Guo, Haishan Zhang, Qiang Tan, Kai Zhao, Lianbo Hu. "The Research on Borehole Stability in Depleted Reservoir and Caprock: Using the Geophysics Logging Data", The Scientific World Journal, 2013 Publication	1%
11	www.ged.rwth-aachen.de Internet Source	1%
12	Xiaochen Wei, Qi Li, Xiaying Li, Zhiyong Niu, Xiangjun Liu, Lixi Liang. "Effects of Different Penetration Patterns on a Fault during	1%

Underground Fluid Injection", Geofluids, 2019
Publication

13	Altmann, Johannes Benedikt. "Poroelastic effects in reservoir modelling", Universität Karlsruhe, 2010. Publication	1%
14	Submitted to Australian National University Student Paper	<1%
15	R D Nugraheni, D Sunjaya, S Agustini. "Regional tectonic and geochemical approach to distinguish bauxite characteristics in Pahang, Malaysia and West Kalimantan, Indonesia", IOP Conference Series: Earth and Environmental Science, 2018 Publication	<1%
16	Marte Gutierrez, Magnus Wangen. "Modeling of compaction and overpressuring in sedimentary basins", Marine and Petroleum Geology, 2005 Publication	<1%
17	pg.geoscienceworld.org Internet Source	<1%
18	Ahmad Jahrudin, M. Syamsu Rosid, Imam Setiaji Ronoatmojo, Solehudin, Ricky Adi Wibowo. "Identification of Potential HC Reservoir in field “x” by using 3D Inversion Gravity Modeling and Magnetic Data", IOP Conference Series: Earth and Environmental	<1%

Science, 2019
Publication

Exclude quotes	Off	Exclude matches	< 15 words
Exclude bibliography	Off		